Reliability Based Power Distribution Network Planning Using Fuzzy Logic

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Abstract. *This paper presents a fuzzy system for reliability-based power distribution network planning. The proposed Mamdani type fuzzy inference system with subsequent application of the Bellman-Zadeh decision-making method is used to evaluate the reliability of the power line feeders as criteria for power system planning. Unplanned outages of system components, the Energy Not Supplied (ENS) and age of the power lines are used as input variables of the system and are fuzzified using triangular fuzzy functions. The proposed model was tested on a model of a realistic distribution network in order to prove its relevance and applicability. Results demonstrated that this model could make a contribution in this field as it can be used in practical planning situations for project priority ranking.*

Keywords

Bellman-Zadeh method, fuzzy logic, Mamdani fuzzy inference system, power distribution system planning, reliability.

1. Introduction

Power systems throughout Europe have gone through numerous organizational, structural, technical, and regulatory changes in the past few decades. These changes are mainly driven by the processes of market liberalization and energy transition. The market liberalization changed the monopolistic nature of the electricity industry into a deregulated one, establishing competitive electricity markets [1]. One of the direct consequences of a new energy paradigm is a shift in planning policy and requirements. In an increasingly deregulated and competitive market, the Regulator's and customers are placing ever-increasing reliability expectations on the network operators. These shifts must be met with a fresh approach to power system operation and management philosophy.

In particular, Electrical Power Distribution Systems (EPDS) have not been the focus of reliability and long-term planning studies, unlike generation and transmission systems. Instead, distribution planning departments have traditionally focused on capacity issues, in order to satisfy customer demand during peak periods within acceptable voltage levels and without violating equipment rating [2]. Therefore, numerous changes are required in the area of EPDS planning, operation and innovation, and regulatory directions in order to respond to the new energy paradigm as discussed in [3]. On the other hand, EPDSs are complex, non-linear and dynamic systems whose operation and planning require collections, processing, interpretation and storing large amounts of information. The complexity is further added to the problem due to the inherent power system planning constraints and conflicting objectives [4]. It is also noted that most of the traditional planning approaches fall short of addressing numerous physical properties of the system which are consequently excluded from the decision-making process.

In recent years, there have been many types of research and reviews of existing models and methodologies published regarding the ample field of EPDS planning. A comprehensive review of optimization models and solution strategies involving distribution system planning is presented in [5]. The key features of the active distribution system planning problems were reviewed in [6], where the problems were examined from different perspectives.

Further, a lot of progress has been reported relative to the EPDS reconfiguration. For example, a two-stage robust model for the distribution system reconfiguration problem with load uncertainties is presented in [7]. The new energy paradigm caused a shift toward DG inclusion in planning problems. For example, in [7], the authors proposed a new method to change the distribution system planning from a passive to an active network. The designed network should be able to work reliably with the uncertainty of generation. The proposed approach was the conversion from the passive distribution system to an active distribution system by incorporating photovoltaics and battery as a hybrid generation into the system. The key features presented in the paper were: optimal allocation of DG and ESS and the multiple-objective approach. Overview of methods and models for the distributed generation placement in the distribution system and the methods applied were presented in [8].

Also, there has been a rapid increase in the application of intelligent computational methods in this field. A network reconfiguration methodology for radial distribution networks based on a fuzzy multi-objective approach for power loss reduction and maintaining acceptable branch current limits as the objectives were proposed in [9]. The result showed that the network reconfigurations resulted in a significant decrease in losses for most consumers. However, for a small number of consumers, the losses increased, requiring the modification of the tariff structure. The loss reduction through hourly reconfiguration in distribution networks with high DG was presented in [10].

In particular, the application of fuzzy logic in the area is increasing. In [11], a fuzzy-based approach was applied to model generation and load uncertainty. Reference [12] presented a strategy for the DG placements in the distribution system in an uncertain environment. A fuzzy-based model was created for load uncertainties in the distribution network. In [13], the fuzzy set theory was applied to model uncertainty of component failure rate in a distribution system considering environmental influences on the components as well as operational conditions.

In [14], the reliability of the distribution system is analysed through the integration of DG in the electrical grid. Reliability evaluation is carried out using fuzzy logic, where uncertain variables which described reliability parameters are presented with fuzzy numbers and fuzzy membership functions which are further evaluated for different uncertain parameters. The application of the fuzzy inference system to assess renewable energy options was presented in [15]. The alternative evaluation was based on two types of criteria, namely the benefit and cost criteria to determine the best option of the given alternatives.

