Justification of Ice Melting Power on 10 kV Overhead Power Lines

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DOI: 10.15598/aeee.v17i2.2912

Abstract. *The fuzzy multicriteria model of the ice melting system on radial 10 kV overhead power lines was developed. Three criteria were taken into account: the minimum of reduced annual costs for ice melting system, the minimum of amount of electric energy not provided to consumers during melting, and the minimum of the amount of electricity consumed for the ice melting. The model also takes into account the fuzzy limitation of the permissible ice melting power associated with the uncertainty of weather conditions. Based on the model we justified the value of ice melting power, which should be provided by serial ice melting devices of industrial production, intended for use on radial 10 kV overhead power lines, taking into account the uncertainty of initial data.*

Keywords

Fuzzy modeling, ice melting device, ice melting power, melting of ice, overhead power line.

1. Introduction

One of the most effective ways of protecting distribution Overhead Power Lines (OPL) of medium voltage class, including radial 10 kV lines, from the ice is its melting [1]. Ice melting technology is based on the use of a certain melting scheme, which, on the basis of the Joule effect, allows to achieve an allocation of thermal energy in a unit of the length of wire, sufficient for the melting of deposits. To define this amount of thermal energy in this work, the term "ice melting power" is used.

Ice melting power is the main characteristic of the melting scheme, which affects the cost of energy for melting, the time of consumers electricity supply interruptions in case of need to shut down. These parameters have feedback with ice melting power.

To harmonize parameters of a power system with radial 10 kV lines' parameters in melting schemes based on three-phase short circuit often used special Ice Melting Devices (IMD) – autotransformers [2], [3] and [4], reactors [5], special transformers [6]. In this case, the rated power of IMD will depend on the approved value of ice melting power, and there is a direct connection between these quantities. The same nature of the connection exists between the ice melting power and the rated power of a power transformer installed at 110–35/10 kV substation.

Thus, in the case of using of IMD in the melting schemes, there is a problem of the choice of an independent parameter of the melting scheme – the value of ice melting power, which should be provided by IMD.

The analysis of approaches in the design of ice melting schemes on distribution OPL of medium voltage class, including radial 10 kV lines, showed that existing methods do not allow to take into account the influence of the value of ice melting power on cost characteristics of melting scheme and to make an economically sound choice of this parameter [1], [2], [3] and [4]. According to accepted approaches, ice melting power is usually taken equal to the value, which allows, under the average conditions, to provide an acceptable melting time on the line in long-term mode – about 1 hour. It is sometimes advisable to take the maximum value of ice melting power to reduce the melting time and energy consumption, although this does not take into account the negative effect of increasing the rated power of IMD and the substation power transformer [5].

In [7], an approach in the design of ice melting schemes on distribution 10 kV OPL was proposed based on the criterion of reduced annual costs, which takes into account the impact of ice melting power on such factors as amount of electric energy not provided to consumers during melting, amount of electricity consumed for the ice melting, the cost of IMD, the cost of additional power of the substation transformer. On the basis of the proposed approach, optimization of ice melting power was performed, which should be provided by different IMD with the assumption of determinism of initial data that leads to the conventions of the solution. In addition, the used criterion of reduced annual costs does not satisfy the condition of the identity of the compared options for such properties as the reliability of power supply, energy efficiency. In essence, this criteria provides a reduction of multi-criterion to single-criterion task statement.

The development of serial IMD for industrial production intended for use on 10 kV overhead lines and the choice of ice melting power to be provided by such devices should be carried out taking into account the ambiguity of the parameters of distribution networks. It is also advisable to optimize the ice melting power on the basis of the cost of qualitatively different resources for melting (for example, the amount of energy for melting, the amount of electric energy not provided to consumers during melting, the cost of IMD, etc.), which is possible in the case of using multicriteria (vector) approach [8].

The analysis showed that the solution to this problem, taking into account listed factors, is possible on the basis of the fuzzy set theory [9]. This mathematical apparatus is widely used for decision-making in solving the problems of power engineering [10] and [11], as well as many other engineering tasks.

