Fuzzy Numbers Based Algorithm for Interruptions Frequency Estimation on Distribution Smart Grids

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Abstract—**The reliability of a distribution system can be considered from the point of view of a particular customer or from the entire supply system, e.g. average interruption frequency (SAIFI) and system average interruption duration (SAIDI). The reliability indices which are referring at the interruption frequency are mainly influenced by the adopted operational configuration and the minimization in operation of SAIFI represents an important aim. A substantial change in the power distribution systems behavior appears because of the large-scale introduction of distributed generation as distributed generators connected directly to the main distribution system or inside of microgrids which are also connected to the main distribution system. In the paper, authors propose an original fuzzy based method for the estimation of the average interruption frequency on distribution smart grids.**

Keywords-reliability; smartgrids; microgrids; distributed generation; fuzzy numbers

I. Introduction

The reliability of a distribution system can be considered from the point of view of a particular customer (e.g. the average number of interruptions in the power supply) or from the entire supply system, e.g. average interruption frequency (SAIFI) and system average interruption duration (SAIDI) [1]. Those reliability indices which are referring at *interruption duration* (e.g. SAIDI) are predominantly influenced by the distribution system structure and the existing automations. On the other hand, the reliability indices which are referring at the *interruption frequency* (e.g. SAIFI) are mainly influenced by the adopted operational configuration [2]. Consequently, the minimization in operation of SAIFI represents an important aim. Moreover, the minimization of SAIFI implies also the minimization of SAIDI because "if the time required to restore service is the same as the time required to isolate a fault, minimizing SAIFI will lead to minimization of SAIDI" [3].

Nowadays, a substantial change in the power distribution systems behavior appears because of the large-scale introduction of distributed generation. Distributed generators can be connected directly to the main distribution system or can be inside of *small scale energy zones* [4], well known as *microgrids* (microgrids, which are also connected to the main distribution system). If fault occurred in the main distribution system, the distributed generators directly connected to the main distribution system will be switched off. It is considered unacceptable an operation as a purely island (without the main/system source) of a power distribution system with distributed generators; even the distribution system has the characteristics of a smartgrid. Consequently, in the case where we have microgrids which are behaving as sources, connected to the main distribution system, the microgrids are expected to operate as islands. The customers from a microgrid will be supplied even if a fault has occurred in the main distribution system because a microgrid must have control algorithms, especially *primary* (with momentary adjustment) and *secondary* [5].

Usually, reliability parameters (e.g. failure rates) are numerical data (real numbers). For instance, a numerical failure rate is statistical obtained but we can obtain the value of this parameters, also, from experts (which has experience in use and in operation of a particular equipment). In order to use data from experts, the fuzzy numbers theory represents an important tool. On the other hand, the operations with fuzzy numbers are laborious and it is hard to use them on large systems. In order to simplify the computational problems, the modeling of fuzzy numbers as *abstract data types* [6] is proposed. The term *type of data* designates a *set of values* (the domain of type, e.g. real numbers set) and a *set of operations* that can be performed with these values (addition, multiplication etc.). The *abstract data types* represent artificial data types which can be defined in high level programming languages (C++, Java, Object Pascal etc.). The set of operations can be divided in three subsets: operations among the same type of data, operations among the specified type of data and another type of data and operations performed on the data itself. For instance, if is considered a data belonging to the real numbers set (the domain of type), we can perform arithmetical operations with another real number (operations among the same data types), arithmetical operations with an integer number (operations among the

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specified type of data and another type), and the extraction of integer part (operation applied to the data type itself).

Consequently, a method which can provide the reliability indices regarding to the interruptions on active systems it is of great interest. The authors propose an original fuzzy based method for the estimation of the average interruption frequency on distribution smart grids.

II. Trapezoidal Fuzzy Numbers as Abstract Data Types

In what follows, the modeling of fuzzy numbers as abstract data types is proposed. By the implementation of this model, any fuzzy number will be considered a "fuzzy" object. In electrical engineering fuzzy numbers can represent different physical quantities as well as voltages, currents, resistances, reliability parameters etc. It should be noted that although the following model is for trapezoidal fuzzy numbers (*TrFN*) it can be adapted for any type of fuzzy number. Moreover, for multiplication and division operations were applied approximate formulas in order to obtain also *NFTr*.

