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Research Article

Reliability Estimation of Low-Voltage Power Distribution Systems

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Many accidents always happen in the electricity distribution sector, which requires the use of control strategies in this field. Therefore, this study presented a risk assessment method based on a fuzzy Bayesian network (FBN) and William Fine method in low-voltage power distribution systems to reduce the structural uncertainties of the studies and examined the reliability of these systems to achieve proper performance in emergencies. The first step is to develop a fault tree (FT) and event tree (ET) in bow tie (BT) format. In this study, fuzzy theory and expert judgment were used to qualitatively analyze the root events affecting the system failure and determine the relevant probabilities. Then, deductive and inductive reasoning was done after determining the likelihood of basic events (BEs) and establishing the Bayesian network (BN). Then, the final risk was estimated using William Fine's method and fuzzy logic. The results of a case study in a low-voltage power distribution system showed that there were 36 BEs and 20 intermediate events (IEs) for system failure, and the reliability of the system was obtained as 0.96654476 and 0.96654476 based on the FT and FBN, respectively. According to the results of BE25 (no installation of the earth) and BE18 (contact of metal objects with the live wire), the most critical events were based on FBN. The results showed that FBN simulation and its combination with static methods such as BT and William Fine provide a suitable method for the accurate identification of distribution systems. Therefore, the approach of the present study can help the decision makers and analysts of the electricity industry to prevent possible failures due to system changes.

1. Introduction

Electricity is produced in various power plants, such as thermal, gas, and so on, and is provided to the distribution department through transmission networks. The distribution system is also the interface between the transmission system and electricity consumers. Since many groups such as ordinary people and repair and renovation groups are exposed to distribution network facilities, the possibility of accidents in these networks is high, which causes irreparable financial and human losses [1]. In the decade from 1999 to 2009, contact with overhead power lines is the biggest cause of death from electrocution and 42% of deaths in America happened by contact with transmission and distribution overhead power lines [2].

Based on the information collected in the 5-year period from 2010 to 2015, 91 accidents related to distribution networks occurred in Golestan Province (Iran), which resulted in the death of 15 people, which requires special attention to safety issues [3]. The application of control measures can reduce the risk of accidents or control their consequences. Due to resource limitations, effective management should be applied [4, 5]. Safety is the degree of avoiding danger, and it is one of the human rights. Risk assessment is a clear example to ensure this right in design and operation [6]. There are various methods for risk assessment or system reliability assessment, and most of them such as fault tree analysis (FTA) and event tree analysis (ETA) have two problems of uncertainty and structural statics [7–9].

Equipment reliability assessment is a challenging problem for engineers and reliability researchers [10]. In order to respond to emergency situations, systems must perform well. Therefore, any defect in these systems can lead to dangerous conditions. The systems may sometimes not function properly due to the lack of continuous monitoring and periodic visits in critical situations. Therefore, it is necessary to identify the parameters affecting their performance so that the failure rate of these parameters can be reduced by providing intervention measures. Therefore, the failure rate of these parameters should be determined in order to estimate the reliability of the system and improve the performance of these systems in critical conditions by providing intervention measures [11]. A question is often raised: what is the reliability of the systems during their future working life and how much is its safety? Part of this question can be answered by evaluating and quantifying reliability [12].

The complexity of the situation, the problems related to the combination of information, and the existence of uncertainty in decisions are among the most important reasons for the development of risk analysis methods [13]. Frank Knight distinctly distinguished between risk and uncertainty regarding the nature of decisions made almost a century ago in a business company in relation to the process of profit generation in the markets [14]. In most cases, the two words, uncertainty and risk, are used as equivalent and have the same meaning. However, uncertainty is not equivalent to risk despite its close relationship with risk [15]. The Oxford English Dictionary defines uncertainty as "not able to be relied upon and not known or definite," pointing out that uncertainty is a state of ignorance, where a person lacks complete knowledge of a situation [16].

There are four sources of failure rate, including technical data on the failure rate of the desired system, data from testing and predicting the failure rate of components, data from general reliability books, and data from expert knowledge and judgment for risk assessment studies [17]. In safety issues, using the knowledge and judgment of experts is very helpful in situations of lack of information. The ambiguous, qualitative, and subjective nature of judgments will also cause cognitive uncertainty [18, 19]. Methods including imprecise probability (interval probability), random sets (evidence theory), fuzzy logic, and Bayesian network (BN) have been developed for analyzing uncertainty in risk assessment [20–22].

In recent years, BN has been widely used for safety evaluation. In the Bayesian method, the preevent data are used in the form of a probability function through Bayes' theorem to update the analyst's previous belief about the probability of an accident or the probability of failure of safety barriers [23–25]. BN has been used as a reliable method in evaluating the safety of a wide range of process equipment and factories due to its flexible graphical display and strong reasoning engine [26].

In the electricity distribution industry, the lack of sufficient information about previous accidents and their consequences is an important challenge that can be overcome to some extent by relying on fuzzy reasoning [1]. The low-voltage power network is one of the riskiest among other types of power distribution networks [27]. Therefore, in this study, we tried to investigate and analyze low-voltage power systems.

1.1. Literature Review. There are several uncertainties in different stages of risk assessment studies, which can be mentioned as completeness, modeling, and parameter uncertainties [28, 29]. Incorrect interference between different factors and variables in the accident scenario models is also related to modeling, and the lack, insufficiency, or vagueness of the values for the model variables is also a parameter type [28]. The inaccuracy in identifying the types of consequences and the interactions between them is also a type of completeness uncertainty [28]. Various studies have tried to reduce uncertainties in different stages of risk assessment [30, 31]. Table 1 shows the advantages and disadvantages of common approaches. It should be noted that the literature review in this study was done with different keywords such as risk assessment, fuzzy logic, Bayesian network, power plan, low voltage, uncertainty, safety risk assessment, reliability, electricity distribution industry, FTA, ETA, bow tie, and so on.

Most of the studies conducted, such as Sansavini et al. 's study, focus on reducing uncertainties such as uncertainties related to consumption variability, ambient temperature variability, wind speed variability, and wind power generation variability which is not completely in the field of safety and health risk assessment [39]. The study of Tancredo Borges also provides evaluation methods based on analytical techniques, Monte Carlo simulation, or hybrid approaches to evaluate the reliability of distribution systems in the field of electricity generation and not its safety [40].

