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Justification of ice melting capacity on 6-10kV OPL distributing power networks based on fuzzy modeling

***Abstract**. We developed a fuzzy technical and economic model for optimization the parameters of the ice melting schemes at 6-10 kV OPL of distribution power networks based on which we justified the value of ice melting deposits fusion power, taking into account the uncertainty of initial data.*

***Streszczenie.** Opracowano rozmyty model techniczny i ekonomiczny do optymalizacji parametrów schematów topienia lodu w napowietrznych sieciach dystrybucyjnych o napięciu 6-10 kV. Na podstawie tych modeli uzasadniono wartość mocy potrzebnej do stopnienia osadzonego lodu, biorąc pod uwagę niepewność danych początkowych. (**Uzasadnienie zdolności do topienia lodu w napowietrznej sieci rozdzielczej 6-10 kV w oparciu o modelowanie rozmyte**).*

Keywords: melting of ice, fuzzy sets, electric networks.
Słowa kluczowe: topienie lodu, zbiory rozmyte, sieci elektryczne.

Introduction

As it is known [1], the key circuit parameters of ice melting are the value of active power losses per unit of wire length in the mode of melting deposits (melting capacity) and the time of melting deposits, which is a function of the melting capacity. When designing the ice melting schemes with using the special electric power plants of ice melting (limiting reactors, bearish autotransformers [2], ice-protected transformers [3]), which have recently used more often for harmonization of power system with the lines' parameters. There is a problem of choosing an independent option of melting schemes (the melting capacity of deposits that must be provided by such a facility). The feasibility of mass industrial production of standardized installations for ice melting on 6-10 kV overhead power line (OPL) wires and a variety of parameters of electrical networks 6-10 kV lead to the need to solve this problem, taking into account factors of input data uncertainty.

Approaches for designing of ice melting at 6-10 kV OPL electric distribution networks [1, 4] showed that the existing technical and economic models do not allow to take into account the effect of melting deposits power on cost of melting schemes characteristics and make selecting this option.

In [5] we developed a single criterion technical and economic model for optimization the parameters of the ice melting schemes at 6-10 OPL using the reduced cost criterion, which takes into account the impact of melting capacity of deposits on such factors of the melting schemes as insufficient outputting of electrical energy to consumers during melting, electric power consumption for melting, the cost of electric power installations for ice melting, the cost of additional capacity of power transformer of the 110-35 / 6-10 kV district substation. Basing on the model we carried out optimization of power ice melting, which should be provided by different electric power plants with the assumption of determinism outputs that lead to the conventions of the solution. In addition, the used criteria of the costs does not satisfy the condition of options identity which are compared for such properties as the reliability of power supply, energy conservation. In essence this criterion provides a reduction of multi-criterion to single-criterion problem statement. Taking into account the qualitatively different costs of resources in the selection of the optimal solution are possible in the case of multi (vector) approach. The analysis showed that the final decision of power optimization problem of ice melting in multicriterion statement considering the output data uncertainty factor may be based on the device of fuzzy set theory [6-8].

The purpose of the studies is to justify capacity of ice melting deposits, taking into account the uncertainty of initial data based on fuzzy modeling.

Materials and Methods

Determined model research [5] on sensitivity to changes in output data showed that given the expenditure on ice melting is the most sensitive to changes in the number of exhaust 6-10 kV OPL, which provides using of common electric power installation for ice melting. Therefore we have made a conclusion that ice melting optimizing power, which should be provided with electric power plant, should be done with regard to the number of OPL uncertainty. The ice melting power optimization on 6-10 kV OPL, taking into account the uncertainty of the initial data, was carried out on the basis of the theory of fuzzy sets apparatus. This mathematical apparatus is widely used for decision making in conditions of uncertainty during electric power solving problems of [6], and also many other engineering and economic problems [7]. To solve the optimization problem based on the apparatus of the fuzzy sets theory, we used the Bellman-Zadeh approach, which involves the symmetry of fuzzy goals and constraints on the universal set of alternatives [9-11].

As it is known [4], in the case when the melting power exceeds some maximum value of P_{0max}, which depends on a large number of random variables (first of all, on the air temperature and wind speed, which accompany the formation of sediments), ice melting is possible only in repeated-short-term mode.

This method of ice melting is characterized by significant wear and tear of contact systems of high-voltage switches due to the large number of switching on and off in the short-circuiting mode, and also due to the negative effect on the working conditions of consumers connected to the line. That was why it was advisable that the melting power provided by the electric power plant does not exceed the maximum limit in which the melting of deposits is possible in the long run.