Thus, the purpose of the research is to substantiate the value of ice melting power, which should be provided by serial ice melting devices of industrial production intended for use on 10 kV overhead power lines, based on the multi-criteria approach and taking into account the uncertainty of the initial data.

2. Building a Fuzzy Model

2.1. General Formulation of the Task

The justification of the ice melting power was carried out for two types of IMD – reducing autotransformer [2] and special transformer [6], called "heating transformer". In general, the problem of optimizing the ice melting power is formulated as follows: for the ice melting device that is used at a substation with a quantity n of radial OPL 10 kV, to find the optimal value P_{0opt} of the ice melting power, that should be provided by the device on each of the lines, for which the melting scheme will have the highest efficiency in accordance with the adopted integrated fuzzy optimization criterion $\tilde{D}$.

To solve the optimization task based on the fuzzy set theory, we used the Belman-Zade approach, which involves the symmetry of fuzzy goals and restrictions on the universal set of alternatives [12].

2.2. Fuzzy Restrictions

At the initial stage, the fuzzy limitation of the task was formulated. When designing the ice melting scheme, the melting power is checked to fulfill the condition [5]:

$$P_{0\,\min} \leq P_0 \leq P_{0\,\max}, \tag{1}$$

where $P_{0\,\min}$ is the minimum value of the melting power, determined on the condition of ensuring the required rate of removal of deposits on the group of interconnected OPLs, for which a common IMD is used; and $P_{0\,\max}$ is the maximum value of the melting power for long-term mode, determined on the condition of maximum allowable heating of a wire free of ice.

However, the clear double restriction Eq. (1) is rather conditional, since the lower and upper limits of the ice melting power are calculated with the assumption that the majority of the values on which they depend are equal to the mean value that does not correspond to reality. Given the dependence of the minimum and maximum melting power on a large number of random variables, it is quite reasonable in this case to replace this clear limitation with a fuzzy interval. It should be noted that in the case when the melting power exceeds the maximum value of $P_{0\,\max}$ ice melting is possible in repeated-short-term mode [5]. This method of ice melting is characterized by significant wear of contact systems of high-voltage switches due to a 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. Therefore it is advisable that the melting power provided by IMD does not exceed the maximum limit in which the melting of deposits is possible in the long-term mode. However, even if the maximum melting power is exceeded under certain conditions, ice melting may be carried out in a repeated-short-term mode. On the other hand, the case when the melting power is less than the minimum value of $P_{0\,\min}$ should not be considered inappropriate, because in this case on the latter OPL ice loads will slightly exceed the normative value, which does not mean the fact of line damage, because it has some stock for mechanical strength. Thus, the use of a fuzzy interval to limit the ice melting power can be considered quite permissible.

The upper and lower permissible values of the melting power depend on a number of random variables, such as air temperature, wind speed and its direction, the intensity of solar radiation during the melting of sediments. However, it is permissible, with sufficient accuracy, to determine the maximum and minimum values of the melting power, taking into account the temperature of the air and the wind speed, which are the most significant parameters [5].