A model for solving multistage distribution system planning problems was presented in [16]. The most relevant reliability indices were computed for each obtained solution and the associated cost. The results showed the discrepancy that can occur when the regulator applies penalties for violating the limits of reliability indices and the approximated cost for the customers willing to pay to receive redundancy.

Authors in [17] proposed fuzzy criteria ground decision-making method for distribution system planning. An approach for capacitor placement in the distribution system by using voltage and loss reduction indices as fuzzy membership functions to reduce losses in the distribution system was presented in [18]. This approach can be adapted for capacitor allocation in EPDS operation and expansion.

The author in [19] presented a fuzzy multi-objective approach to improve the efficiency of the radial distribution system with DG. The capability to reduce the active power losses and increase the voltage magnitude presented the main advantages of this approach. The inclusion of DG improved the loss reduction and voltage magnitude increase.

In [20] a multi-objective algorithm that uses a fuzzy optimization technique to handle contradicting objectives was proposed. The planning formulation and the algorithm include a multi-objective function that chooses the best planning option by using Battery Energy Storage Systems (BESS) and traditional assets. Fuzzy-based power management and power quality improvement in microgrid BESS was recently presented in [21].

Based on reviews of the existing developments in the field, it can be concluded that power system planning remains an important area of research with numerous research opportunities with real-world applications. Further, the emergence of computational intelligence in the field has been noteworthy in the recent period and this trend continues to increase. However, it can also be concluded that intelligence methods are mostly used in optimisation problems. There is much less evidence of their application to the multi-criteria decision-making models. Considering the importance and ampleness of this area, new methods for system planning are required and must include innovative, more rational, efficient, and profitable electrical power distribution network management. This paper is part of these endeavours as it presents a fresh look at the planning problem definition.

The main objective of this paper is to design, construct and test a logical and easy to follow decision-making framework based on modern computational methods that can be used to model, identify and rank development and reconstructions projects according to their ability to deliver long-term benefits to both customers and Distribution System Operator (DSO). The proposed algorithm was tested on a realistic medium-voltage network in Bosnia and Herzegovina in order to prove its practical relevance and applicability in EPDS.

The proposed algorithm is based on the Mamdani type Fuzzy Inference System (FIS) and Bellman-Zadeh decision-making method in a fuzzy environment. This paper makes a contribution to the field in the following ways:

- Design, development, and validation of a flexible decision-making model based on fuzzy logic that can be used for determining critical components that affect the end-consumer, and is useful for determining reconstruction project and electrical distribution system investments. The model was created using the fuzzy logic toolbox in MATLAB.
- Providing a practical tool for decision making that can be used in practical situations by planning engineers, regulators, and DSO managers. This model can further be expanded by adding criteria, based on the expert needs for evaluation of different project types or control of different processes inside the distribution system.
- Providing an additional example of a possible application of modern computational intelligence tools in relatively new problems, such as EPDS reconstruction and development planning.

The remainder of this paper is organised as follows: In the next chapter, the problem description is presented, followed by a detailed representation of the model development procedure including the mathematical formulations of input and output variables. Then, the application of the proposed model on a realistic EPDS system is presented, including the results presentation and discussion. Finally, conclusions, limitations and future research directions are outlined in the concluding sections.

2. Problem Description

EPDS planning the development of an electricity distribution system requires collection, processing interpretation and storage of large data which is collected on a daily basis by the DSO. Further, it is required to classify the available data into various sets and subsets based on their properties. Decision-making related to the development plan requires an adequate logical framework of inference within which it is possible to categorize the properties of the elements of a particular set, interpret the data and rank the offered alternatives.

However, the classical approaches based on Aristotelian binary logic did not offer an adequate framework for solving various practical engineering problems, such as EPDS planning. In classical set theory, unambiguous sets are uniquely determined by their elements, where a certain element x either belongs to the set A (χ A $=1$) or does not belong to the set A (χ A $=0$), so the membership function can have only two values. This approach gives existence to sharp boundaries between two data sets and therefore oversimplifies the real-world processes.

The rigorous application of classical sets to the categorization of failure rates in EPDS or estimation of power lines condition is problematic because continuous variables are artificially reduced to discrete values. These problems are overcome in practice by using expert knowledge since human abstraction has a softer approach to the boundary regions of the sets and categorizes the meanings on the basis of our inherent tolerance for imprecision and ambiguity assessment. In mathematical terms, a softer approach to describing boundary conditions, ambiguities, and inaccuracies can be accomplished using fuzzy logic.

