Proceedings of the
34th International Conference on Information Technologies (InfoTech-2020)
IEEE Conference, Rec. # 49733, 17-18 September 2020, Bulgaria

POWER SUBSTATIONS RELIABILITY EVALUATION USING FUZZY SET THEORY

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Abstract: Power substations as infrastructures with highest outage rate closest to the consumers and power generation facilities, should be well analysed. This paper presents an upgrade of a method for evaluation of the reliability of power substations, considering uncertainty and imprecision of the input data, based on fuzzy logic. The probability of failure is modelled as a triangular fuzzy number and the Energy Not Supplied (ENS) is calculated. The method is presented on a 400/110 kV/kV substation. The case study shows that the usage of triangular fuzzy numbers gives satisfactory results from an engineering point of view and provides a high level of precision and model simplicity.
Keywords: Reliability, power substations, fuzzy logic, uncertainty

1. INTRODUCTION

Power substations are power facilities that are part of the power system and their main function is to distribute the electrical energy and/or transform it to certain voltage levels. Power substations are supposed to perform reliably in a way that provides quality electrical energy supply, with lowest exploitation costs.

Considering that the failures in the power substations are relatively rare, acquisition of reliable data for the statistical probability of components' failures is a long and hard work. The observation of the equipment's behaviour should be classified to components and voltage levels. Also, regular preventive maintenance of the installed equipment is of great importance for the number of failures, which can increase the period between two failures. For greater qualitative value, the human factor, location of the substation and its part in the power system should not be taken into consideration.

Analysing the power substations built in Macedonia leads to a conclusion that they consist of equipment from many different producers [1]. This implies that components' reliability depends highly from their constructive characteristics and the technology used in the design process. It is important to mention that modern technology and the usage of contemporary materials and isolation mediums find their way in power substations construction. That imposes implementation of a new type of equipment, for there are not reliability parameters known. Therefore, they have to be estimated based on engineering logic and judgment, as well as on the experience from working on similar technical systems.

The estimation of the reliability parameters of the components in the power substations contains a high level of insecurity and uncertainty, which are still given statistical character. This data was subjected to statistical analysis, calculating the mean value, standard deviation and the level of reliability. The statistical analysis starts with the calculation of the mean value of the reliability parameters of the components and further this data are used for estimation of the reliability parameters of a certain single line diagram of power substation [1]. However, it is more appropriate to assume that the unavailability of the components and the uncertainty belongs to a certain range, rather than assuming that they have fixed value [1]. The development of the contemporary method of interval mathematics, especially the development of fuzzy logics offers effective procedures and techniques that can include the imprecise and unavailability of the input data [2].

A fuzzy logic based reliability estimation method was proposed in [1]. The method analyses the probability of failure of a substation, considering that the unavailability rates of the equipment are given as fuzzy triangular numbers. The method is used for calculation of the total Energy Not Supplied (ENS), which is one of the main reliability indexes. In [3], reliability estimation approach based on fuzzy numbers is presented. The fuzzy numbers are used for evaluation of the load duration curve and the probabilities of failure of the generators that are in service. Calculating the Expected Energy Not Supplied (EENS), the Loss of Energy Expectation (LOEE) and the Energy Index of the Reliability (EIR), case study of the Malaysian distribution network is analysed.

In this paper, the fuzzy logic theory is used for estimation of the reliability of power substations, considering the reliability of the power lines. The substation is divided into blocks, and each of the blocks has a certain impact on the substation’s reliability. This method, compared to the conventional methods, offers a wider range of scenario analysis that can cause the failure of the power substation. The main characteristic is that the values of the unavailability of the substation, the duration of energy not supplied, as well as the energy not supplied due to component failure in the substation, are also fuzzy numbers, defined with proper membership function.

2. FUZZY LOGIC THEORY

Conventional Boolean logic is based on the fact that in the decision-making process, humans make simple decisions (yes or no) and the statements are whether true or false (1 or 0) [2]. However, it was shown that human thinking and the natural phenomena do not always correspond to this logic, and sometimes they contain a high level of uncertainty, imprecise and ambiguity [2].