As the fuzzy interval of allowable alternatives (permissible melting power), the trapezoidal one was used, which is described by the cortege $\tilde{S} =< a; b; \alpha; \beta > T$, where a, b are the lower and upper modal values of the interval, respectively; α, β are the left and right coefficients of fuzziness, respectively [9]. The most unfavorable cooling conditions of an ice-free wire are observed in the case of $t = 0$ °C, v=0 m·s^{-1}. The maximum permissible melting power determined for these conditions will be equal to the upper modal fuzzy interval value: $b = P_{0\,\max 1}(t = 0; v = 0)$. In the case of the minimum temperature and the maximum wind speed $(t = t_{\min}; v = v_{\max})$, which accompany the formation of sediments, the conditions are most unfavorable to ensure the required rate of removal of deposits on a group of interconnected OPL. Therefore, the minimum permissible melting power determined for these conditions will correspond to the lower modal value of the fuzzy interval: $a = P_{0\,\min 1}(t = t_{\min}; v = v_{\max})$. On the basis of the values $P_{0\,\min 2}(t = 0; v = 0)$ and $P_{0\,\max 2}(t = t_{\min}; v = v_{\max})$, the left and right coefficients of interval fuzziness can be obtained: $\alpha = P_{0\,\min 1} - P_{0\,\min 2}$; $\beta = P_{0\,\max 2} - P_{0\,\max 1}$, respectively. The value of the minimum allowable melting power for various meteorological conditions was determined using a simulation model of melting of ice on interconnected 10 kV OPL [13]. The maximum melting power was estimated on the basis of the heat balance equation of the ice-free wire [5]. In the calculations, the values $t_{\min} = -6$ °C; $v_{\max} = 8$ m·s^{-1} were used, which corresponds to the vast majority of cases of ice formation. The calculations conducted for the conditions of Ukraine have gave the result $\tilde{S} =< 46; 62; 17; 182 > T$. The graph of the membership function of the fuzzy interval of admissible alternatives $\mu_{\tilde{S}}(P_0)$ is shown in Fig. 1.

The membership function $\mu_{\tilde{S}}(P_0)$ characterizes the measure of the admissibility of each alternative P_0. Thus, for all values of $P_0 < P_{0\,\min 2}$, even with the best melting conditions ($t = 0$ °C, $v = 0$ m·s^{-1}), the rate of removal of deposits on the OPL group will be insufficient, so the quantitative measure of the admissibility of these alternatives is zero. For the values $P_{0\,\min 1} < P_0 < P_{0\,\max 1}$, even under the most unfavorable factors, the conditions for ensuring the required rate of removal of deposits and preventing overheating of the ice-free wire are completely satisfied; therefore the degree of admissibility of these alternatives is estimated by one. For values $P_0 > P_{0\,\max 2}$, the tolerance level is zero, as even with the best cooling conditions, the temperature of the ice-free wire will exceed the permissible value. For the values $P_{0\,\min 2} \leq P_0 \leq P_{0\,\min 1}$ and $P_{0\,\max 1} \leq P_0 \leq P_{0\,\max 2}$, the degree of tolerance varies from zero to one by the equation of the straight line.

2.3. Fuzzy Input Data

Researches on the determined model [7] showed that the reduced annual costs of ice melting system are the most sensitive to changes in the number of substation OPL, on which it is envisaged to use a common IMD. Therefore we have made a conclusion that optimizing of the ice melting power, which should be provided by IMD of industrial production, must be done with regard to the number of substation OPL uncertainty.

The membership function for the fuzzy set $\tilde{n}$ of amount of substation OPL was obtained by a method based on the expansion of the set at the α-levels [14]. According to this method, the membership function of the fuzzy value is based on the distribution of the probabilities of this value. Figure 2 shows probability distribution $p(n)$ of the number of 10 kV OPL, obtained on the basis of the analysis of 32 substations of Kharkivoblenergo JSC. The same figure shows the value of the membership function of each value of the OPL number $\mu_{\tilde{n}}(P_0)$ at the universal set N = [3, 4...7].

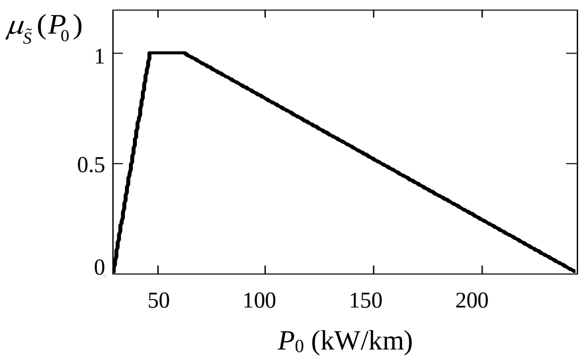

Fig. 1: Fuzzy interval of admissible ice melting power.