In particular, EPDS reliability is defined as the ability to perform the intended function over some time under given external conditions is a key indicator and planning criteria. Traditionally, reliability is defined using standard indices and was traditionally oriented towards generation systems. However, in recent years, more attention is dedicated to EPDS planning due to regulatory and customer requirements of the new energy era. The optimal solution is a delicate balance between a number of conflicting goals, primarily cost minimization and reliability maximization. These factors inevitably lead to complex questions such as when to invest, how much and in what technologies. It is a delicate issue because overinvestment in power systems leads to an increase in reliability of supply but causes an increase in cost. On the other hand, underinvestment results in a decrease in cost, but also in a decline in reliability, causing outages and social issues. The optimal solution is the technically acceptable alternative with the lowest cost and can be represented by the following equations [22]:

$$
\begin{gathered}
Z \equiv \min_{\varphi} \{C\}, \\
C = I_{\sum 0} + \sum_{j=1}^{n} \left(I_j + C_{Lj} + E_j\right)(1+i)^{-j} + \\
+ (1+i)^{-n} I_{\sum n}, \\
\mathrm{T} \subseteq \mathrm{T}_a, \\
\mathrm{R} \subseteq \mathrm{R}_a,
\end{gathered} \tag{1}
$$

where C is the total cost during the planning period, n is the duration of the planning period expressed in number of years, $I_{\sum 0}$ is the investment cost until the start of the first year of the investment, $I_{\sum n}$ is the remaining value at the end of the planning period, I_j is the investment cost in year j, E_j is the exploitation cost in year j, i is the discount rate, φ is the general symbol for possible solutions, T is a set of technical parameters of possible solutions, R is the set of reliability indicators of possible solutions and the index a represents the set of acceptable parameter values.

These equations show that the most important objective of generation planning is to minimize the total cost function which includes the cost of total investment and operational cost, such as losses. However, the solution of this equation is not straightforward. Determination of function global optimum is additionally complicated by the uncertainty and imprecision which are inherent properties of a power system. Further, modern EPDS planning requirements propose the extension of the existing reliability framework in order to include an additional aspect of the reliability which are not captured by traditional indices but are apparent to human observation and expert knowledge.

Even if Eq. (1) represents a general power system planning problem, it is applicable to distribution systems. However, this type of optimisation is computationally prohibitive and new approaches for the solution of this problem are required.

This work seeks to offer a possible solution to this problem in form of Mamdani-type fuzzy inference systems. The proposed model is used for project ranking and evaluation of the reliability of a system based on the number of unplanned outages of system components and the ENS as input variables as the first criteria, and Age of the line and Unplanned Outages to determine the degradation rate of the line as the second criteria. The input variables represent the physical properties of the system and are fuzzified using triangular fuzzy functions. In order to obtain the best compromise among candidate solutions, the Bellman-Zadeh method in a fuzzy environment is applied. This method is useful for determining the critical components that affect the end-consumer. Furthermore, it is useful for determining reconstruction projects and electrical distribution system investments. Additionally, it can be further be expanded by adding criteria that are based on the expert needs for evaluation of different project types or control of different processes inside the distribution system.

3. Model Development

Let us define a fuzzy set as a set with elements (objects) containing varying grades of membership. Considering a classical set A of the universe U, then a fuzzy set A is defined by a set of ordered pairs, a binary relation [23]:

$$A = \{(x, \mu_A(x)) \mid \mathrm{x} \in \mathrm{A}, \mu_{\mathrm{A}}(\mathrm{x}) \in [0,1]\} \ , \qquad (2)$$

where $\mu_A(x)$ is called membership function that specifies the grade or degree to which any elements x in A belongs to the fuzzy set A. Each element x in A is a real number $\mu_{\mathrm{A}}(\mathrm{x})$ in the interval [0, 1] which is assigned to x. Greater values of membership function $\mu_{\mathrm{A}}(\mathrm{x})$ indicate a greater degree of membership [23]. This definition is crucial for future reference in the model development procedure.

3.1. Mamdani Type Fuzzy Inference

One of the fuzzy inference methods is the Mamdani fuzzy inference method proposed by Mamdani and Assilian in 1975 [24]. First, the crisp input values are fuzzified into membership functions according to the appropriate fuzzy set. Then, the consequent of the if-then rule will be defined by the fuzzy set, and then defuzzification is required after aggregations of all the reshaped fuzzy sets [24]. The results of the Mamdani fuzzy inference can be obtained by the following steps:

- fuzzifying the inputs,
- determine the appropriate set of rules,
- implication,
- aggregation,
- defuzzification.