Following the nature of human thinking, Lotfi Zadeh in 1965 sets the basics of the Fuzzy set theory and the Fuzzy logic. They represent branches of science and computer engineering, which belong to the artificial intelligence field. Unlike the conventional Boolean logic, where each element belongs to the given set or not, in the fuzzy set theory, each element has its membership degree [4]. The membership degree varies between 0 (the element does not belong to the set) and 1 (the element completely belong to the set). Therefore, fuzzy logic is also known as multi-value logic and represents an expansion of the classical bi-value Boolean logic.

The fuzzy set **A** in the universe of discourse **U** defines as a set of ordered pairs:

$$A = \{(x, \mu_A(x)) \mid x \in U\} \tag{1}$$

where $\mu_A(x)$ represents the membership function of the fuzzy set **A.** The membership function defines the degree of membership of the variable x to the fuzzy set **A.**

The fuzzy set definition is an expansion of the classical set theory. Respectively, if the range of the membership function expands, the uncertainty and the indeterminacy increase. Otherwise, if the range of the membership function reduces, the uncertainty and the indeterminacy decrease, and the fuzzy set turns into a conventional set.

The design of the fuzzy sets depends on two factors: identifying the state space and the corresponding membership function. The specification of the membership function is subjective, which means that there is a diversity of solution to one problem since different experts take a different approach. The reason behind that is the individual differences of human perspective to the world and abstract concepts.

Membership function might have a different form. The simplest and the most used is the triangular membership function. Other standard membership functions are trapezoidal, Gauss, ring and polynomial function.

2.1. Data modelling with fuzzy numbers

Real numbers can be written as fuzzy numbers with a proper membership function given as:

$$\mu_a(x) = \begin{cases} 1 & for \quad x = a \\ 0 & for \quad x \neq a \end{cases} \tag{2}$$

However, if the number contains a certain level of uncertainty and unreliability or the analysed variable's value can be estimated in a certain range$[a_1; a_3]$, it is more suitable to model an interval number, with membership function defined as:

$$\mu_{A\sim}(x) = \begin{cases} 1 & for \quad a_1 \leq x \leq a_3 \\ 0 & for \quad x < a_1 \wedge x > a_3 \end{cases} \tag{3}$$

Fuzzy numbers are fuzzy subsets that are normal and convex. Fuzzy numbers are expansion of the ordinary real numbers $a \in \Re$ and interval numbers. They are used for modelling unreliable data and information with convex membership function defined with values in the range [0, 1] (for instance, the value is approximately *a*). On figures 1, 2 and 3 a fuzzy number **A** and its alpha-cuts α and α' are shown, defined with proper interval number.