System safety, reliability, and risk analysis are important tasks performed throughout the system life cycle to ensure the reliability of critical systems [41]. The application of probabilistic risk assessment (PRA) approaches, such as FTA, ETA, and FMEA, currently faces many challenges due to the complexity and dynamics of modern systems [42, 43].

Comprehensive and accurate analysis of complex systems should consider various features such as functional dependencies between components, temporal behavior of systems, multiple failure modes for components, and uncertainty in system behavior and failure data [44, 45]. Unfortunately, as mentioned, classical approaches are unable to account for these aspects.

In most of the risk studies in power generation and transmission industries, less attention has been paid to human, organizational, and management issues and more attention has been paid to the analysis of technical failures. One of the great sources of uncertainty in risk calculations and estimations is human behavior, and existing data banks

Table 1: A review of literature on risk assessment studies in power systems.

Goal of study (ref)	Location	Method	Advantages	Disadvantages
Quantitative risk assessment (QRA) [27]	Electricity distribution processes	ETBA, VICOR, and fuzzy TOPSIS	Application of decision-making models in fuzzy environment minimizes the judgment of assessors in the risk assessment	The static nature of the ETBA structure Uncertainty in the selection of interventions and failure to consider cause-and-effect relationships
Identification of hazards [32]	Power plant	System theoretic process analysis (STPA) methodology	Ability to identify and analyze risk method for sensitive and complex systems Applicability for all phases of the system Ability to integrate with FMEA method	It merely identifies the hazards of the electrical industry It is a static method and is not able to resolve uncertainties
Quantitative risk assessment (QRA) [1]	Electricity distribution industry	Fuzzy fault tree (FFT) and center of gravity for defuzzification	Uncertainty reduction by experts and fuzzy logic Identification of critical events with minimal cut set (MCS)	Failure to do deductive and inductive reasoning and cause-effect relationships Static structure Not considering the time factor
Risk assessment [33]	Power line	William Fine method	Risk prioritization	Failure to use uncertainty reduction methods Static structure Not considering the time factor
Risk assessment [34]	Gas power plant	AHP, TOPSIS, Delphi method, entropy, and eigenvector technique	Risk prioritization with MCDM methods Assessment of safety, health, and environmental risks	Uncertainty
Environmental, health, and safety risks [35]	Power transmission lines nearby the human settlements	Environmental failure mode and effects analysis (EFMEA) parameters and a risk priority number (RPN)	Assessment of emerging contaminants in human dwellings Risk prioritization with RPN	The focus of the study was only on environmental hazards and magnetic flux, and static methods were used in the evaluation
Reliability modeling [36]	Medium-voltage distribution systems of nuclear power plants	Generalized stochastic Petri nets (GSPNs)	Obtaining a workable tool based on generalized stochastic Petri nets (GSPNs) Dynamic system modeling The possibility of better modeling of dependencies of system components	Uncertainty due to data failure rate Lack of attention to human factors Lack of comprehensiveness
Probabilistic safety assessment (PRA) [37]	Nuclear power plant	Petri net modeling FTA	Ability to represent the time sequence of the events along with their duration	It is recommended that future research should investigate Petri nets' role with dynamic systems The limitation of Petri nets due to its software and the unavailability of code for dynamic gate modeling
Risk barometer [38]	Review article	Review article	Technical indicators are integrated with preventive organizational/operational indicators in order to assess early deviations that potentially lead to unwanted accidents	It relies on linear models It is partly based on expert judgment

regarding human errors do not have high reliability. In developing countries, due to the lack of a suitable database, documentation system, and defect rate, it is not possible to calculate the probability, so fuzzy logic can reduce these uncertainties [46]. The fuzzy logic method can obtain the experience and knowledge of an expert to predict the behavior of the system [47]. Therefore, according to what has been said, non-fuzzy methods are challenged in the conditions of insufficient documentation of accidents and consequences and always bring some degree of uncertainty.

Therefore, in the current study, a comprehensive approach was presented to cover the shortcomings of previous studies, such as uncertainty, static structure, and failure to investigate cause-effect relationships, pure attention to technical errors, failure to provide deductive and inductive reasoning, and failure to calculate human risk. So, the present study was carried out with the aim of evaluating the reliability of low-voltage power systems and maintaining the dynamics of risk analysis in variable working conditions, using fuzzy Bayesian network (FBN) and William Fine approaches. It should be noted that according to the available sources, no study has been conducted in this field with the current approach in the electricity distribution industry.

2. Materials and Methods

Figure 1 shows the general flowchart of the present study. According to Figure 1, this approach consists of several steps that we will discuss. First, the risks of the process were identified using the BTA technique. Also, experts' opinions and fuzzy logic were used to estimate the rate of occurrence. In the next step, the general nomogram of the study was drawn and the information was mapped in a BN. In the following, the implementation steps of this method are described in more detail.

2.1. BTA Technique. The bow tie model is used to better show the cause-effect relationship of a specific event. A bow tie model is created by connecting fault tree (FT) and event tree (ET) models to a critical event [20]. FTA is a hierarchical diagram that is drawn inferentially from the functional structure of a system and depicts all the possible ways for a system to fail [8]. ETA is also a graphical approach that shows the logical relationship in the sequence of events from the first to the final consequences in the system, and the probability of the final consequences can be estimated using this approach [48]. Therefore, at this stage, after drawing the diagram and investigating the causes of the events, the probability of the outcome of the scenario was calculated statically with fuzzy logic. In this way, the probability of the occurrence of basic events (BEs) was also obtained by using experts' opinions and fuzzy logic. Then, the probabilities of intermediate events (IEs) and top events (TEs) were calculated according to the input gate using equations (1)–(3). The reliability of the system was also determined according to the probability of failure of the TE from equation (4) [11].

$$P = \prod_{i=1}^{n} P_i, \tag{1}$$

$$P = 1 - \prod_{i=1}^{n} (1 - P_i), \tag{2}$$

$$P(t) = 1 - e^{-\lambda t}, \tag{3}$$

$$R(t) = 1 - P(t), \tag{4}$$

where P is the probability of the port exit event, n is the number of port input events, P_i is the probability of each of the BEs, $P(t)$ is the probability of failure of the TE, failure rate (number of failures per year), and time interval t, and $R(t)$ is the reliability of the system.