On the other hand, to ensure the required rate of deposits removal on interconnected OPL, the melting power must be greater than a certain minimum value of P_{0min}, which also essentially depends on the air temperature and the wind speed that accompany the sediments formation. In

[12], an imitation model of ice melting on interconnected 6-10 kV OPL has been developed. It allows to estimate theoretically the value of the minimum allowable ice melting capacity for various meteorological conditions.

It should be noted that the case where the melting power is less than the minimum cannot be considered inappropriate, because in this case, in the latter case, the OPL loading from ice will slightly exceed the normative value, which does not mean the fact of line damage, because it has some stock for mechanical strength.

Thus, taking into account the effect of a large number of random variables, the "desirability" of the ice melting power, which must be provided by an electric power plant, can be interpreted as fuzzy value. The trapezoid-type interval is used as the fuzzy interval of allowable alternatives (permissible melting power). The interval is described by the tuple S = < *a*; *b*; *α*; *β* >$_T$, where *a*, *b* are respectively the lower and upper modal values of the interval; *α*, *β* are respectively the left and right coefficients of fuzziness [13, 14]. The parameters of the fuzzy interval are determined on the basis of variation of the main random factors affecting on the minimum and the maximum allowable value of melting power (the air temperature and wind speed during sediment formation). The calculations conducted for the territory of Ukraine have gave the result S = <46; 62; 17; 182>$_T$. The graph of the belonging function of the fuzzy interval of admissible alternatives $\mu_{\tilde{S}}(P_0)$ is shown in Fig. 1. The content belonging function $\mu_{\tilde{S}}(P_0)$ characterizes the measure of the admissibility of each alternative P_0.

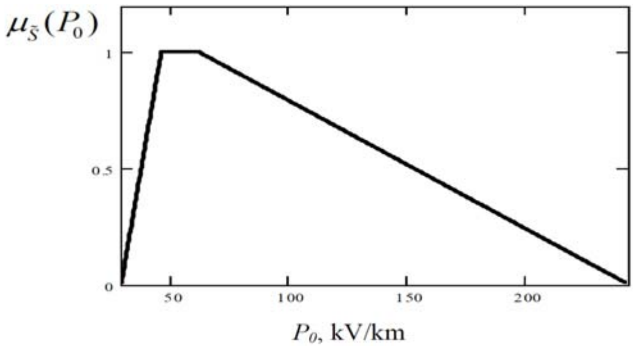

Figure 1 Fuzzy interval of possible ice melting capacity

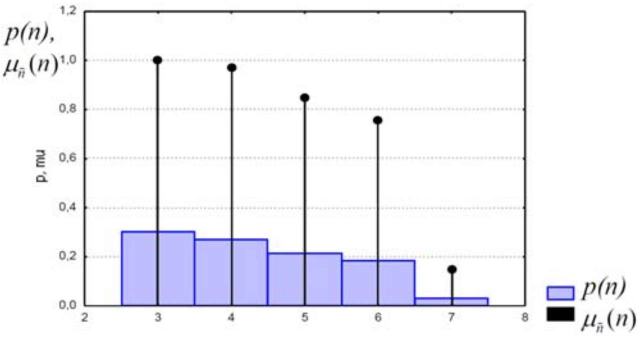

Fig. 2 Distribution probability and set of the amount of 10 kV OPL

The belonging function for the fuzzy set $\tilde{n}$ of amount of 10 kV OPL RTP was obtained with the method [12] based on the expansion of the set at the α-level. According to this method, the belonging function of the fuzzy value is based on the distribution of the probabilities of this magnitude. Fig. 2 shows the distribution of probabilities p(n) of the number of 10 kV OPL, obtained on the basis of the analysis of 32 RTPs of Kharkiv-oblenergo join-stock company. The same figure shows the value of the belonging function of each values of the OPL number $\mu_{\tilde{n}}(P_0)$ at the universal set N = [3, 4 ... 7].

Results and discussion

During the optimizing the ice melting power, three criteria were taken into account: reduced costs for ice melting C, lack of electricity supplying to consumers during the breaks of electricity during the melting of W, and the amount of electricity consumed for the melting of deposits E.