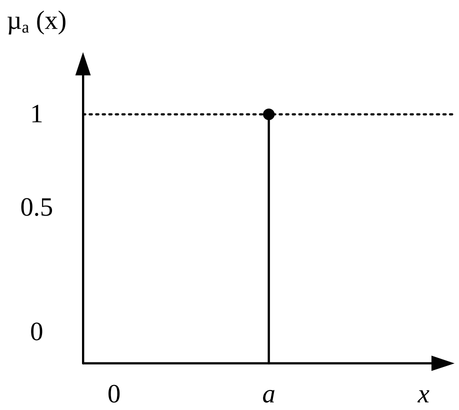

Fig. 1. Real number

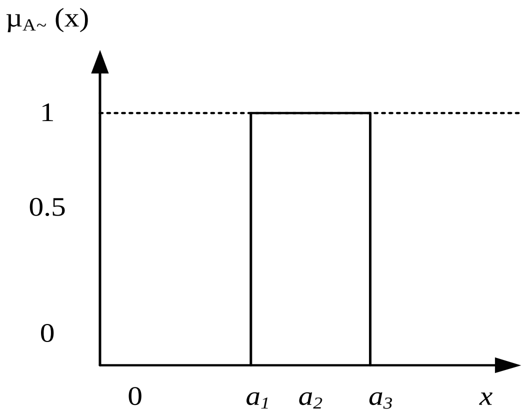

Fig. 2. Interval number

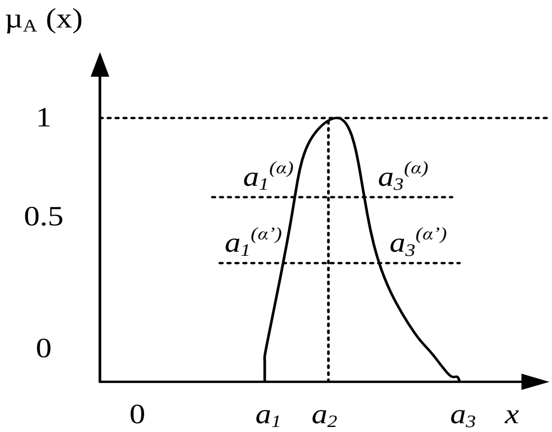

Fig. 3. Triangular fuzzy number

2.2. Triangular fuzzy numbers and basic mathematical operations

Triangular fuzzy numbers find their usage for modelling technical and engineering systems, whose input data characterize with uncertainty. Their design is intuitive and can be easily specified by experts in the research process. In that matter, the formation of a fuzzy model for estimation of the reliability parameters of the electric substation, the upper and lower limits, as well as the most probable reliability value of the substation components, have to be defined. These three values can model three different forms of imprecise and uncertain reliability parameters: the failure rate, the failure time duration, the Energy Not Supplied (ENS) duration, ENS etc.

The basic mathematical operations can be applied to triangular fuzzy numbers, which makes them more popular and applicable in reliability calculations [2][4]. The mathematical operations of triangle fuzzy numbers are defined according to the Zadeh's principle of extension of the proper α-cuts. The α-cut defines the safety level range and $\alpha \in [0,1]$. For given triangular number $A=(a_1,a_2,a_3)$, presented in Fig. 4, the α -cut defines in the following manner:

$$A_\alpha = [a_{1\alpha}, a_{2\alpha}] = [a_1 + (a_2 - a_1)\alpha, a_3 + (a_2 - a_3)\alpha] \quad (2)$$

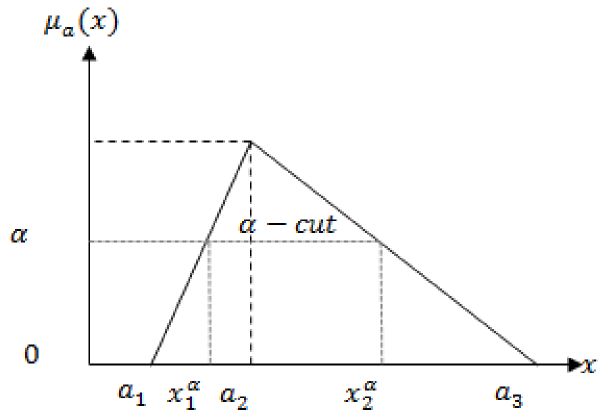

Fig. 4. Triangular fuzzy number

In fuzzy set theory, the result of addition and subtraction of two triangular fuzzy numbers is a triangular fuzzy number:

$$A(+)B = (a_1,a_2,a_3) + (b_1,b_2,b_3) = (a_1+b_1, a_2+b_2, a_3+b_3) \quad (5)$$

$$A(-)B = (a_1,a_2,a_3) - (b_1,b_2,b_3) = (a_1-b_1, a_2-b_2, a_3-b_3) \quad (6)$$