To specify an abstract data type, it is necessary to indicate the two elements of the type, i.e. the domain and the operations set:

- *the domain:* is specified as a mathematical set;
- *the operations set:* any operation is described by its mathematical definition.

By implementing this model, all arithmetic operations with trapezoidal fuzzy numbers are reduced to simplified expressions. Consequently, it is possible to represent a trapezoidal fuzzy number through four real numbers (figure 1):

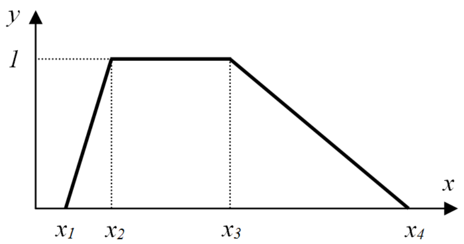

Figure 1. Example of a trapezoidal fuzzy number (TrFN).

A. The Domain

The domain is denoted by *trapezoidal fuzzy numbers* (*TrFN)* and is specified as:

$$TrFN = \{(x_1, x_2, x_3, x_4) \mid x_1, x_2, x_3, x_4 \in R\} \quad (1)$$

B. The Operations Set

In the *trapezoidal fuzzy numbers set*, the following operations are defined:

- For any two quantities $A, B \in TrFN$, it is possible to compute the quantity $C \in TrFN$, with parameters *c1, c2, c3, c4*, defined through:

Addition: C = A + B, where:

$$\begin{aligned} c_1 = a_1 + b_1; \quad c_3 = a_3 + b_3 \\ c_2 = a_2 + b_2; \quad c_4 = a_4 + b_4 \end{aligned} \quad (2)$$

Subtraction: C = A - B, where:

$$\begin{aligned} c_1 = a_1 - b_4; \quad c_3 = a_3 - b_2 \\ c_2 = a_2 - b_3; \quad c_4 = a_4 - b_1 \end{aligned} \quad (3)$$

*Multiplication: C = A * B*, where:

$$\begin{aligned} c_1 = a_1 \cdot b_1; \quad c_3 = a_3 \cdot b_3 \\ c_2 = a_2 \cdot b_2; \quad c_4 = a_4 \cdot b_4 \end{aligned} \quad (4)$$

Division: C = A / B, where:

$$\begin{aligned} c_1 = a_1 / b_4; \quad c_3 = a_3 / b_2 \\ c_2 = a_2 / b_3; \quad c_4 = a_4 / b_1 \end{aligned} \quad (5)$$

- For any quantity $A \in TrFN$, it is possible to determine the quantity $r \in R$ defined as:

Remote: r = Rem(A, 0), where:

$$r = \frac{a_1 + a_2 + a_3 + a_4}{4} \quad (6)$$

Width: r = Width(A), where:

$$r = a_4 - a_1 \quad (7)$$

III. The Estimation of Interruptions Frequency

We define the *average interruption frequency* (*AIF*) as total average number of customer interruptions per total number of customers served:

$$AIF = \frac{\sum_{i=1}^{n} \left(TANI_i(T) \cdot N_i \right)}{N} \quad (8)$$

where:

$TANI_i$ - the total average number of customer interruptions supplied from the node *i* in the reference period *T*;

N - the total number of customers served;

N_i - the total number of supplied customers from the node *i*;

T - the reference period [*year*] (*T = 1 year*);

n - the number of load nodes of the system.

The total average number of customer interruptions supplied from the node *i* in the reference period *T* is given by the relationship [7]:

$$TANI_i(T) \approx \lambda_{ti} \cdot T \qquad (9)$$

where λ_{ti} represents the total failure rate of the equivalent element corresponding to the reliability block diagram at the level of the node i [$year^{-1}$];

The total failure rate has three components:

$$\lambda_{ti} = \lambda_i + \lambda_i^{'} + \lambda_i^{''} \qquad (10)$$

where:

λ_i - the failure rate when the restoring of supply is performed after the fault repair;

$\lambda_i^{'}$ – the failure rate when the restoring of supply is performed after the fault isolation through non-automatic maneuvers;

$\lambda_i^{''}$ – the failure rate when the restoring of supply is performed after the fault isolation through automatic maneuvers.