2.2. Fuzzy Logic Approach. In this study, the expert judgment method was used as a scientific consensus approach to calculate the failure probabilities of BEs [49]. Lavasani et al.'s [46] method was used to determine the weighted importance of experts [46]. The importance score of each of the available indicators was also calculated according to the study of Renjith et al. [50]. The final weight of each expert was calculated by dividing the points obtained by each of them by the total points of the experts. There are various applications of fuzzy set theory to deal with uncertainties and inaccuracies of expert judgment, including triangular, intuitionistic, trapezoidal, and Gaussian fuzzy numbers [51, 52]. Trapezoidal and triangular fuzzy numbers describe the fuzzy membership linearly. Also, the Gaussian function describes the fuzzy membership in a non-linear and more flexible way. But this method is more complicated than linear methods, which may reduce the accuracy of studies [53]. The choice of a particular type of membership function depends on the nature of the problem [54]. Therefore, in order to quantify probabilities, trapezoidal membership functions were used due to their simplicity, proper accuracy, and application in risk assessment studies [55–57]. Then, the corresponding fuzzy numbers for linguistic terms were obtained according to Chen and Hwang's method (Table 2) [58]. Meanwhile, the weight of the experts was calculated according to the study of Celemen and Winkler [59].

$$M_i = \sum W_i \times A_{ij} (i = 1, 2, 3, \ldots, m), \tag{5}$$

where W_i is the weight of experts, A_i is the number of experts with weight W_i, j is the verbal expression of the expert i's opinion, and M_i is the consensus of experts' opinion.

In this study, the center of area (CoA) was used to convert fuzzy numbers into definite numbers. Because this method considers all the points of the definition domain and their degree of membership, it is the most accurate defuzzification method [1]. There are two main reasons for choosing the CoA. The computational effort of this technique is very high and continuous. An important aspect of a defuzzification method is the continuity of the output signal. CoA is continuous because assuming overlapping output membership functions, the best compromise does not jump to a different value with a small change to the inputs [60]. Also, in Yazdi and Zarei's study, which aims to address uncertainty in risk assessment and compare different approaches, the combined CoA/sum product approach was

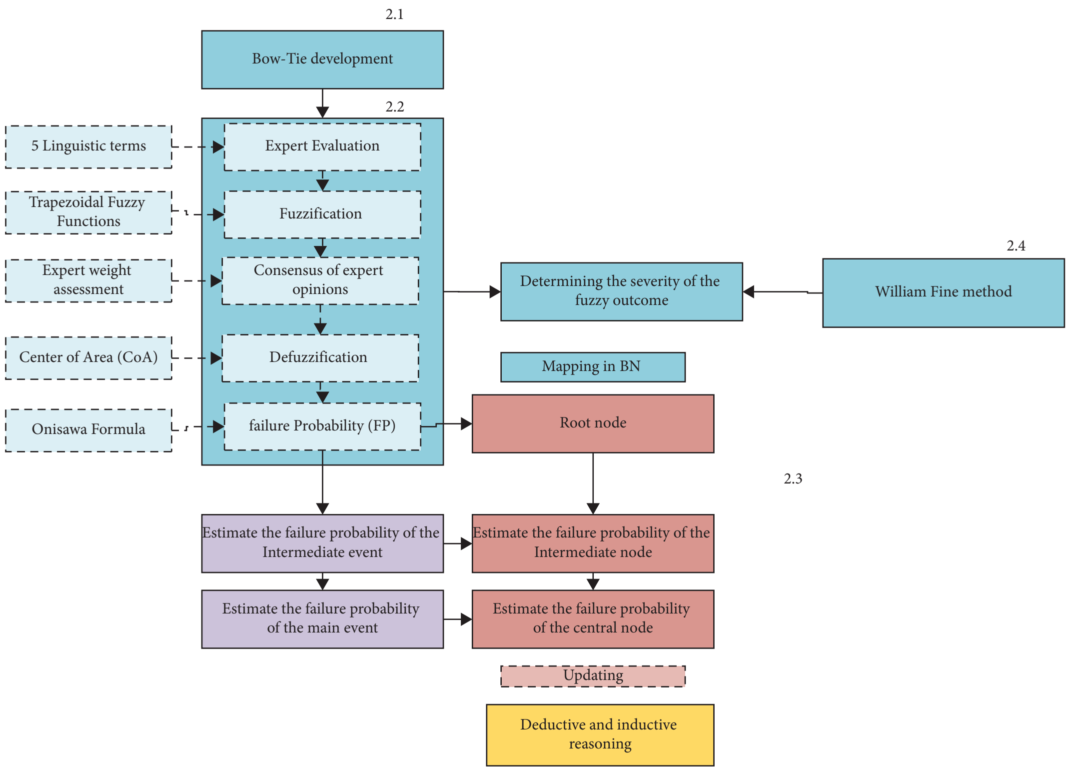

FIGURE 1: Flowchart of the study.

TABLE 2: Weight of verbal expressions (linguistic terms).

Descriptions		a1	a2	a3	a4
Very low	VL	0	0	0.1	0.2
Low	L	0.1	0.3	0.3	0.4
Medium	M	0.3	0.3	0.5	0.7
High	H	0.6	0.8	0.8	0.9
Very high	VH	0.8	0.9	1	1

better than other approaches in terms of computational complexity, reliability, and time spent for calculations [61].

Then, using the trapezoidal CoA formula, it is entered in a diffuzy form and converted into possible numbers.

$$\mathrm{DE} = \frac{1}{3}\left(\frac{\left(\left(a_4 + a_3\right)^2 - \left(a_4 \times a_3\right) + \left(a_1 \times a_2\right) - \left(\left(a_1 + a_2\right)\right)^2\right)}{\left(a_4 + a_3 - a_2 - a_1\right)}\right). \tag{6}$$

In the above relationship, the a_i values are related to fuzzy numbers corresponding to linguistic variables and are obtained from Table 2. The fuzzy number obtained in the previous step is still possible, and since the FT accepts probability, in this step, using equations (7) and (8) (Onisawa relations) [61], the above numbers are converted from possibility to probability.

$$K = \left[(1 - DE) \times DE^{-1}\right]^{0.5} \times 2.301, \tag{7}$$

$$\text{probability} = 10^{-K}. \tag{8}$$

Then, the gate by gate approach and OR and AND type gates were used to calculate the probabilities of intermediate and main events, and reliability was calculated (equations (1)–(4)).