Each alternative P_0 and each value of the number of OPL *n* form fuzzy binary relations of satisfying the criteria *C*, *W* and *E* C; respectively $\tilde{\mathrm{R}}_{\mathrm{C}}(P_0,n)$, $\tilde{\mathrm{R}}_{\mathrm{W}}(P_0,n)$ and $\tilde{\mathrm{R}}_{\mathrm{E}}(P_0,n)$ that are given on Cartesian multiplication of universes P × N [10]. Since the accepted optimization criteria should be minimized, the belonging functions of fuzzy relations $\tilde{\mathrm{R}}_{\mathrm{C}}$, $\tilde{\mathrm{R}}_{W}$ and $\tilde{\mathrm{R}}_{E}$, were found with means of unit normalization in terms of expression [6]

$$\mu_{\tilde{R}k}(P_0,n)=\frac{K_{\max}(n)-K(P_0,n)}{K_{\max}(n)-K_{\min}(n)}, \tag{1}$$

where *Kmax(n)*, *Kmin(n)* are the maximum and the minimum value of the criterion *K* in the universe *P* for the number of OPL *n*; *K(P0, n)* is the value of the criterion *K* for the alternative P_0 and the number of OPL *n*.

The belonging functions of these relations characterize quantitatively the measure of the optimality of alternatives by the corresponding criterion for the given value of the OPL number. For universe alternatives, taken with a certain step, the result of normalization can be represented as matrices of fuzzy relations. The unclear ratio $\tilde{\mathrm{R}}_{\mathrm{C}}$ of the criterion satisfaction of the expenses for ice melting (for the melting circuit with the protection transformer from the $\tilde{\mathrm{C}}$ $\tilde{n}$ $\tilde{\mathrm{R}}_{\mathrm{C}}$ ice) is given in Table 1 for the step ΔP_0=30kW/km.

Fuzzy sets of criteria satisfaction and, taking into account the degree of belonging of specific values of the OPL number to the fuzzy set, are determined on the basis of the composite rule of the conclusion [15]

$$\tilde{C}=\tilde{n}\circ\tilde{R}_C; \tag{2}$$

$$\tilde{W}=\tilde{n}\circ\tilde{R}_W; \tag{3}$$

$$\tilde{E}=\tilde{n}\circ\tilde{R}_E, \tag{4}$$

where the sign "∘" means the operation (max-min) – combinations of fuzzy sets.

The belonging functions of alternatives to fuzzy sets, and are determined by expressions [16]

$$\mu_{\tilde{C}}(P_0)=\max_{n\in N}\left\{\min\left\{\mu_{\tilde{n}}(n),\mu_{\tilde{R}_C}(P_0,n)\right\}\right\}\quad(\forall P_0\in P) \tag{5}$$

$$\mu_{\tilde{W}}(P_0)=\max_{n\in N}\left\{\min\left\{\mu_{\tilde{n}}(n),\mu_{\tilde{R}w}(P_0,n)\right\}\right\}\quad(\forall P_0\in P) \tag{6}$$

$$\mu_{\tilde{E}}(P_0)=\max_{n\in N}\left\{\min\left\{\mu_{\tilde{n}}(n),\mu_{\tilde{R}_{\mathrm{E}}}(P_0,n)\right\}\right\}\quad(\forall P_0\in P) \tag{7}$$

Fuzzy sets (they are formed out of the elements of fuzzy relations $\tilde{\mathrm{R}}_{\mathrm{C}}$, $\tilde{\mathrm{R}}_{W}$ and $\tilde{\mathrm{R}}_{E}$ and taken with the step of alternatives ΔP0 = 30 kW / km), and the fuzzy quantity of OPL $\tilde{n}$ have terminal carriers. Therefore, the composition operation for these sets reduces to the maximization product of the corresponding matrices. The result of the composition of these fuzzy sets is shown in Table. 2.

Table 1. Fuzzy relation of melting power and quantity of 10 kV OPL to meet the minimum criterion of the costs for ice melting

OPL number	Melting capacity, kW / km							
	30	60	90	120	150	180	210	240
3	0,966	0,956	W̃ $\tilde{C} = \tilde{n} \circ \tilde{R}_C$ $\tilde{E}$ $\tilde{E} = \tilde{n} \circ \tilde{R}_E$ 0,809	0,650	0,490	0,331	0,174	0,020
4	0,929	0,994	0,849	0,685	0,518	0,350	0,185	0,022
5	0,883	1,000	0,891	0,722	0,547	0,371	0,196	0,023
6	0,826	0,999	W̃ $\tilde{W} = \tilde{n} \circ \tilde{R}_W$ $\tilde{E}$ C̃ 0,934	0,761	0,578	0,392	0,207	0,024
7	0,757	0,991	0,979	0,801	0,609	0,414	0,219	0,026