By introducing the relationships 9 and 10 into relationship 8, we obtain:

$$AIF = \frac{\sum_{i=1}^{n}\left((\lambda_i + \lambda_i^{'} \cdot k_i) \cdot N_i\right) \cdot T}{N} \qquad (11)$$

where k_i ($k_i = \overline{0,1}$) estimates the weight of restoring after 3 minutes.

In practice, we can consider k = 1, which corresponds to the most unfavorable case (when all restorations of supply after fault isolations through non-automatic maneuvers are performed after 3 minutes) [9]. If $k_i = 1$, *AIF = SAIFI* (Total number of customer interruptions longer than 3 minutes / Total number of customers served) [1].

A. Transforming of System Topology

In what follows, we will take into account the following assumptions: simple contingencies and independent system components from the reliability point of view. Also, in order to solve the problem, we will make some changes on the existing system topology following the procedure:

a. If the system has more than one source node, it will be reduced to a system with one source by introducing of a *fictive source*. This fictive source is linked to the real sources by fictive lines which have failure rate equal with zero and are equipped with circuit breakers. In figure 2 is presented a system with two sources A and A' where a fictive source O is introduced. The fictive source is linked to the real sources through two fictive lines O-A and O-A'.

b. A (multi)graph will be associated with the analyzed system. In the specified (multi)graph the busbars are considered as nodes, while the lines are considered as branches (figure 3) [8].

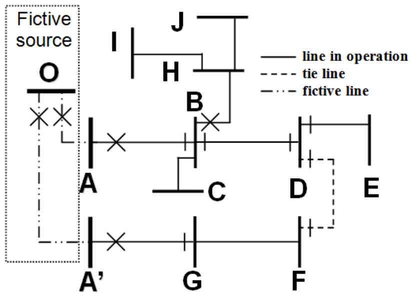

Figure 2. Initial test system.

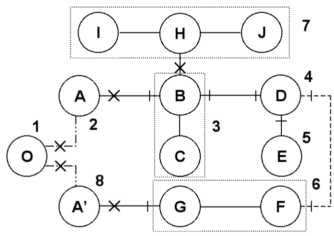

Figure 3. Graph associated with the electric system.

c. Reducing of inseparable system elements (elements between there isn't any type of switches) to a single equivalent node. The obtained equivalent node has the failure rate equal with the failure rates sum of nodes and branches which are replaced. For instance, in the case presented on figure 3 will result three equivalent nodes: 3, 6 and 7. E.g., the failure rate of node 7 represents the failure rates sum of nodes H, I, J and branches H-I and H-J.

d. For the resulted graph (figure 4) critical nodes and critical branches are determined by using the algorithms from [8].

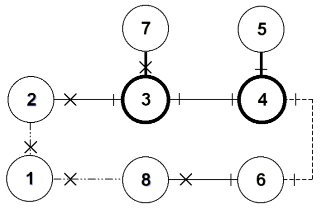

Figure 4. Reduced graph with critical elements.

e. Preservation of the tree corresponding to the operational system scheme through elimination of tie lines (the line 4-6 from figure 4) – figure 5.

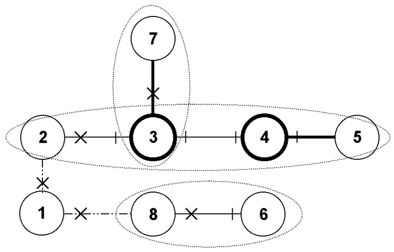

Figure 5. The tree coresponding to the operational scheme.

B. *Algorithm for SAIFI Estimation*

The concrete algorithm for calculating the average interruption frequency index in what follows is presented:

i. Starting from the source node and going towards the end nodes, each scrolled node is retained. For the tree from figure 5, the array will be 1-2-3-4-5-7-8-6.

ii. For each node, the failure rates are calculated:

- Determine the source node of current node. Starting from the current node and going towards the source node, *the source node for the current node* is considered the first found node which is equipped with circuit breaker. E.g., if we consider the node 5 (figure 5) as current node, the source node will be the node 2;
- Starting from the source node and going towards the current node, all nodes which are not linked via branches with circuit breakers are retained. In figure 5 we have three such sub-trees;
- compute the failure rates of current node *i*:

$$\lambda_i^{'} = \lambda_{source}^{'} + \lambda_{\text{uncritical}} \qquad \lambda_i = \sum_{Treeelements} \lambda - \lambda_i^{'} \tag{12}$$

where $\lambda_{\text{uncritical}}$ represents the failure rates sum of tree elements which are not critical (are redundant);

iii. The average interruption frequency index (SAIFI) is computed:

$$N = \sum_{i=1}^{n} N_i$$

For (i = 1 to n)
If (node i is a microgrid which is behaving as source)
Then $N_i = 0$
Compute SAIFI (equation 11)