In order to obtain the results from this example, the input is fuzzified to map the inputs to the appropriate set of input membership functions. Then, the fuzzy operators ("and", "or") are applied to the if-then rules. Subsequently, the rule weight is applied to the values given to the input (antecedent). The weighted input determines the effect of one rule relative to the others. Afterward, the implication method is applied. The input for the implication is a single number obtained from the antecedent, and the output (consequent) is a fuzzy set. The "and" method is implemented, which truncates the shape of the consequent fuzzy set. After each if-then rule, generating a fuzzy output, aggregation is implemented which combines all the consequent into a single fuzzy set. Finally, through defuzzification, the aggregated fuzzy set will output a crisp value.

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It should be noted that there are many different defuzzification methods. In this paper, the center of mass, also known as the center of gravity or centroid method will be used for defuzzification. This method was chosen because it is the most applied method for the defuzzification process. This method finds the center of the output distribution function to obtain a single crisp value. The centroid method can be mathematically defined as [24]:

$$z = \frac{\sum_{j=1}^{q} Z_j \mu_c(Z_j)}{\sum_{j=1}^{q} \mu_c(Z_j)}, \tag{3}$$

where z is the center of mass, μ is the membership function at value Z_j.

1) Input and Output Variables

The distribution system must reliably supply its end users with electrical energy. For safe transmission of electricity to the consumer requires the proper operation of components of the distribution system. However, there are many reasons why the reliability of a distribution system may be compromised. One of the reasons is the high number of components for which failures, caused by external events, can affect the operation of the distribution system. Overhead lines are exposed to external events that can cause interruption in energy supply. These events include weather conditions, falling tree branches on cables, as well as the damage caused by birds, traffic accidents, and so on. Those events cannot be easily predicted. Also, unplanned outages can be caused by over usage of the lines, which can result in line degradation. Although underground lines are safe from external influences, the duration of long-term outages is longer than with overhead lines due to the time it takes to find the fault location. In a deregulated environment, where the end-users can actively participate in selling produced electrical energy, component failure would be detrimental for the end-user. Furthermore, loss of energy supply would incur monetary losses for the end-consumer. Therefore, it is not enough for utilities to only supply electrical energy, but also guarantee the reliability of the supply.

Calculating the power system reliability is usually done according to the failure rate and outage duration indices of its components [13]. However, for this model, the parameters for the first criteria were taken from a real MV network. The parameters were chosen from real indices that quantify the harm caused by a component failure in a straightforward and easy-to-follow manner.

Therefore, two criteria were taken into consideration. The first criterion, based on ENS, in which Unplanned Outages and ENS were used as input variables to determine Reliability. The number of unplanned outage occurrences of a feeder during the year does not necessarily mean greater loss of supply. It may depend on the number of end-users connected to the particular feeder. The second criterion is based on the age of the power line, where Unplanned outages and the Age of the feeders were taken as the variables to determine the rate of degradation of the feeders. Over time, feeders degrade during their application inside the distribution system. However, the frequency of the number of outages over a given period can increase the degradation of a feeder caused by some unfavorable events. Therefore, it is of interest to verify the reliability of the distribution system number of outages and the age of a distribution line.

For the two criteria, the fuzzy set of the input values needs to be defined. Based on these variables, with the implementation and application of the Mamdani fuzzy inference model, the reliability of a system can be determined. The input and output variables were created using triangular membership function, defined as [25]:

$$\mu_A(x) = \begin{cases} \dfrac{x - a_1}{a_2 - a_1} & \text{for } \mathrm{a}_1 \leq \mathrm{x} \geq \mathrm{a}_2 \\ \dfrac{a_3 - x}{a_3 - a_2} & \text{for } \mathrm{a}_2 \leq x \geq \mathrm{a}_3 \end{cases}. \tag{4}$$

For the input variables Unplanned outages, we used the fuzzy sets that are based on the data obtained from a real MV network. The input is based on the number of feeder outages and expected ENS in a single year. The data of the input variables were normalized for the interval [0,1], where 0 represents the smallest value and 1 is the highest values of the variables. Unplanned outages are represented in Fig. 1.