2.3. Bayesian Network (BN). In the BN, the probabilities were updated using conditional rules. Also, the joint probability distribution of a set of variables X_1 to X_n was calculated using inductive reasoning [62], and then deductive reasoning was also done [63]. According to the conditional dependence of variables and chain rules, Jensen and Nielsen stated that BN is a probability distribution that includes a set of variables as described in the following equation [64].

$$P(U) = \prod_{i=1}^{n-1} P\left(X_i \,\middle|\, X_{i+1}, \ldots, X_n\right), \tag{9}$$

where $U = \{X_1, X_2, \ldots, X_n$ and $X_{i+1}, \ldots, X_n$ are its parents. BN uses Bayesian theory to update the probabilities of the initial events as new information is received to calculate updated probabilities based on the following equation.

$$P(UE) = \frac{P(U \cap E)}{P(E)} = \frac{P(U \cap E)}{\sum_U P(U \cap E)}. \quad (10)$$

2.4. Determining the Intensity of the Fuzzy Result with William Fine's Approach. William Fine's approach was used in this study to determine the severity of the outcome. This method is a suitable technique in risk assessment, which is based on the calculation of three parameters: consequence, exposure, and probability [65, 66]. Therefore, Table3, which is derived from William Fine's method, was used for classifying human injuries and evaluating their severity. This method is now used to calculate the risk of activities in electricity distribution companies in Iran, based on the relevant instructions. Then, the risk of human injuries due to electrocution with low voltage was calculated by multiplying the intensity (William Fine) by the probability of their occurrence (fuzzy method).

3. Results

3.1. Bow Tie. In order to determine the causes of the electrocution accident, the corresponding FT status was drawn by a team of electrical and safety experts, which is shown in Figure 2. As shown in Figure 2, electrocution caused by low-pressure electricity can occur in two ways, direct and indirect. Direct electrocution (X1) can be caused by unwanted contact with the power grid (X11) or caused by the unwanted electrification of facilities (X12) that are being installed or repaired. Unwanted contact with the power grid can be caused by human error (X14), entering the privacy of the electricity network (X15), or availability of electrical network equipment (X16). Indirect electrocution can also occur due to contact with wet parts and the body of equipment and panels (X3 and X4). Table 4 shows the description of intermediate and BEs.

According to the results of the FT and possible defects in safety barriers in low-voltage power systems, the corresponding ET is drawn for the possible consequences, which is shown in Figure 3. Table 3 shows the description of the possible consequences of low-voltage electrocution. The probability of the consequences in case of an accident was identified in 6 tasks according to Table 3 and Figure 3. Figure 3 shows a bow tie diagram of low-voltage electrocution.

3.2. Results of Fuzzy Logic

3.2.1. Selection of Experts to Determine the Probability of BEs. In order to determine the probability of BEs in the occurrence of low-voltage electrocution, a questionnaire was designed and sent to each of the experts. In this study, an expert is someone who is fully familiar with the issues of electricity and related system maintenance, and Table 5 shows the characteristics and weighted scores of the experts in this study. According to Table 5, expert 2 (head of the section) with a value of 0.124, had the highest weight.

3.2.2. Collecting Experts' Opinions and Performing Fuzzy Calculations. First, experts' opinions were collected in the form of 5 linguistic terms. Then, the consensus of their opinions regarding the probability of the occurrence of the basic causes of the low-pressure electrocution accident was carried out. Also, defuzzification calculations and conversion of possible numbers to probability were also done, the results of which are presented in Table 6. Then, the probability of human injuries caused by the above accident was calculated using fuzzy logic, the results of which are presented in Table 7. The additional information based on the work method is presented in Tables 6 and 7. BE16 (not using personal and group protection equipment to work with the electrical network) and BE25 (no installation of the earth) had the highest fuzzy probabilities and BE1 (sliding the wire over the insulator and hitting the base) and BE5 (insulator breakage) had the lowest fuzzy probabilities according to Table 5. According to the fuzzy results, the effect of direct electrocution (0.029762553) was more than indirect electrocution (0.003805967) in the general results of low-pressure electrocution (0.03345524).

3.3. BN Modeling. In this study, BNs and deductive reasoning were used to investigate the probability of the TE of low-pressure electrocution. Figure 4 shows the cause-effect modeling of electrocution with low voltage in BNs. The results of this modeling showed that the ultimate probability of being electrocuted by low-pressure electricity is equal to 0.033448026.

3.3.1. Deductive Reasoning. According to Figure 5, deductive reasoning was used for this study. According to the results, BE25 (no installation of the earth) and BE18 (contact of metal objects with the live wire) were the most critical events of the study (Figures 5 and 6).

The reliability of the main event using the FFT and BN was obtained as 0.96654476 and 0.96654474, respectively. The results did not show much difference between the two approaches. According to Figure 7, if any of the critical events (BE25 or BE18 or both) deduced from the inductive reasoning (FBN) are removed, the overall reliability of the system will increase significantly, and also, the possibility of system failure will be reduced. System reliability will increase by 0.4, 0.3, and 0.7%, respectively, if BE25, BE18, and both are removed.

3.4. Calculation of Human Risk of Consequence Using Fuzzy Logic and William Fine Method. According to Table 7, most of the accidents will not result in consequences because C6 (multiple deaths) had the lowest fuzzy probability and C1 (no damage) had the highest fuzzy probability. Therefore, the probability of multiple deaths was assigned

Table 3: Describing the consequences of a low-voltage electrocution.

Row	Symbol	Description	Severity
1	C1	No damage	1
2	C2	Minor damage, normal operation	5
3	C3	Minor damage, stopping operation for less than three days	15
4	C4	Minor permanent damage, long-term cessation of operation	25
5	C5	Permanent general disability, death of one person	50
6	C6	Multiple deaths	100

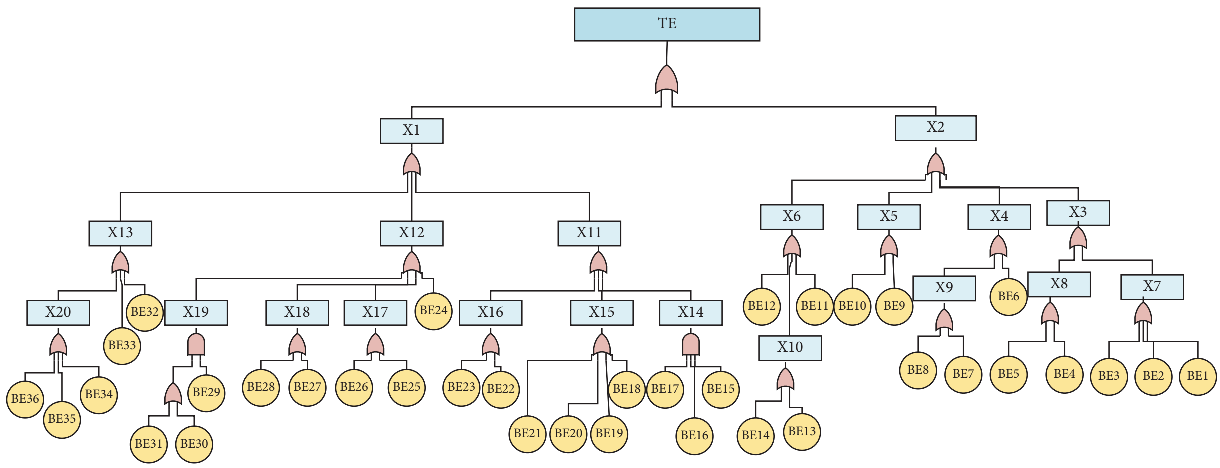

Figure 2: Electrocution FT with low-voltage electricity.