Other basic mathematical operations, such as multiplication and division are defined with the safety level, i.e. the α-cut. If the α-cuts of triangular fuzzy numbers **A** and **B** are $A_\alpha = [a_{1\alpha}, a_{2\alpha}]$ and $B_\alpha = [b_{1\alpha}, b_{2\alpha}]$, respectively, the multiplication and division are defined in the following manner:

$$A_\alpha(\cdot)B_\alpha = \left[\min_{i,j=1,2}(a_{i\alpha}b_{j\alpha}), \max_{i,j=1,2}(a_{i\alpha}b_{j\alpha})\right] \quad (7)$$

$$A_\alpha(:)B_\alpha = \left[\min_{i,j=1,2}\left(\frac{a_{i\alpha}}{b_{j\alpha}}\right), \max_{i,j=1,2}\left(\frac{a_{i\alpha}}{b_{j\alpha}}\right)\right] \quad (8)$$

The result, defined by α –cuts, is a fuzzy number with polynomial membership functions, which is not triangular. The expression given in (8) applies only if the interval B_α does not contain the zero. To remain a triangular fuzzy number, for engineering purpose, the multiplication and division are calculated as:

$$A_\alpha(\cdot)B_\alpha = [a_1b_1, a_2b_2, a_3b_3] \quad (9)$$

$$A_\alpha(:)B_\alpha = \left[\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right] \quad (10)$$

3. RELIABILITY CALCULATION OF COMPONENTS IN A SYSTEM

The components in the substations are grouped to form a functional whole with precisely defined function in normal operational condition. So far, the experiences have shown that substations have high reliability rate, which depending on the components and the voltage rate, varies between 10^{-4} and 10^{-6}.

In the following, the analysis of the basic structural connection of the components in substations is made. The components can be connected in series, in parallel or a combined manner, as shown in figures 5, 6 and 7.

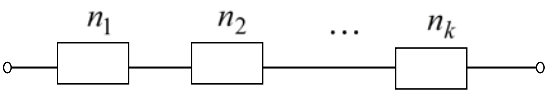

Fig. 5. Serial connection of the components

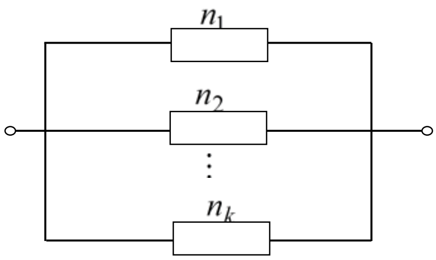

Fig. 6. Parallel connection of the components

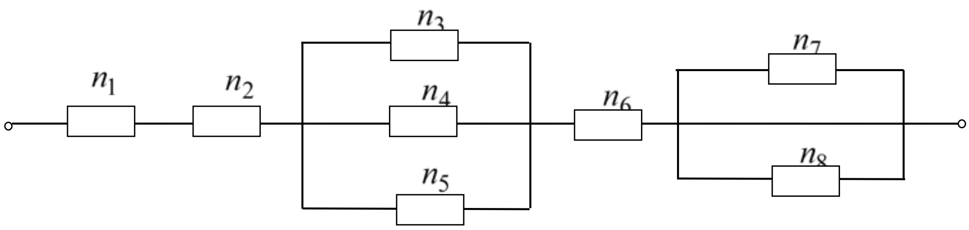

Fig. 7. Parallel connection of the components

If K denotes the number of components which form a functional whole are connected in series and if the unavailability of each component is described with a fuzzy number $\mu_i(x, \mu_i(x))$, the equivalent unavailability of the system, with a certain safety level α is:

$$u_e^{(\alpha)} = \sum_{i=1}^{K} u_i^{(\alpha)} - \sum_{i=1}^{K}\left(u_i^{(\alpha)} \cdot \sum_{j=i+1}^{K} u_j^{(\alpha)} \right) + \cdots \cong \sum_{i=1}^{K} u_i^{(\alpha)} \qquad (11)$$

If the unavailability of series components is described with triangular fuzzy numbers: $u_i = [u_{e1}; u_{e2}; u_{e3}]$, then the equivalent unavailability is also a triangular fuzzy number:

$$u_i = [u_{e1}; u_{e2}; u_{e3}] = \left[\sum_{i=1}^{K} u_{1i}; \sum_{i=1}^{K} u_{2i}; \sum_{i=1}^{K} u_{3i} \right] \qquad (12)$$