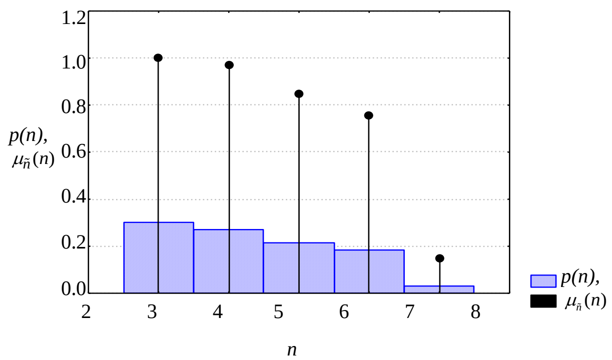

Fig. 2: Probability distribution and fuzzy set of the amount of 10 kV OPL at 110–35/10 kV substation.

2.4. Fuzzy Criteria of Optimization

Optimization of the melting power was carried out taking into account three criteria: the minimum of reduced annual costs for ice melting system (C), the minimum of the amount of electric energy not provided to consumers during melting (W), and the minimum of the amount of electricity consumed for the ice melting (E). The methodology for determining these criteria is highlighted in [7].

Each alternative P_0 and each value of the number of OPL n form fuzzy binary relations $\tilde{R}_C(P_0, n)$, $\tilde{R}_W(P_0, n)$ and $\tilde{R}_E(P_0, n)$ satisfying the criteria C, W and E, respectively. These fuzzy binary relations are given on Cartesian multiplication of universes $\mathbf{P} \times \mathbf{N}$ [9]. Since the accepted optimization criteria should be minimized, the membership functions of fuzzy relations $\tilde{R}_C$, $\tilde{R}_W$ and $\tilde{R}_E$ were found with means of unit normalization in terms of expression:

$$\mu_{\tilde{R}_k}(P_0, n) = \frac{K_{\max}(n) - K(P_0, n)}{K_{\max}(n) - K_{\min}(n)}, \tag{2}$$

where $K_{\max}(n)$, $K_{\min}(n)$ are the maximum and the minimum value of the criterion K in the universe P for the number of OPL n, and $K(P_0, n)$ is the value of the criterion K for the alternative P_0 and the number of OPL n.

The membership 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 example, for some melting power P_0 and a given number n, the value of a particular criterion will be minimal $K(P_0, n) = K_{\min}(n)$. In this case, according to expression Eq. (2), the membership function of the fuzzy relation to satisfy this criterion will be $\mu_{\tilde{R}_k}(P_0, n) = 1$. In terms of the theory of fuzzy set, it speaks about the greatest "desirability" of this value of the melting power P_0 for a given n. In the case when for a certain value P_0 the value of the criterion $K(P_0, n) = K_{\max}(n)$, the membership function of the fuzzy relation will have a value $\mu_{\tilde{R}_k}(P_0, n) = 0$, that says about the inadmissibility of this value P_0.

For universe alternatives, taken with a certain step, the result of normalization can be represented as a matrix of fuzzy relations [9], the rows of which correspond to the elements of the first universe (the melting power), and the columns to the elements of the second universe (the number of 10 kV lines on substation). In this case, the elements of the matrix are equal to the corresponding values of the membership function of fuzzy relation. In Tab. 1 for the step $\Delta P_0 = 30$ kW·km^{-1} is shown a matrix of fuzzy relation $\tilde{R}_C$, which satisfies the criterion of reduced annual costs for ice melting system (in case of using a heating transformer [6]). The values of the membership function were calculated by the Eq. (2).

Fuzzy sets of criteria $\tilde{C}$, $\tilde{W}$ and $\tilde{E}$, taking into account the membership function of values of the OPL number, are determined on the basis of the composite rule [9]:

$$\tilde{C} = \tilde{n} \circ \tilde{R}_C, \tag{3}$$

$$\tilde{W} = \tilde{n} \circ \tilde{R}_W, \tag{4}$$

$$\tilde{E} = \tilde{n} \circ \tilde{R}_E, \tag{5}$$

where the sign "$\circ$" means the operation of (max-min)-combination of fuzzy sets.