Table 2 – The result (max-min) – computations of fuzzy relations $\tilde{R}_C$, $\tilde{R}_W$ and OPL fuzzy amount $\tilde{n}$

Fuzzy target	The value of the belonging function of the melting power (kW / km) on the fuzzy set of target satisfaction							
	30	60	90	120	150	180	210	240
The minimum of the expenses $\tilde{C}$	0,966	0,97	0,849	0,758	0,578	0,392	0,207	0,026
The minimum of undisclosed electricity $\tilde{W}$	0,045	0,630	0,800	0,881	0,929	0,960	0,982	0,998
The minimum of energy expenditure on melting $\tilde{E}$	0,047	0,641	0,807	0,886	0,932	0,961	0,983	0,998

At the next stage, we dealt with the task of transition from the vector criterion of optimization to scalar one. The vector of criteria rank and restrictions was obtained on the basis of expert evaluations. Criteria and constraints were compared in pairs on a nine-rate linguistic scale, followed by averaging assessments of different experts. The resulting matrix of pair comparisons A={aij} is given in the form of Table 3. The elements of the ranks vector were determined on the basis of the Saati method [15, 16] as the geometric average values of each row of the matrix of pair comparisons and they are shown in Table. 4.

Table 3 – Matrix of pair comparison of criteria of optimization and constraints

Criterion or restriction	Criterion or restriction			
	$\tilde{C}$	$\tilde{W}$	$\tilde{E}$	$\tilde{S}$
$\tilde{C}$	1,00	8,80	9,0	2,60
$\tilde{W}$	0,11	1,00	1,20	0,12
$\tilde{E}$	0,11	0,90	1,00	0,11
$\tilde{S}$	0,40	8,60	8,80	1,00

Table 4 – Vector of criteria ranks optimization and constraints

Criterion or restriction	$\tilde{C}$	$\tilde{W}$	$\tilde{E}$	$\tilde{S}$
Relative importance coefficient	2,22	0,21	0,19	1,38

According to the coagulation method, the unclear solution to the problem of optimizing the ice melting power on a 6-10 kV OPL is the result of the intersection of fuzzy sets of criteria and the restrictions which were taken with an index of power that is numerically equal to the rank of the corresponding criterion or restriction

(8) $$\tilde{D} = \tilde{C}^{2,22} \cap \tilde{W}^{0,21} \cap \tilde{E}^{0,19} \cap \tilde{S}^{1,38},$$

with the membership function

(9) $$\mu_{\tilde{D}}(P_0) = \min\left\{\mu_{\tilde{C}}^{2,22}(P_0), \mu_{\tilde{W}}^{0,21}(P_0), \mu_{\tilde{E}}^{0,19}(P_0), \mu_{\tilde{S}}^{1,38}(P_0)\right\}$$

The values of the belonging function of the fuzzy problem solution characterize quantitatively the measure of the optimality of alternatives. Fig. 3 shows the graphs of the membership functions of the sets $\mu_{\tilde{C}}^{2,22}(P_0)$, $\mu_{\tilde{W}}^{0,21}(P_0)$, $\mu_{\tilde{E}}^{0,19}(P_0)$ and $\mu_{\tilde{S}}^{1,38}(P_0)$, also the fuzzy set of solutions $\mu_{\tilde{D}}(P_0)$.

In accordance with the Belman-Zade approach, the optimal solution to the problem is an alternative that has the maximum degree of belonging to the fuzzy set $\tilde{D}$. Consequently, the multicriterion task of optimizing the ice melting power on a 6-10 kV OPL, taking into account the uncertainty of the limitations on the melting power and uncertainty of the number of submarines, will look like

(10) $$\begin{cases} \mu_{\tilde{D}}(P_0) \to \max; \\ P_0 \in P. \end{cases}$$

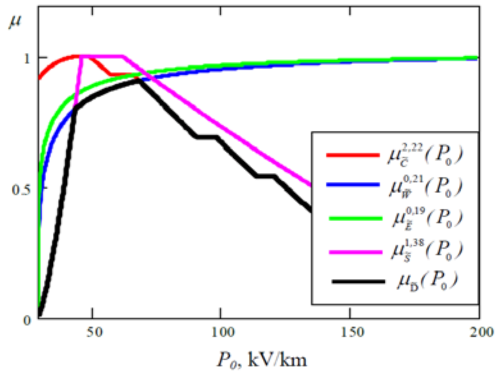

Figure 3 Graphs of membership functions

Table 5 – Results of ice melting capacity optimization

The maximum OPL length for which th installation of ice melting is intended, km	The type of ice melting plant	
	P_0, kV/km icing	autotransformer ice melting
10	66,8	56,9
16	66,6	56,8
25	66,0	54,7

When designing the series of electro-power ice melting equipment, it was assumed that each of the series includes three standard sizes, which differ in the maximum length of 10kV OPL, protection of which they can provide – installations for lines with length from 10km to 16km and to 25km. The problem (10) was solved within Mathsad using the quasi-Newton numerical method. Table 5 shows the optimization results.