If K denotes the number of components connected in parallel, the equivalent unavailability of the system with α-cut is calculated in the following way:

$$u_e^{(\alpha)} = \prod_{i=1}^{K} u_i^{(\alpha)} \tag{13}$$

If the unavailability of components connected in parallel is presented as triangular fuzzy number $u_i = [u_{e1}; u_{e2}; u_{e3}]$, then the equivalent unavailability is not a triangular fuzzy number, but a fuzzy polynomial:

$$u_e^{(\alpha)} = \left[u_{1e}^{(\alpha)}, u_{2e}^{(\alpha)}\right] = \left[\prod_{i=1}^{K}\left[u_{1i} + \left(u_{2i} - u_{1i}\right)\alpha\right]; \prod_{i=1}^{K}\left[u_{3i} + \left(u_{2i} - u_{3i}\right)\alpha\right]\right] \tag{14}$$

If the system consists of serial and parallel-connected components, the equivalent unavailability is calculated with a combination of the previously presented equations (11-14). Also, according to the minimal path and minimal cuts methods, every system can be represented as a structure of components connected in series and parallel.

4. TEST EXAMPLE

The test example, analysis a substation as presented in Fig. 8. The substation consists of two transformer branches connected in parallel and two power lines. Each of the transformer branches consists of a transformer with voltage rate 400/110 kV, circuit breakers and disconnectors on both voltage levels. The measurement units, such as current transformer and voltage transformers are not taken into consideration because they do not have an impact on power supply interruptions.

The unavailability of each of the components is defined with a triangular fuzzy number, based on the results shown in [5] and also evaluation based on experience. The unavailability rates depend on the voltage level, and they are shown in Table 1.

The transformers are identical since they are connected in parallel. Each of them has a power of 100 MW. If there is an outage in one of the transformer branches, power greater then $P_L = 100$ MW will not be supplied, while, if there is an outage in both of the transformer branches, no power will be supplied.

According to the equations for equivalent unavailability of the components connected in series, the equivalent unavailability of each of the parts is calculated.

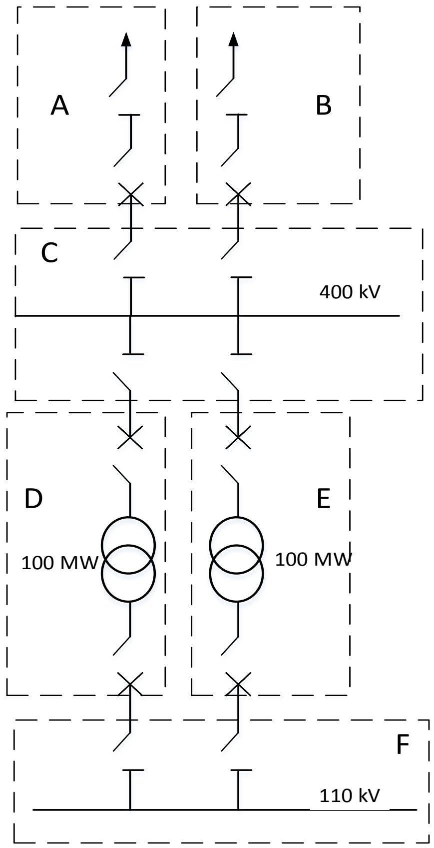

Fig. 8. Single line diagram of 400/110 kV/kV substation

Table 1. Unavailability rates of the installed equipment

Component	Voltage (kV)	Unavailability rates
Circuit breaker	400	$[1.75; \quad 2.00; \quad 2.50]\cdot 10^{-5}$
Disconnector	400	$[3.30; \quad 3.50; \quad 3.60]\cdot 10^{-6}$
Bus 400 kV	400	$[4.28; \quad 4.33; \quad 4.47]\cdot 10^{-6}$
Circuit breaker	110	$[3.22; \quad 3.60; \quad 3.65]\cdot 10^{-5}$
Disconnector	110	$[3.06; \quad 3.25; \quad 3.43]\cdot 10^{-6}$
Bus 110 kV	110	$[4.40; \quad 4.50; \quad 4.67]\cdot 10^{-6}$
Power transformer	400/110	$[4.80; \quad 4.95; \quad 5.15]\cdot 10^{-4}$