The membership functions of fuzzy sets $\tilde{C}$, $\tilde{W}$ and $\tilde{E}$ are determined by expressions [9]:

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

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

$$\mu_{\tilde{E}}(P_0) = \max_{n \in N} \left\{ \min \left\{ \mu_{\tilde{n}}(n), \mu_{\tilde{R}_E}(P_0, n) \right\} \right\} \quad (\forall P_0 \in P), \tag{8}$$

Fuzzy sets which are formed out of the elements of fuzzy relations $\tilde{R}_C$, $\tilde{R}_W$ and $\tilde{R}_E$ (taken with the step of alternatives $\Delta P_0 = 30$ kW·km^{-1}), and the fuzzy quantity of OPL $\tilde{n}$ have terminal carriers. Therefore, the composition operation for these sets is equivalent to the (max-min)-multiplication of the corresponding matrices. The result of the composition of these fuzzy sets is shown in Tab. 2.

2.5. Transition to the Scalar Criterion of Optimization

In the next stage, we dealt with the task of transition from the vector criterion of optimization to scalar one. The collapse of the criteria on the basis of the theory of fuzzy sets was carried out using the approach outlined in [15]. According to this approach, the unclear solution of the multicriteria problem with constraints has the form:

$$\tilde{D} = \tilde{G}_1^{a_1} \cap \tilde{G}_2^{a_2} \cap ... \cap \tilde{G}_k^{a_k} \cap \tilde{S}_1^{b_1} \cap ... \cap \tilde{S}_m^{b_m}, \tag{9}$$

where $\tilde{G}_1, \ldots, \tilde{G}_k$ are the fuzzy sets of individual optimization criteria, $\tilde{S}_1, \ldots, \tilde{S}_m$ are the fuzzy sets of limitations of the task, $a_1, \ldots, a_k$, $b_1, \ldots, b_m$ are non-negative coefficients of relative importance (ranks) of the criteria and constraints that satisfy the condition:

$$\frac{1}{k+m}\left(\sum_{i=1}^{k} a_i + \sum_{j=1}^{m} b_j\right) = 1. \tag{10}$$

Tab. 1: Fuzzy relation of melting power and quantity of 10 kV OPL in order to get the minimum of the reduced annual costs for ice melting system.

OPL number	Melting power (kW·km^{-1})							
	30	60	90	120	150	180	210	240
3	0.966	0.956	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	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

Tab. 2: The result of the (max-min)-multiplication of criteria fuzzy relations and the fuzzy set of OPL amount.

Fuzzy target	The value of the membership function for target satisfaction (kW·km^{-1})							
	30	60	90	120	150	180	210	240
The minimum of reduced annual costs for ice melting system $\tilde{C}$	0.966	0.97	0.849	0.758	0.578	0.392	0.207	0.026
The minimum of the amount of electric energy not provided to consumers during melting $\tilde{W}$	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

The sign «∩» in Eq. (9) means the operation of intersection of fuzzy sets [9].

The membership functions of fuzzy solution:

$$\mu_{\tilde{D}}(x) = \min\left\{\mu_{\tilde{G}_1}^{a_1}(x), ..., \mu_{\tilde{G}_k}^{a_k}(x), \mu_{\tilde{S}_1}^{b_1}(x), ..., \mu_{\tilde{S}_m}^{b_m}(x)\right\}, \tag{11}$$

where $\mu_{\tilde{G}_1}(x), ..., \mu_{\tilde{G}_k}(x), \mu_{\tilde{S}_1}(x), ..., \mu_{\tilde{s_m}}(x)$ are the membership functions of fuzzy sets of optimization criteria and constraints.

The ranks vector of criteria and restrictions were obtained on the basis of expert evaluations. As experts (10 persons), personnel of services of exploitation of OPL acted. Criteria and restrictions were compared in pairs on a nine-rate linguistic scale [16], followed by averaging assessments of different experts. The resulting matrix of pair comparisons $A = \{a_{ij}\}$ is given in the form of Tab. 3. The elements of the ranks vector were determined on the basis of the Saati method [17] as the geometric average values of each row of the matrix of pair comparisons. The value of the rank vector is given in Tab. 4.