Conclusions

On the basis of studies of fuzzy technical and economic model of optimization of ice melting schemes parameters at 6-10 kV OPL distribution networks, it was established that the optimum value of the melting capacity of deposits, which should be provided by the ice-protected transformer, taking into account the uncertainty of the OPL number and constraints, is 66-67 kW / km, for melting autotransformer – 55-57 kW / km. Design the protection transformers from ice and the melting autotransformers should be made taking into account the optimum values of melting power, which will provide the maximum possible technical and economical effect from the ice melting introduction on the 6-10 kV switchgear power distribution networks.

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REFERENCES

1. Farzaneh M., Volat C., Leblond A., Anti-icing and De-icing Techniques for Overhead Lines, Atmospheric Icing of Power Networks Springer, (2008), 229–268
2. Scientific and technical report on the topic "Choice of methods and development of suitable schemes for ice melting on the HVL of various voltage classes in the Moldovan energy system" – Chisinau: STC "Tehnikalnenergo", 2001.
3. Rudakova R., Vavilova I., Golubkov I., Fighting against ice-cold in power grid enterprises: Handbook for organizing the fight against ice / R. Rudakova, I. Vavilova, I. Golubkov – Ufa: OAO Bashkirenergo, Ufa. State Techn. Univ, 1995.
4. Toliupa S., Kravchenko Y., Trush A., Organization of implementation of ubiquitous sensor networks, Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska - IAPGOS, 8(2018), no. 1., 36-39
5. Bilash I., Savchenko O., Optimization of the ice melting power on the OPL 6-10 kV distribution electrical networks, Problems of power supply and energy saving in the agroindustrial complex of Ukraine, 101(2010), 31–38
6. Mauris G., Lassere V., Foulley L., A fuzzy approach for the expression of uncertainty in measurement, Measurement, (2001), no. 29., 109–121
7. Wojcik W, Bieganski T., Kotyra A., et al., Application of algorithms of forecasting in the optical fibre coal dust burner monitoring system, *Proc. SPIE*, 3189 (1997), 100-109.
8. Tymchuk S., Miroshnyk O., Svergun Y., Avramenko A., Fuzzy assessment of asymmetric modes of rural networks 0,38 / 0,22 kV, Problems of energy supplying and energy saving in the agroindustrial complex of Ukraine 142(2013), 42–44
9. Kłosowski G., Rymarczyk T., Using neural networks and deep learning algorithms in electrical impedance tomography, Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska - IAPGOS, 7(2017), no. 3., 99-102
10. Hsiao-Fan W., Ruey-Chyn T., Insight of a fuzzy regression model, Fuzzy Sets and Systems, 112 (2000), no. 3, 355–369
11. Asai K., Wadada D., Iwai S. et al., Applied fuzzy systems, Moscow: Mir, (1993)
12. Savchenko O., Investigation of the ice melting on a group of interconnected 6–10 kV OPL on the basis of simulation modeling, Problems of power supply and energy conservation in the AIC of Ukraine, 101(2010), 53–55
13. Miroshnyk O. Tymchuk S., Determination of electric power losses depending on its quality in fuzzy form in rural distribution networks, Eastern-European Journal of Enterprise Technologies, 73(2015), no. 1/8, 4-10
14. Diligensky N., Dymova L., Sevastyanov P., Fuzzy modeling and multicriteria optimization of production systems under uncertainty: technology, economics, ecology, Mechanical Engineering, (2004), 397
15. Buckley J.J., Buckley T.F., Linear and non-linear fuzzy regression: Evolutionary algorithm solutions, Fuzzy Sets and Systems, 112(2000) – no. 3, 381–394
16. Mauris G., Berrah L., Foulloy L., Haurat A., Fuzzy handling of measurement errors in instrumentation, IEEE Transaction and measurement, 49(2000), no.1, 43–58