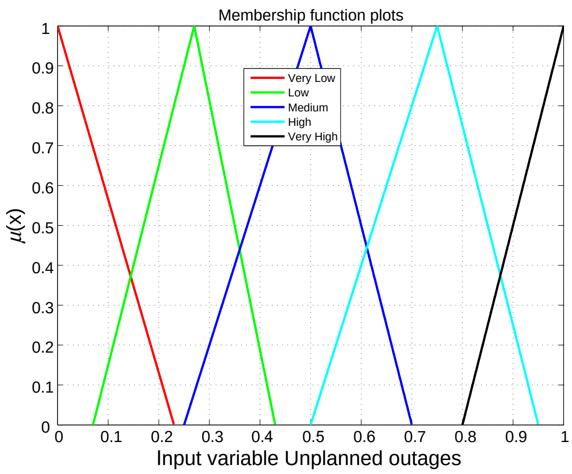

Fig. 1: Membership function plot for the input variable Unplanned outages.

The data for ENS was obtained from an MV network for the expected ENS for a single year. This data was then normalized into [0,1], where 0 represents the smallest amount, which corresponds to 0.15 kWh, and 1 represents the highest amount, corresponding to 9143.20 kWh of the unsupplied energy. Figure 2 represents the membership function for the input ENS.

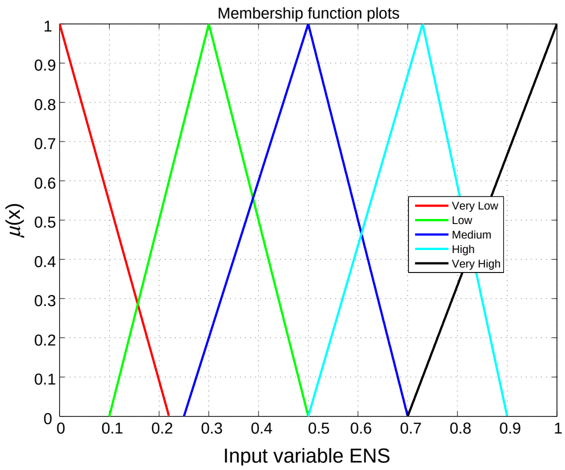

Fig. 2: Membership function plot for the input variable ENS.

Same as for the input variables, the membership function has been created for the output variable. As the output variable, Reliability has been used in an interval [0,1] where 0 represents an unreliable network, and 1 represents a reliable network. The created fuzzy set can be seen in Fig. 3.

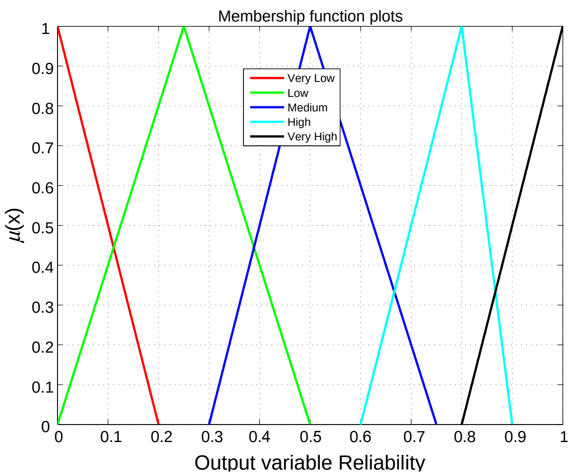

Fig. 3: Membership function plot for the output variable Reliability.

For the second criteria, Age and Rate of Degradation were created based on expert opinion. The Age of the feeder encompasses the range from 0–60 years. For consistency with the other variables, this input variable was normalized in the range 0–1. Figure 4 represents the membership function for Age.

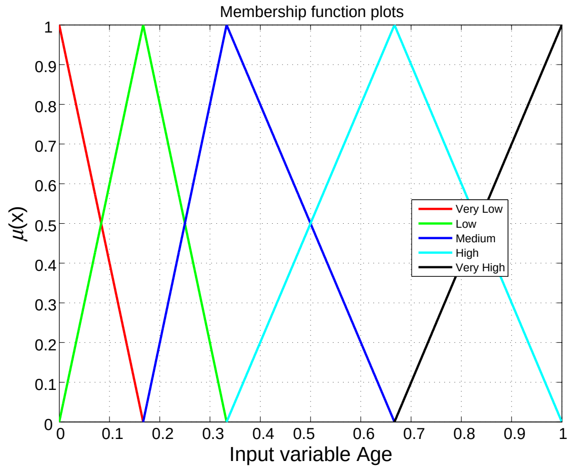

Fig. 4: Membership function Age used in Criteria 2.