IV. CASE STUDY

By implementing of the model from chapter II, the operations with trapezoidal fuzzy numbers are reduced to the evaluation of simplified expressions. Thus by defining failure rates as TrFN(λ_1, λ_2, λ_3, λ_4) and replacing them into relationship 11, the fuzzy equation for *SAIFI* is obtained. The presented models for *TrFN* and the algorithm for the evaluation of *SAIFI* in *C++* programming language were implemented in an original program.

In order to test the correctness of the program implementation the authors have studied the test system from figure 4 in two scenarios:

- *configuration 1:* tie line (4-6);
- *configuration 2:* tie line (4-3).

Table I indicates the failure rates of distribution system nodes and the number of supplied customers by each node. The failure rates of distribution system branches are also presented in Table II.

TABLE I. FUZZY FAILURE RATES OF SYSTEM NODES

Node	Fuzzy failure rates [year^{-1}]					Customers number
	Type	*1*	*2*	*3*	*4*	
2	λ	0.08	0.1	0.13	0.15	
	λ'	0.2	0.25	0.29	0.33	
3	λ	0.06	0.066	0.093	0.12	17
4	λ	0.02	0.022	0.031	0.04	32
5	λ	0.03	0.033	0.0465	0.06	22
6	λ	0.08	0.088	0.124	0.16	43
7	λ	0.1	0.11	0.155	0.20	28
8	λ	0.09	0.12	0.14	0.15	
	λ'	0.3	0.32	0.34	0.35	

TABLE II. FUZZY FAILURE RATES OF SYSTEM BRANCHES

Branch		Fuzzy failure rates λ [year^{-1}]			
		1	*2*	*3*	*4*
3	2	0.12	0.135	0.165	0.18
4	3	0.04	0.045	0.055	0.06
4	6	0.04	0.045	0.055	0.06
5	4	0.032	0.036	0.044	0.048
6	8	0.08	0.09	0.11	0.12
7	3	0.1	0.1125	0.1375	0.15

The results are presented in Table III and Table IV. In Table III, the fuzzy SAIFI index, in the case when the distribution system contains customers and independent DG units is presented. We can observe that SAIFI is smaller for configuration 1 than in the case of configuration 2 because the comparison criterion "remote from zero" Rem(SAIFI, 0) has priority. In Table IV, the fuzzy SAIFI index, in the case when the distribution system contains besides customers and independent DG units, also one microgrid connected to the node 6. This microgid contains the 43 customers and behaves as a source from the point of view of the distribution system.

TABLE III. SAIFI WHEN DISTRIBUTION SYSTEM CONTAINS CUSTOMERS AND INDEPENDENT DG UNITS

Configu-ration	Fuzzy SAIFI				Rem (SAIFI, 0)	Width (SAIFI)
	1	*2*	*3*	*4*		
1	0.612	0.710	0.869	0.994	0.796	0.382
2	0.644	0.734	0.880	0.991	0.812	0.347

TABLE IV. SAIFI WHEN DISTRIBUTION SYSTEM CONTAINS CUSTOMERS, INDEPENDENT DG UNITS AND ONE MICROGRID

Configu-ration	Fuzzy SAIFI				Rem (SAIFI, 0)	Width (SAIFI)
	1	*2*	*3*	*4*		
1	0.445	0.523	0.654	0.758	0.595	0.313
2	0.441	0.505	0.611	0.692	0.562	0.251

V. CONCLUSION

The paper presents an original fuzzy based method for the estimation of the average interruption frequency index on distribution smart grids. Related mathematical model for *trapezoidal fuzzy number* abstract data type is developed. This model was implemented as object in C++ programming language.

The algorithm for SAIFI estimation was detailed presented. By defining failure rates as trapezoidat fuzzy numbers (λ_1, λ_2, λ_3, λ_4) the fuzzy equation for SAIFI is obtained. Also, a numerical example is given to confirm the computer implementation of proposed method. This program represents an important tool in order to estimate interruptions frequency on distribution smart grids.

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