Table 4: Description of intermediate and BEs in the FT.

Symbol	Description
TE	Low-voltage electrocution
X1	Direct low-voltage electrocution
X2	Indirect low-voltage electrocution
X3	Contact with electrified wet foundations
X4	Contact with the body of electrified panels
X5	Energizing of etrye
X6	Contact with pedestals of the street lights
X7	Contact of electrified wire with base
X8	Energizing pole with etrye
X9	Lack of protective layers (subcategory of X4)
X10	Lack of protective layers (subcategory of X6)
X11	Unwanted contact with the power grid
X12	Unwanted electrification
X13	No power outage
X14	Human error of personnel
X15	Entering the privacy of the electricity network
X16	Availability of electrical network equipment
X17	Human error (subcategory of X12)
X18	Induction of parallel or cross lines
X19	Reversible voltage
X20	Human error (subcategory of X13)
BE1	Sliding the wire over the insulator and hitting the base
BE2	Unwanted collision with wires and conductors of adjacent circuits
BE3	Tearing the wire and falling on the power poles
BE4	Insulator leakage (subcategory of X8)
BE5	Insulator breakage (subcategory of X8)
BE6	Connecting the electrified wire and colliding with the body of the panel
BE7	Lack of protective earth (subcategory of X9)
BE8	Lack of double insulation (subcategory of X9)

Table 4: Continued.

Symbol	Description
BE9	Insulator leakage (subcategory of X5)
BE10	Insulator breakage (subcategory of X5)
BE11	Unwanted collision with wires and conductors of adjacent circuits
BE12	Connecting live wire and colliding with the metal body of the street light
BE13	Lack of protective earth (subcategory of X10)
BE14	Lack of double insulation (subcategory of X10)
BE15	Lack of attention to adjacent networks
BE16	Not using personal and group protection equipment to work with the electrical network
BE17	Use of inappropriate tools
BE18	Contact of metal objects with the live wire
BE19	Scaffold contact with the live wire
BE20	Contact of crane boom with the live wire
BE21	Stealing electrical wires
BE22	Non-observance of horizontal and vertical privacy in network construction
BE23	The openness of doors for public distribution panels
BE24	Dealing with adjacent conductors
BE25	No installation of the earth (subcategory of X17)
BE26	Connecting wrong
BE27	No installation of the earth (subcategory of X18)
BE28	Failure to observe the allowable line spacing
BE29	No installation of the earth (subcategory of X18)
BE30	Return of street lighting
BE31	Return from subscribers
BE32	Short circuit of the electrical circuit breaker equipment
BE33	Defective power cut equipment
BE34	Disconnecting the circuit incorrectly
BE35	Lack of familiarity with network topology
BE36	Starting work in a hurry and forgetting about the circuit breaker

the lowest numerical value. The risk number was obtained after the impact of the severity of the outcome from the William Fine method in the probability calculated from the fuzzy method, and C3 (minor damage, stopping operation for less than three days) was assigned the highest risk number.

4. Discussion

In this study, a comprehensive method for human risk analysis of low-voltage power distribution systems was presented using a FBN. In previous studies, such as the study by Marhavilas et al. [67], the study by Pasman et al. [68], and the study by Khan et al. [20], different classifications have been used to evaluate reliability. Therefore, this study used a new and comprehensive approach for risk assessment in this industry. This approach was used for risk analysis using the bow tie method, William Fine method, and FBN. Currently, most of the studies for designing preventive strategies have a special focus on the bow tie model and the identification and classification of different events [69, 70]. Bow tie consists of a combination of FTA and ETA, which were used to find the causes of various events. The results of FTA provide the possibility of prioritizing preventive and corrective measures to minimize the possibility of failure. Finally, after drawing the causal tree, the bow tie model was completed.

In various studies, the results of similar studies were used to estimate the probability of failure, which has uncertainty, so in this study, fuzzy logic was used to estimate the probability of failure of BEs and consequences. Rahmani and Omidvari also conducted a study with the aim of assessing the safety risk in electricity distribution using the improved ET and BA method, VICOR, and TOPSIS models in a fuzzy environment. They came to the conclusion that the use of multi-criteria decision-making methods in the fuzzy environment improves the results and minimizes the inappropriate judgments of evaluators in the risk assessment process [27]. It should be noted that there was no reliable database to determine the failure rate of BEs in the electricity industry, which can be considered a limitation of the studies. Databases such as OREDA [71], CCPS [72], Lee [73], and so on have provided information in this field, which will be different according to the type of industry and equipment and different cultures. Also, these data may not be up to date and therefore have high uncertainty. The bow tie model is a static model and is unable to consider system changes dynamically. Therefore, in this study, BN was used to update conditional probabilities. BN is able to perform four types of reasoning: prediction, diagnosis, causal relations, and combinational reasoning. Because the Bayesian belief network provides the effect of various factors through changes in the network outputs, researchers can investigate the expected consequences of uncertainty before establishing an effective intervention [74]. In the study of Rui et al., the topics of dynamic phases, time delay, and zero-order hold were simultaneously embedded in the small signal model. Then, the closed-loop transfer function of the droop-controlled inverter is built. The results showed that, compared