Tab. 3: Matrix of pair comparisons of criteria of optimization and restrictions.

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

Tab. 4: Ranks vector of optimization criteria and restrictions.

Criterion or restriction	$\tilde{C}$	$\tilde{W}$	$\tilde{E}$	$\tilde{S}$
Relative importance coefficient	2.22	0.21	0.19	1.38

Thus, according to Expression Eq. (9), the unclear solution of the problem of optimizing the ice melting power on 10 kV OPL corresponds to a fuzzy set:

$$\tilde{D} = \tilde{C}^{2,22} \cap \tilde{W}^{0,21} \cap \tilde{E}^{0,19} \cap \tilde{S}^{1,38}, \tag{12}$$

with the membership function:

$$\mu_{\tilde{D}}(P_0) = \min\left\{\mu_{\tilde{C}}^{2,22}(P_0), \mu_{\tilde{W}}^{0,21}(P_0), \mu_{\tilde{E}}^{0,19}(P_0), \mu_{\tilde{S}}^{1,38}(P_0)\right\}. \tag{13}$$

The values of the membership function of the fuzzy solution characterize quantitatively the measure of the optimality of alternatives. Figure 3 shows graphs of membership functions of fuzzy sets satisfying each of the criteria and constraints (taking into account the corresponding ranks), as well as fuzzy set of solutions $\mu_{\tilde{D}}(P_0)$. This figure illustrates the Belman-Zade approach used to solve the problem.

3. Optimizing of the Ice Melting Power

In accordance with the Belman-Zade approach [12], the optimal solution is an alternative that has the maximum degree of the membership function. Consequently, the multicriteria task of optimizing of the ice melting power on 10 kV OPLs, taking into account the uncertainty of the limitations on the melting power and uncertainty of the number of OPLs, will look like:

$$\begin{cases} \mu_{\tilde{D}}(P_0) \to \max; \\ P_0 \in P. \end{cases} \tag{14}$$

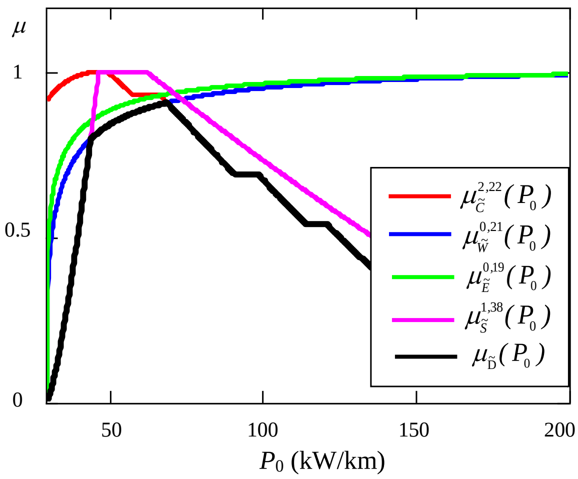

Fig. 3: Graphs of membership functions of fuzzy sets satisfying each of the criteria and constraints (taking into account the corresponding ranks) and fuzzy set of solutions.

When designing the series of ice melting devices for industrial production, it was assumed that each of the series includes three standard sizes, which differ in the maximum length of 10 kV OPL, protection of which they can provide – devices for lines with length less than 10 km, 16 km, and 25 km. The task Eq. (14) was solved within Mathcad using the Quasie-Newton numerical method. Table 5 shows the optimization results.

Tab. 5: The results of ice melting power optimization.

The maximum of OPL length (km)	Optimum value of ice melting power for the type of ice melting device (kW·km^{-1})	
	heating transformer	autotransformer
10	66.8	56.9
16	66.6	56.8
25	66.0	54.7

4. Discussion of Results

As can be seen from the results of calculations, the optimal melting power almost does not depend on the OPL length, for which the ice melting device is designed. For the melting scheme with a heating transformer, the optimal melting power is slightly higher than for the melting scheme with an autotransformer. This is due to the presence in the first melting scheme of the non-inductive circuit [6], which results in lower investment in the IMD and the additional power of the substation power transformer, for the same value of melting power for both schemes. Consequently, it leads to the displacement of the optimal value of the melting power towards higher values.