Figure 5 represents the membership function for the output variable Rate of degradation.

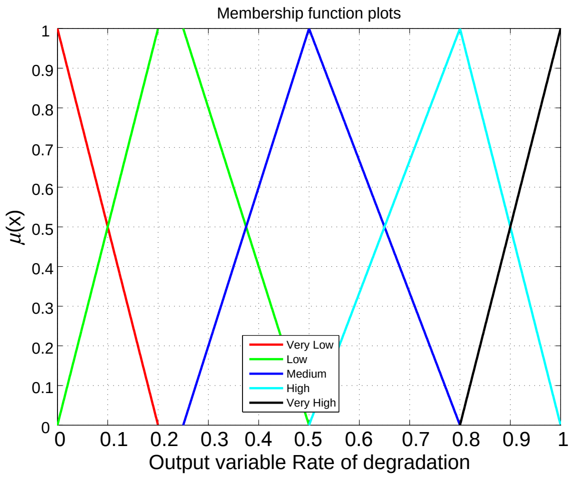

Fig. 5: Membership function Rate of Degradation used in Criteria 2.

After creating the membership function for the mentioned model, a rule base consisting of 25 rules will be created using if-and-then linguistic expressions. After that, aggregation and defuzzification will be presented using the Matlab fuzzy logic toolbox. The set of rules for both criteria will be presented in Tab. 1.

2) Decision-Making in a Fuzzy Environment

In cases where different criteria need to be considered, it is necessary to make decisions by choosing alternatives. To make a decision, a decision matrix **M** needs to be constructed, where each column n represents a particular alternative (X_1, X_2, …, X_n), and each

Tab. 1: Fuzzy rules for input and output variables.

Unplanned outages	ENS/Age				
	Very Low	Low	Medium	High	Very High
Very Low	Very High	Very High	High	Medium	Medium
Low Very	High	High	Medium	Medium	Low
Medium	High	High	Medium	Medium	Low
High	Medium	Medium	Very Low	Low	Very Low
Very High	Medium	Medium	Low	Very Low	Very Low

row m corresponds to a particular criterion (Cr_1, Cr_2, ..., Cr_m). The decision matrix $\mathbf{M}$ represents the ranking of alternatives X_i with respect to criteria C_j [26].

$$\mathbf{M} = \begin{array}{c} \\ Cr_1 \\ Cr_2 \\ \vdots \\ Cr_m \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \cdots & X_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ \mathrm{x}_{21} & \mathrm{x}_{22} & \cdots & \mathrm{x}_{2n} \\ \vdots & \vdots & \cdots & x_{3n} \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array}. \tag{5}$$

To obtain the matrix $\mathbf{M}$, the goals G_g can be formed from a set of criteria C_j. The remaining criteria from the set C_j can be used to form the set of constraints C_c. The set G_g, where r is the number of goals can be written as [26]:

$$G_1 = \frac{\mu_{G1}(x_{11})}{X_1} + \cdots + \frac{\mu_{G1}(x_{1n})}{X_n} = \sum_{i=1}^{n} \frac{\mu_{G1}(x_{1i})}{X_i}, \tag{6}$$

$$G_r = \frac{\mu_{Gr}(x_{r1})}{X_1} + \cdots + \frac{\mu_{Gr}(x_{rn})}{X_n} = \sum_{i=1}^{n} \frac{\mu_{Gr}(x_{ri})}{X_i}, \tag{7}$$

$$G_g = \left\{ \sum_{i=1}^{n} \frac{\mu_{Gg}(x_{gi})}{X_i} \right\}_{g=1}^{g=r}. \tag{8}$$

Likewise, for the fuzzy set of constraints C_c, where h is the number of constraints, it can be expressed as [26]:

$$C_c = \left\{ \sum_{i=1}^{n} \frac{\mu_{Cc}(x_{r+c,i})}{X_i} \right\}_{c=1}^{c=h}. \tag{9}$$