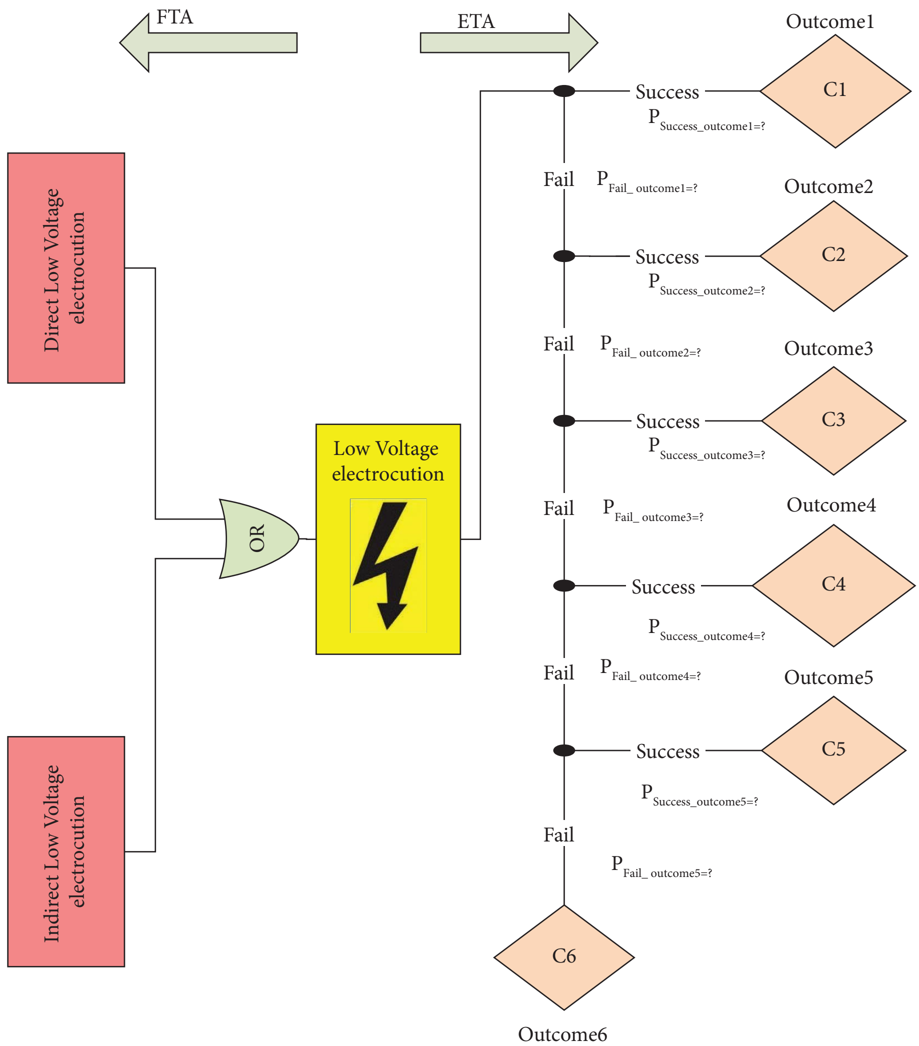

Figure 3: Electrocution bow tie diagram with low-voltage electricity.

Table 5: Characteristics and weight scores of selected experts.

No	Job	Education level	Work experience	Age	The weighted score of each expert
Expert 1	Electrical expert	Diploma	20–30	40–50	0.088
Expert 2	Head of the section	MSc	>30	30–40	0.124
Expert 3	Electrical technician	BSc	10–20	40–50	0.088
Expert 4	Electrical technician	With a technical degree	<5	30–40	0.071
Expert 5	Head of the section	BSc	10–20	<30	0.088
Expert 6	Electrical technician	MSc	20–30	40–50	0.106
Expert 7	Electricity operator	BSc	>30	30–40	0.088
Expert 8	Electrical expert	With a technical degree	20–30	40–50	0.097
Expert 9	Electricity operator	BSc	10–20	30–40	0.071
Expert 10	Electrical technician	MSc	<5	<30	0.071
Expert 11	Electrical expert	BSc	20–30	40–50	0.106

with the existing studies, the model accuracy has been improved by embedding dynamic phase, zero-order hold, and time delay at the same time [75]. This topic is also mentioned in the “Future Work” section.

Therefore, in this study, the results showed that, in addition to the events with the greatest impact, the most likely set of events that lead to the failure of the main event are also determined using the BN [76]. It is possible to help relevant managers to prioritize control measures, by presenting the most critical BEs (BE25 and BE18). One of the important aspects of system reliability assessment is identifying important components and determining their

Table 6: The consensus of experts and the probability of the BEs of low-voltage electrocution.

Basic events	Expert opinions											DE	K	Probability
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11			
BE1	VL	VL	L	VL	VL	VL	L	H	L	VL	M	0.2409	4.0851	$8.2204E-05$
BE2	VL	VL	VL	L	L	L	L	H	VL	L	M	0.2595	3.8871	0.00012969
BE3	VL	VL	L	VL	VL	VL	H	H	L	VL	M	0.2540	3.9431	0.000114
BE4	VL	VL	L	VL	L	VL	L	M	M	VL	L	0.2195	4.3386	$4.5856E-05$
BE5	VL	VL	VL	VL	L	VL	M	M	L	L	L	0.2166	4.3762	$4.2049E-05$
BE6	VL	L	L	L	H	L	H	M	M	VL	M	0.3638	3.0426	0.00090658
BE7	VL	M	L	VL	H	L	L	H	L	VL	M	0.3272	3.2998	0.00050143
BE8	VL	VH	L	L	L	L	M	H	VL	VL	M	0.2880	3.6183	0.00024082
BE9	VL	VL	L	VL	L	VL	L	M	M	VL	M	0.2272	4.2441	$5.6997E-05$
BE10	VL	VL	VL	VL	L	VL	L	M	L	VL	M	0.2212	4.3176	$4.8129E-05$
BE11	VL	L	L	L	M	L	L	M	VL	L	M	0.3008	3.5080	0.00031045
BE12	VL	VL	L	L	H	L	M	M	VL	L	H	0.3357	3.2367	0.00057983
BE13	VL	M	L	VL	H	VL	L	M	VL	VL	H	0.3383	3.2180	0.00060535
BE14	VL	VH	VL	L	L	VL	L	M	VL	VL	H	0.2655	3.8273	0.00014885
BE15	L	VL	L	VL	VH	L	L	VH	H	VL	VH	0.4357	2.6187	0.00240625
BE16	M	VH	VH	L	H	M	M	VH	M	M	VH	0.5422	2.1144	0.00768359
BE17	M	VH	H	VL	H	M	L	VH	M	L	M	0.4714	2.4364	0.00366068
BE18	L	L	H	VL	M	L	H	VH	L	L	M	0.4576	2.5054	0.00312334
BE19	L	L	H	L	H	M	H	VH	M	VL	H	0.4498	2.5449	0.00285155
BE20	L	L	H	VL	M	M	M	VH	M	VL	M	0.3825	2.9236	0.00119245
BE21	VL	L	VH	L	H	VL	H	VH	L	L	L	0.4535	2.5258	0.00297986
BE22	VL	VL	VL	L	VH	L	M	VH	M	L	H	0.4080	2.7720	0.0016905
BE23	VL	L	L	L	M	L	H	VH	H	VL	L	0.4050	2.7889	0.00162574
BE24	VL	VL	VL	VL	H	VL	VL	H	L	VL	M	0.3203	3.3521	0.00044448
BE25	M	H	H	L	H	M	M	H	M	VL	H	0.4855	2.3685	0.00428047
BE26	L	L	H	VL	M	L	M	VH	H	VL	VH	0.3816	2.9289	0.00117784
BE27	VL	H	VL	L	L	L	L	H	L	VL	M	0.3226	3.3347	0.00046272
BE28	VL	VL	VL	VL	H	L	M	H	L	L	M	0.2752	3.7340	0.00018452
BE29	M	H	L	L	H	VL	M	H	M	VL	H	0.4634	2.4760	0.00334168
BE30	L	L	L	VL	L	VL	M	H	H	VL	M	0.3752	2.9694	0.00107303
BE31	L	L	L	VL	H	VL	M	VH	M	VL	M	0.3807	2.9349	0.00116177
BE32	VL	VL	VH	VL	H	L	L	H	L	VL	VH	0.4035	2.7979	0.00159242
BE33	VL	L	VH	L	VH	L	M	H	M	VL	VH	0.4273	2.6637	0.00216909
BE34	L	L	VH	VL	M	L	M	VH	M	VL	H	0.4178	2.7161	0.00192269
BE35	L	L	M	VL	L	L	H	VH	M	L	H	0.4037	2.7964	0.00159815
BE36	VL	M	H	VL	H	M	L	VH	M	VL	VH	0.4504	2.5416	0.00287321