The equivalent unavailability of the whole system is calculated with a combination of the expressions for series and parallel connected components.

$$U_{eqv} = [2.78 \quad 2.91 \quad 3.04]\cdot 10^{-5} \tag{15}$$

The results show that the safety level $\alpha = 0.5$ corresponds to calculated unavailability of $[2.85 \quad 2.98]\cdot 10^{-5}$, while for $\alpha = 0.8$ the range of the resulting unavailability is $[2.89 \quad 2.94]\cdot 10^{-5}$, as shown in Fig. 9.

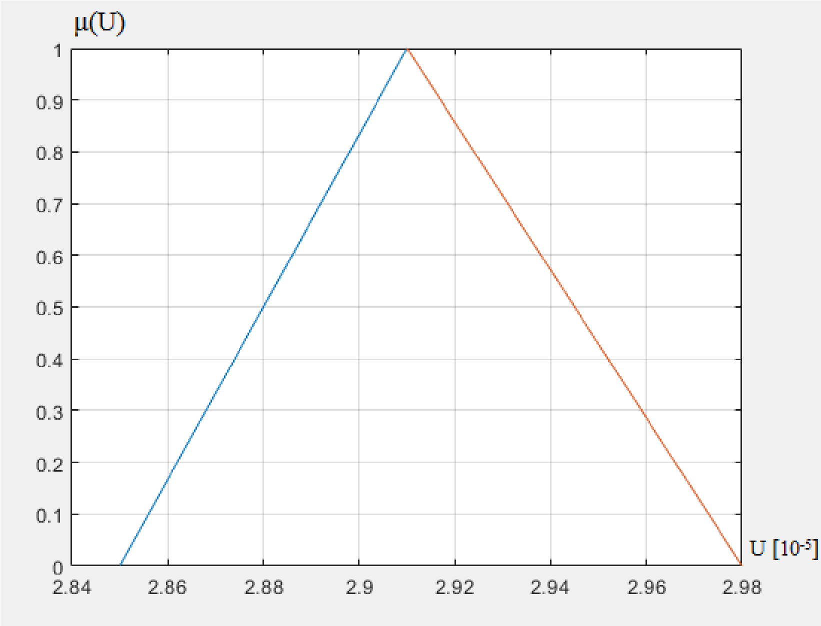

Fig. 9. Representation of the α-cuts

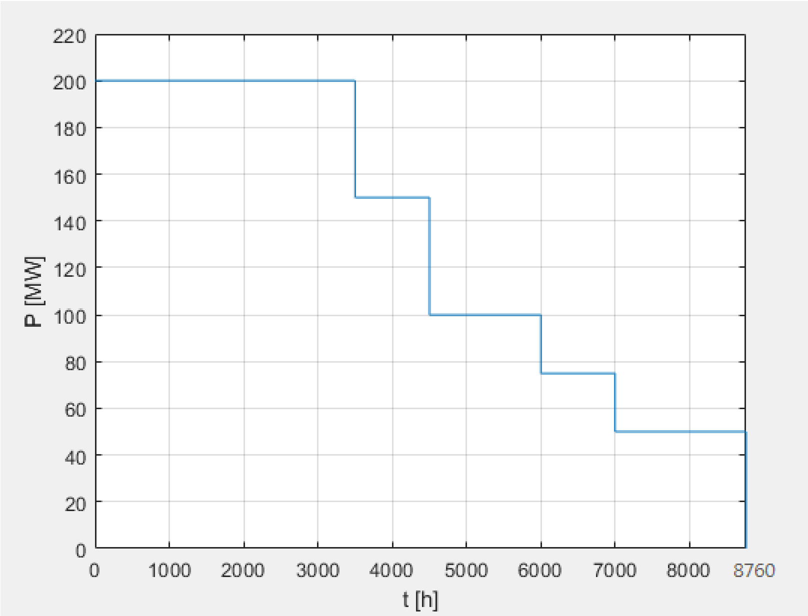

Fig. 10. Load duration curve of the analysed substation

Considering the calculated unavailability rates, the annual Energy Not Supplied (ENS) can be calculated, if the load duration curve is known (Fig.10). The results are presented in Table 2. It can be concluded that the annual ENS of the substation is mainly due to an outage of one transformer branch. The probability of an outage of the two transformer branches at the same time is drastically lower.