As mentioned in the article, according to the traditional approach, the melting power is taken to provide, under the average conditions, the melting time of ice on a separate line for about 1 hour. For wire type AS–70 with a section of the aluminum part of 70 mm^2 which is characteristic for distributive 10 kV OPL, under the average conditions of ice formation (air temperature $t = -2$ °C, wind speed $v = 5$ m·s^{-1}) and the thickness of ice 25 mm in order to ensure the melting time of 1 hour, the melting power should be $P_0 \approx 43$ kW·km^{-1} [5]. Whereas, according to the proposed approach for the melting scheme with heating transformer and the length of all substation OPLs <10 km, the optimum value of the melting power is $P_0 = 66.8$ kW·km^{-1} (Tab. 5). In Tab. 6, the results of calculation of the economic parameters of the melting scheme with the use of a heating transformer and the number of substation 10 kV OPL $n = 5$ for the existing and proposed approaches for the choice of melting power are presented. The results are received on the basis of the methodology, highlighted in [7]. As can be seen, the decision making based on the proposed approach leads to an increase in the cost of IMD (in this case it is the heating transformer), but at the same time, the cost of compensation for consumer losses due to their switching off during ice melting and the cost of the electricity for melting is reduced. As a consequence, the total reduced annual costs of the melting system, in this case, will be lowered by about 2.1 %. As the calculations have shown, the proposed approach of the choice of melting power can lower the overall reduced annual costs of the melting system by 2–18 % depending on the initial conditions. The economic effect increases with increas-

Tab. 6: Results of comparison of decisions adopted using existing and proposed approaches.

The parameter of melting scheme	The value of the parameter taken using the approach	
	existing	proposed
Optimum melting power (kW·km^{-1})	43.0	66.8
Cost of heating transformer (thous. USD)	18.4	27.4
The annual cost of compensation for consumers losses (thous. USD per year)	10.9	8.3
The annual cost of the electricity for ice melting (thous. USD per year)	4.3	4.1
The total reduced annual costs of the melting system (thous. USD per year)	32.7	31.9
Relative difference of total reduced annual costs (%)	-	-2.1

ing losses of consumers due to their switching off, the number and length of substation 10 kV lines, on which it is planned to use a common ice-melting device.

5. Conclusion

In this article, a new approach is proposed on the choice of the ice melting power, which should be provided by serial ice melting devices of industrial production, intended for use on radial 10 kV overhead power lines, the distinctive feature of which is the consideration of multicriteria and uncertainty of initial data.

On the basis of the research of the developed fuzzy model of the ice melting system on 10 kV overhead power lines, it was established that the optimum value of the melting power, which should be provided by ice melting autotransformers of industrial production, taking into account the uncertainty of the limitations and the number of radial 10 kV lines at the substation, is close to 56 $\mathrm{kW{\cdot}km^{-1}}$. For melting schemes with heating transformers, the optimum melting power is close to 66 $\mathrm{kW{\cdot}km^{-1}}$. The design of ice melting devices of industrial production should be carried out taking into account the optimum values of the melting power, which will provide the maximum possible technical and economic effect from the implementation of ice melting systems at 10 kV overhead power lines.

Using the proposed approach to choose the ice melting power, depending on the baseline conditions, allows reducing the total annual costs of the melting system 2–18 % due to lowering the cost of electricity for melting and the cost of compensation for consumer losses due to their switching off during ice melting, although the cost of ice melting device increasing. The economic effect of using the proposed approach is expressed more significantly in the event of high consumer losses due to their sudden shutdowns and significant lengths of 10 kV lines and their number at the substation.

References

[1] FARZANEH, M. *Atmospheric icing of power networks*. London: Springer, 2008. ISBN 978-1-4020-8531-4.