Table 7: Determination of the probability of consequences of low-voltage electrocution.

Consequences	Expert opinions										DE	K	Probability	Severity	Risk number
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10					
C1	VL	M	VH	L	VH	L	H	VH	H	L	0.4923	2.336	0.004609608	1	0.004609608
C2	VL	L	H	L	H	L	H	H	H	L	0.4554	2.516	0.003046593	5	0.015232965
C3	M	H	H	M	H	M	M	H	M	L	0.4884	2.354	0.00441981	15	0.06629715
C4	M	M	L	L	M	M	H	H	M	M	0.4130	2.742	0.00180834	25	0.0452085
C5	H	L	L	VL	H	L	L	H	M	M	0.3668	3.022	0.00094901	50	0.0474505
C6	H	VL	VL	VL	L	L	VL	M	M	M	0.2736	3.748	0.00017835	100	0.017835

contribution to the occurrence of the main event. Identifying these components can help in providing preventive strategies and improving system reliability.

According to the results, it can be concluded that FBN will not necessarily increase or decrease the possibilities, but it depends on different conditions. Considering events with common failure causes (such as X15 and BE24) and conditional probabilities in BN is one of its causes, while bow tie does not have the ability to do this and checks the possibilities statically.

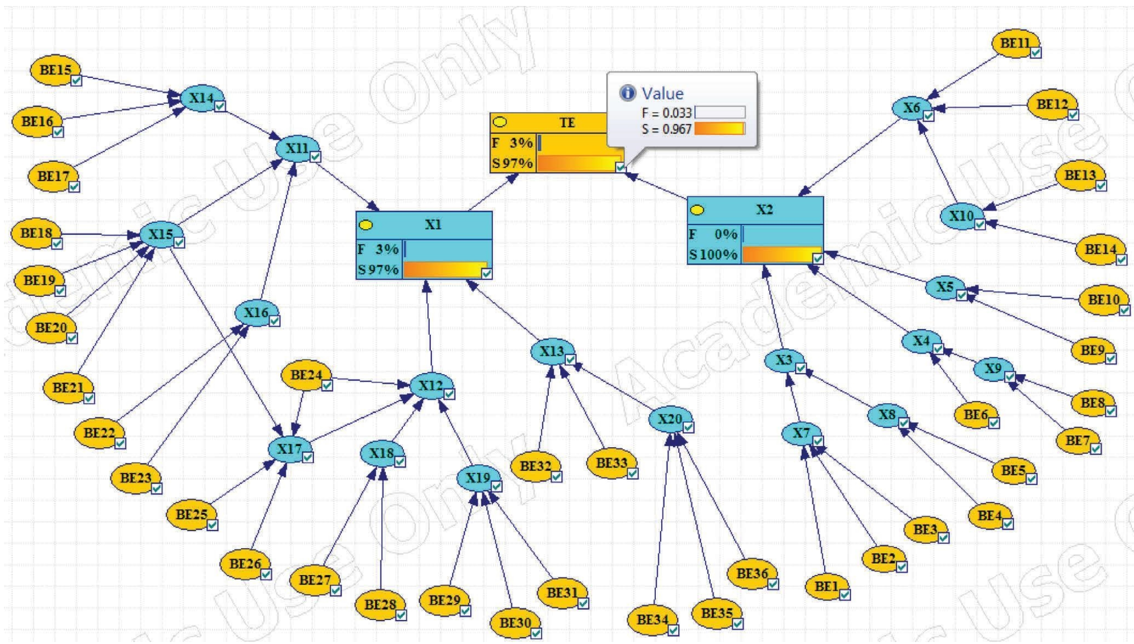

FIGURE 4: Modeling the cause of low-voltage electrocution using BNs.