Since the probability of substation outage is described with a triangular fuzzy number, the ENS is also presented as a triangular fuzzy number. Financial losses due to power supply interruptions can be calculated if the consumers' type is known, for instance, households or industrial load.

Table 2 ENS in different situations

No.	A	B	C	D	E	F	Probability of occurrence	Power [MW]	ENS [MWh/year]
1	1	1	1	1	1	1	/	0	0
2	**0**	1	1	1	1	1	$[2.08;\ 2.35;\ 2.86]\cdot10^{-5}$	100	$[9.36;\ 10.58;\ 12.87]$
3	1	**0**	1	1	1	1	$[2.08;\ 2.35;\ 2.86]\cdot10^{-5}$	100	$[9.36;\ 10.58;\ 12.87]$
4	1	1	**0**	1	1	1	$[1.70;\ 1.78;\ 1.85]\cdot10^{-5}$	200	$[29.78;\ 31.24;\ 32.46]$
5	1	1	1	**0**	1	1	$[5.36;\ 5.58;\ 5.84]\cdot10^{-4}$	100	$[241.23;\ 250.99;\ 262.43]$
6	1	1	1	1	**0**	1	$[5.36;\ 5.58;\ 5.84]\cdot10^{-4}$	100	$[241.23;\ 250.99;\ 262.43]$
7	1	1	1	1	1	**0**	$[1.05;\ 1.10;\ 1.15]\cdot10^{-5}$	200	$[18.43;\ 19.27;\ 20.20]$
8	**0**	**0**	**0**	**0**	**0**	**0**	$[2.78\ \ 2.91\ \ 3.04]\cdot10^{-5}$	200	$[48.72;\ 51.06;\ 53.26]$
							Total:		$[598.62\ \ 625.26\ \ 657.47]$

4. CONCLUSION

This paper presents a method for reliability evaluation of a substation considering the uncertainty of input data, based on fuzzy theory. The method presented is an upgrade of a method presented in [1] and it shows that it is applicable for more complex substations. The results are characterized by a low percentage of error, which makes the method applicable to engineering calculations in the designing process. Also, the results provide a wider range of probabilities of failure, which can be analysed as case scenarios that cause power supply interruptions.

The method was used for calculation of ENS which indicates the level of reliability in power systems and it is of major importance for the selection of equipment and power substation configuration in the designing process.

REFERENCES

[1] Iliev, A., & Zlatanoski, M. **(2004)**: Reliability Evaluation of Electric Substations Considering Uncertainty of the Input Data. *Conference Proceedings of the Fourth Mako Cigre Conference*, Paper No. B3-01, Ohrid, 26-29 September.

[2] Nahman, J. (**1997**). *Fuzzy Logic Based Network Reliability Evaluation*. Belgrade, Republic of Yugoslavia: Faculty of Electrical Engineering.

[3] Shalash, N. A., & Ahmad, A. Z. (**2016**). Fuzzy Numbers Based on Energy Indicators of Reliability Power System. *Electrical and Electronics Engineering: An International Journal* (ELELIJ) Vol. 5, No 2, pp. 51-61.

[4] Zimmermann, H.-J. (**2001**). *Fuzzy Set Theory and Its Applications*, Fourth Edition. New York: Springer Seience+Business Media.

[5] Working Group A3.06. (**2012**). *Final Report of the 2004-2007 International Enquiry on Reliability of High Voltage Equipment*. CIGRE.