The decision set is obtained as the intersection between goals and fuzzy constraints. It can be expressed as follows [26]:

$$D = G_g \bigcap \ C_c, \tag{10}$$

$$D = \left\{ \sum_{i=1}^{n} \frac{\mu_{Gg}(x_{gi})}{X_i} \right\}_{g=1}^{g=r} \bigcap \bigcap \left\{ \sum_{i=1}^{n} \frac{\mu_{Cc}(x_{r+c,i})}{X_i} \right\}_{c=1}^{c=h}, \tag{11}$$

$$D = \min\left(\min_{g=1,r}(\mu_{Gg}(x_{ij})), \min_{c=1,h}(\mu_{Cc}(x_{ij})) \right), \tag{12}$$

where the membership function is defined as [26]:

$$D_1(X_1) = \min\left(\min_{g=1,r}(\mu_{Gg}(x_{1n})), \min_{c=1,h}(\mu_{Cc}(x_{1n})) \right), \tag{13}$$

$$D_n(X_n) = \min\left(\min_{g=1,r}(\mu_{Gg}(x_{mn})), \min_{c=1,h}(\mu_{Cc}(x_{mn})) \right), \tag{14}$$

which produces a fuzzy set of decisions [26]:

$$D = \frac{D_1(X_1)}{X_1} + \cdots + \frac{D_n(X_n)}{X_n} = \sum_{i=1}^{n} \frac{D_i(X_i)}{X_i}, \tag{15}$$

$$D = \frac{\mu_{D1}(\tilde{x}_1)}{X_1} + \cdots + \frac{\mu_{Dn}(\tilde{x}_n)}{X_n} = \sum_{i=1}^{n} \frac{\mu_{Di}(\tilde{x}_i)}{X_i}. \tag{16}$$

Then the optimal decision is an alternative X^* with the greatest membership function to set D [26]:

$$D(X^*) = \max(D_1(X_1), \ldots, D_{\mathrm{n}}(X_n)), \tag{17}$$

$$\mu(x^*) = \max(\mu_{D1}(\tilde{x}_1), \ldots, \mu_{\mathrm{Dn}}(\tilde{x}_n)). \tag{18}$$

4. Results and Discussion

In order to demonstrate the practical relevance of the presented model, testing is performed on a real network, for which data was obtained by the DSO. The test model represents a typical medium voltage (10 kV) EPDS system currently in exploitation in Bosnia and Herzegovina. The typical structure and organisation of these types of systems is described in [26]. The implemented system was tested by applying data from 36 different feeders. An example of the model application results is presented in Tab. 2. Based on the obtained output for both criteria, using the Bellman-Zadeh method, the most critical line can be found. After applying the Bellman-Zadeh method (Eq. (17) and Eq. (18), results are obtained, see Tab. 2.

Tab. 2: Model results.

Line name	Criteria 1	Criteria 2	Membership function	
Feeder 1	0.0695	0.5181	$D_1(X_1)$	0.0695
Feeder 2	0.0634	0.0641	$D_2(X_2)$	**0.0634**
Feeder 3	0.5179	0.2876	$D_3(X_3)$	0.2876
Feeder 4	0.3713	0.2915	$D_4(X_4)$	0.2915
Feeder 5	0.6783	0.4104	$D_5(X_5)$	0.4104
Feeder 6	0.6902	0.7687	$D_6(X_6)$	0.6902
Feeder 7	0.6938	0.5176	$D_7(X_7)$	0.5176
Feeder 8	0.7254	0.3544	$D_8(X_8)$	0.3544
Feeder 9	0.7092	0.4158	$D_9(X_9)$	0.4158
Feeder 10	0.6969	0.3059	$D_{10}(X_{10})$	0.3059
Feeder 11	0.7516	0.5186	$D_{11}(X_{12})$	0.5186
Feeder 12	0.6929	0.7193	$D_{12}(X_{12})$	0.6929
Feeder 13	0.7735	0.3777	$D_{13}(X_{13})$	0.3777
Feeder 14	0.8474	0.4594	$D_{14}(X_{14}$	0.4594
Feeder 15	0.6028	0.3651	$D_{15}(X_{15})$	0.3651
Feeder 16	0.9221	0.4202	$D_{16}(X_{16})$	0.4202
Feeder 17	0.929	0.5177	$D_{17}(X_{17})$	0.5177
Feeder 18	0.9221	0.6452	$D_{18}(X_{18})$	0.6452
Feeder 19	0.9248	0.5313	$D_{19}(X_{19})$	0.5313
Feeder 20	0.9274	0.8117	$D_{20}(X_{20})$	0.8117
Feeder 21	0.9274	0.4743	$D_{21}(X_{21})$	0.4743
Feeder 22	0.9347	0.8416	$D_{22}(X_{22})$	0.8416
Feeder 23	0.9351	0.7760	$D_{23}(X_{23})$	0.776
Feeder 24	0.9221	0.7953	$D_{24}(X_{24})$	0.7953
Feeder 25	0.9319	0.9278	$D_{25}(X_{25})$	0.9278
Feeder 26	0.9351	0.5192	$D_{26}(X_{26})$	0.5192
Feeder 27	0.9362	0.5168	$D_{27}(X_{27})$	0.5168
Feeder 28	0.9319	0.7660	$D_{28}(X_{28})$	0.766
Feeder 29	0.9365	0.5170	$D_{29}(X_{29})$	0.517
Feeder 30	0.9365	0.9339	$D_{30}(X_{30})$	**0.9339**
Feeder 31	0.9351	0.6723	$D_{31}(X_{31})$	0.6723
Feeder 32	0.9366	0.7177	$D_{32}(X_{32})$	0.7177
Feeder 33	0.9366	0.5178	$D_{33}(X_{33})$	0.5178
Feeder 34	0.9351	0.5185	$D_{34}(X_{34})$	0.5185
Feeder 35	0.9351	0.8654	$D_{35}(X_{35})$	0.8654
Feeder 36	0.9367	0.3187	$D_{36}(X_{36})$	0.6375