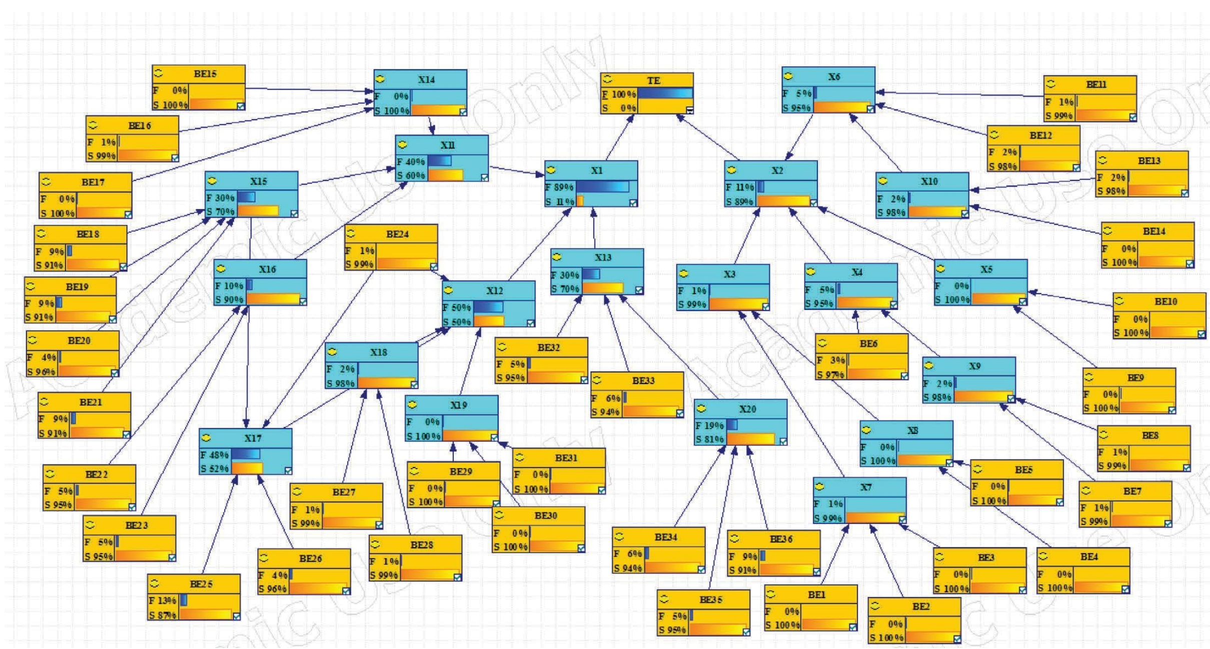

FIGURE 5: Updating the posterior probability of low-voltage electrocution.

In this study, the human risk of consequences was calculated using fuzzy logic and William Fine's method, and the results showed that in the studied industry, the probability of multiple deaths will have the lowest numerical value, and C3 had the highest risk number. This seems logical unless electrical accidents lead to disasters such as explosions and fires.

The use of conventional risk assessment methods such as HAZID, HAZOP, LOPA, bow tie, and so on does not have sufficient comprehensiveness and accuracy, for reasons such as providing qualitative results, not being able to identify all risks, using the risk matrix, and not modeling and considering the conditions governing the scenarios. According to studies, the accuracy of the risk matrix is lower than other

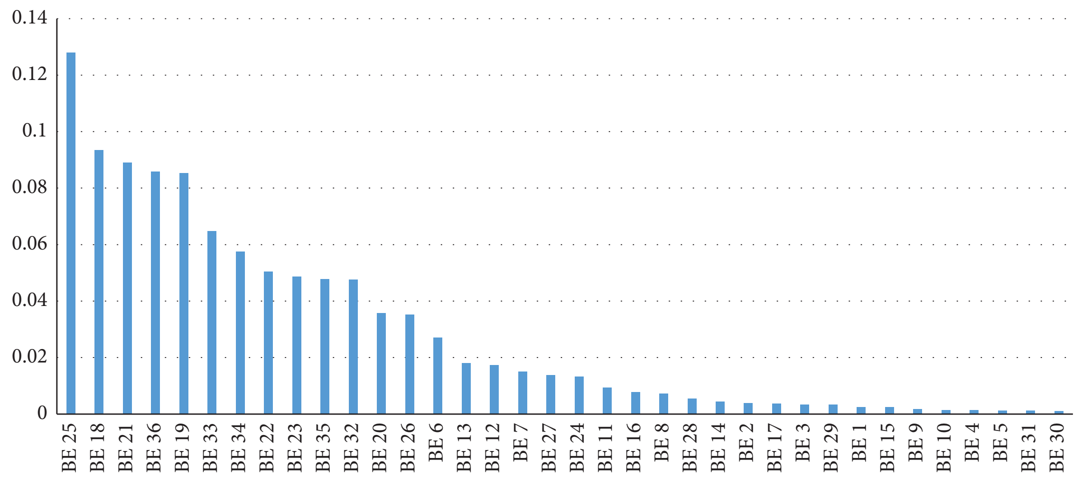

Figure 6: Ranking of base events in BNs using inductive reasoning.

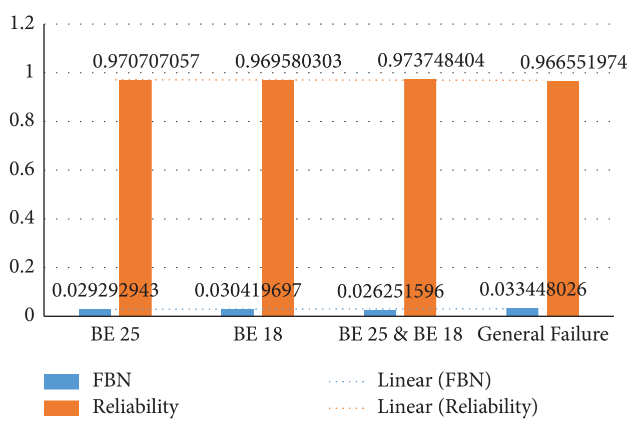

Figure 7: Reliability of the study in case of omission of critical events in deductive reasoning.

methods such as F-N curves [73]. Therefore, in this study, the use of William Fine's tables for risk estimation in the matrix is considered a limitation, and it is suggested to use William Fine's improved methods in future studies, which was out of the scope of this study. Failure to pay attention to natural hazards such as flood, earthquake, lightning, and so on was one of the limitations of the present study.

4.1. Future Work. In future studies, it is recommended that

(a) Risk prediction be done dynamically by considering system dynamic variables such as time delays between variables.

(b) Prediction of risks be done using dynamic gates in bow tie or FT structure in low-pressure power distribution systems.

5. Conclusion

In this study, a method was presented to evaluate the reliability of low-pressure power distribution systems based on BNs and fuzzy logic. The fuzzy theory was used to determine the failure rate of the probability of root events identified in the qualitative analysis of the FT. The fuzzy FT was drawn in the form of regular BNs, and the reliability was calculated according to the static cause-and-effect relationships. The results of the method presented in this study showed that critical events can be eliminated and the reliability of the system can be increased by evaluating the reliability. Although the method presented in this study was used to evaluate the reliability of low-voltage power distribution systems, this method can be used to evaluate the reliability of different types according to their usage.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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