[2] FARZANEH M., F. JAKL, M. P. ARABANI and A. J. ELIASSON. *Systems for prediction and monitoring of ice shedding, anti-icing and de-icing for power line conductors and ground wires*. Paris: Cigre, 2010. ISBN 978-2-85873-126-8.

[3] GINGRAS, J. P., S. BREAULT, R. BRODEUR, C. CREVIER, A. DERY and A. VALLEE. Strategie de renforcement du reseau d'Hydro-Quebec a la suite du verglas exceptionnel de janvier 1998: une demarche pour securiser davantage l'alimentation electrique. In: *PROCEEDINGS CIGRE*. Paris: CIGRE, 2000, pp. 37–101.

[4] HOMME, P. P., A. DUTIL, S. LAURIN, S. LEBEAU, J. BENNY and R. CLOUTIER. Hydro-Quebec TransEnergie line conductor de-icing techniques. In: *Proceedings 11th IWAIS*. Montreal: IWAIS, 2005, pp. 1–6.

[5] *Guidelines for melting of ice with alternating current*. Part 1. Moscow: SPO Soyuztekhenergo, 1983.

[6] BILASH, I. and O. SAVCHENKO. Analysis of electrical processes in the device for air lines protecting from ice and frost deposits. *Problems of power supply and energy saving in the agroindustrial complex of Ukraine*. Kharkiv: KhNTUA, 2003, pp. 91–98. ISBN 5-7987-0176X.

[7] BILASH, I. and O. SAVCHENKO. Optimization of the ice melting power on the 6-10 kV OPL distribution electrical networks. In: *Problems of power supply and energy saving in the agroindustrial complex of Ukraine*. Kharkiv: KhNTUA, 2010, pp. 31–38. ISBN 5-7987-0176X.

[8] EHRGOTT, M. *Multicriteria optimization*. Berlin: Springer, 2005. ISBN 978-3-540-27659-3.

[9] ZIMMERMANN, H. J. *Fuzzy set theory–and its applications*. New York: Springer, 2011. ISBN 978-94-010-0646.

[10] TYMCHUK, S. and O. MIROSHNYK. Assess electricity quality by means of fuzzy generalized index. *Eastern-European Journal of Enterprise Technologies*. 2015, vol. 3, iss. 4, pp. 26–31. ISSN 1729-4061. DOI: 10.15587/1729-4061.2015.42484.

[11] DOMNIN, I., O. LEVON and S. KOZLOV. Control system of the filter-compensating device with the second-order fuzzy regulator. *Tekhnichna Elektrodynamika*. 2018, vol. 2018, iss. 6, pp. 30–33. ISSN 1607-7970. DOI: 10.15407/techned2018.06.030.

[12] BELLMAN, R. E. and L. A. ZADEH. Decision-Making in a Fuzzy Environment. *Management Science*. 1970, vol. 17, iss. 4, pp. 141–164. ISSN 0025-1909. DOI: 10.1287/mnsc.17.4.B141.

[13] 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 saving in the agroindustrial complex of Ukraine*. Kharkiv: KhNTUA, 2010, pp. 53–55. ISBN 5-7987-0176X.

[14] YAGER, R. R. Level sets for membership evaluation of fuzzy subsets. In: *Recent Advances in Fuzzy Subset and Possibility Theory*. New York: Pergamon Press, 1982, pp. 90–97. ISBN 0-08-026294-5.

[15] YAGER, R. R. Multiple objective decision-making using fuzzy sets. *International Journal of Man-Machine Studies*. 1977, vol. 9, iss. 4, pp. 375–382. ISSN 0020-7373. DOI: 10.1016/S0020-7373(77)80008-4.

[16] SASAKI, T. and T. AKIYAMA. Traffic control process of expressway by fuzzy logic. *Fuzzy Sets and Systems*. 1988, vol. 26, iss. 2, pp. 165–178. ISSN 0165-0114. DOI: 10.1016/0165-0114(88)90206-0.

[17] SAATY, T. L. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*. 1977, vol. 15, iss. 3, pp. 234–281. ISSN 0022-2496. DOI: 10.1016/0022-2496(77)90033-5.

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