Based on the input for different feeders, the obtained results can be used in determining the reliability of the system based on different criteria. Based on the obtained results, it was determined that Feeder 30 was shown to be the most reliable, while Feeder 2 was shown as the most critical component. Therefore Feeder 2 should be prioritized for reconstruction projects compared to the other feeders for the first criteria. This model can be used as a decision-making tool in ranking development and reconstruction projects to deliver long-term benefits to both customers and utility. Based on the available data, the model is flexible to evaluate the desired criteria either by directly inserting available data or by normalizing the available data. The model can be further expanded by inserting different criteria required by the decision-maker. This has become important, where criteria encompassing different dimensions (technical, economical, social or environmental) need to be taken into consideration.

One of the very important properties of the proposed system is that it can be applied on very large systems, which contend with hundreds of components, such as power distribution systems, without introducing additional computational complexity. In this way, projects can be readily prioritised based on their real ability to deliver benefits and complex and imprecise computations required by Eq. (1) can be bypassed.

This proposed method gives a possibility to include in the decision-making process some of the criteria used in the process of EPDS planning. Normally, these criteria would be omitted in the traditional EPDS planning methods and models. One of the application of fuzzy logic enables is the inclusion of qualitative criteria which is obvious to expert opinions but cannot be included in traditional models. The proposed method takes advantage of human inherent tolerance to imprecision and models continuous processes without artificial reduction to discrete values. This model is particularly useful in applications such as EPDS because it can quickly process large amounts of data without the introduction of additional computational complexity. Its flexibility also allows for the association of data that may have a large difference in value size between different data used for planning. Lastly, it is a useful tool in the decision-making process by finding the best solution based on the defined goals and constraints that can be used to justify EPDS investments.

5. Conclusions

New technological discoveries and regulations have influenced the development of distribution networks. This paper presented an overview of the objectives and criteria used in distribution system planning. Technical, regulatory, social, and environmental changes have affected the distribution system planning process. With each additional change, the distribution system planning process will have to adapt to the emerging criteria and goals set by decision-makers. With the application of the fuzzy logic toolbox, a model was created that determines reliability based on the decided input variables. The model was used to input variables, which in turn returns a crisp value that can be used as criteria in EPDS planning. The results show that the model is able to determine a critical feeder based on the data used. It was shown that this model can be used for ranking and reconstruction projects in order to deliver long-term benefits to customers and utility. In the future, this model could be expanded by adding and creating new input variables based on expert opinion and the needs of decision-makers. However, based on the project, one criterion could be prioritized over the others, in which case, weight factors should be incorporated. Given the prioritized criterion, different results could be obtained. Therefore, engineers should be careful before applying different criteria to the model. Finally, based on the considerable amount of evidence, it can be concluded that EPDS planning remains a very important and relevant research topic, which is confirmed by the short review presented in this paper.

Author Contributions

M.S. conceived the presented idea. M.S and H.A. conceptualised the model. H.A. performed the analysis. M.S. and J.H. verified the model and supervised the findings in the work. All authors participated and contributed equally in the process of writing and revising the paper.

H.A. and M.S. developed the methodology. H.A. created the model and performed computations. M.S. provided the data used in the analysis. H.A. normalised the available data for model application. M.S. and J.H. verified the methods.

H.A. wrote the initial draft with input from the other authors. M.S. and J.H. provided feedback and made necessary corrections. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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