Petro D. LEZHNIUK[1], Mykola M. CHEREMISIN[2], Veronika V. CHERKASHYNA[3]
Natalia DENISOVA[4], Andrzej SMOLARZ[5], Samal ABDRESHOVA[5]

Vinnytsia National Technical University (1), Kharkiv Petro Vasylenko National Technical University of Agriculture (2), National Technical University "Kharkiv Politechnic Institute" (3), D. Serikbayev East Kazakhstan State Technical University (4), Lublin University of Technology (5)

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Substantiation of parametric series of overhead lines wire cross-sections in conditions market and insufficient initial information

***Abstract**. One of directions in developing overhead lines in conditions market and insufficient initial information by optimizing parametric series of wire cross-sections has been substantiated. An optimization criterion of parametric series of wire cross-sections has been formed, recommendations on unification of overhead lines have been offered.*
***Streszczenie.** Uzasadniony został jeden z kierunków rozwoju linii napowietrznych w warunkach rynku i niewystarczającej informacji wstępnej poprzez optymalizację parametryczną serii przekrojów przewodów. Zostało utworzona kryterium optymalizacji parametrycznej serii przekrojów przewodów a także zaproponowano zalecenia dotyczące ujednolicenia linii napowietrznych. (**Uzasadnienie wielkości w szeregach przekrojów przewodów linii napowietrznych w warunkach rynkowych i niewystarczających informacjach początkowych**).*

Keywords: electric transmission overhead lines, wire cross-sections, criteria method..
Słowa kluczowe: elektryczne linie napowietrzne, przekroje przewodów, metoda kryterialna.

Introduction

Development of competitive relations in the electric power industry is connected with implementation of the model of two-party agreement market and balancing electric energy market (TABM), which expands the possibilities of the electric energy suppliers, users and producers. TABM market model consists of the segments, providing realization of competitive relations between its participants. TABM conditions require new scientific understanding, first of all, for creation of a new scientific platform for the development of electric networks (EN) [1, 2]. Elaboration of the methods for searching optimal solutions, that would substantiate a rational structure and form parametric series of the electric network equipment, is a perspective change in this direction.

Problem statement

The foundation of a rational structure of overhead lines (OL) is standardization and unification level of parametric series of wire cross-sections, reflecting the possibility of using standard design solutions, standard manufacturing processes, standard equipment for OL manufacture and repair.

OL design and construction practice leads to the expanded application of uniform (standardized) OL components. Unification efficiency is most strongly manifested in the system approach to the organization of OL design and construction. Evidently, such approach ensures:

- a shortened time for OL development and construction by using a limited number of poles, foundations, wire brands, insulations and fittings;
- qualitative reliability control during their manufacture;
- reduction of personnel errors during OL construction and operation;
- reduction of service stock of OL separate components;
- lowering OL construction cost due to competition between separate OL manufacturers [3].

Thus, in order to elaborate recommendations on creating a scientific platform for OL development, it is necessary to find the possibilities to reduce separate standard sizes of OL components and, primarily, of OL poles and wires. The task of reducing standard sizes of poles has been, to a certain degree, solved and OL wire cross-sections have been normalized according to the Electrical installation rules of Ukraine [4]. However, there is no feasibility study on the choice of wire cross-sections, which would be relevant in TABM conditions.

The paper aims at considering one of the trends of OL development in TABM conditions - optimization of parametric series of wire cross-sections, formulation of an optimality criterion for parametric series of wire cross-sections and proposing recommendations on OL unification.

Analysis of publications

As the analysis of information sources has shown, optimization of the electric network equipment on the principles of unification, including that of parametric series of wires cross-sections, is of current importance for the world electric power engineering.

First works in this direction were carried out in the 1980s [5]. At present stage, the development strategy of the electric power engineering is based on unification principles. Russian complex modernization program on power engineering for the period till 2030 is based on the principles of unification and standardization, including unification of equipment, technological solutions and configuration [3]. This approach has been implemented in a number of far-abroad countries. It is based on reducing the number of manufactured wire brands. As a basic section for different voltage classes, a single cross section is used, which, taking into account the scale growth factor, satisfy the cross-section nomenclature in terms of bandwidth. E.g., in Great Britain for the lines with the voltage of 132 – 275 – 400kV wires with cross-section AC175 mm^2, AC400mm^2 are used. In Germany for the lines of 110 – 220 – 400 KV one brand of steel-aluminum wire with AC560/50mm^2 cross-section is used (for OL 220 – 400 KV with two wires per phase). In Italy only three wire cross-sections are recommended for wide use: for OL 132 – 380 KV – 128/21 mm^2, 265/43 mm^2, 520/66 mm^2. In Czech Republic 110 KV and more three wire brands are used in networks: AC 240 mm^2, AC 450 mm^2, AC 670 mm^2. In France for the construction of OL with the voltage of 225 – 400KV standard wire cross-section 570 mm^2 is used [1 – 6].

Basic research materials

While searching for optimal solutions, substantiating a rational structure and forming parametric series of electric equipment, the work was performed and recommendations were elaborated on unification of the wire cross-section scale. It is based on the statement that OL has economic power intervals only if the restriction, ensuring distinguishability of the separate variants according to the economic criterion, is satisfied. Conditions for the existence of economic intervals are given by:

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(1) $$\frac{r_i}{r_{i+1}} > 1, \quad \frac{K_{i+1}}{K_i} > 1, \quad \frac{K_i - K_{i-1}}{K_{i+1} - K_i} < \frac{r_{i-1} - r_i}{r_i - r_{i+1}}$$

where r_i - active resistance of the i-th wire; K_i - investments in the i-th line.

Criteria (1) reflect the technical side only and set necessary conditions for the existence of economic power intervals. Since OL is an object of a technical-economic character, certain restrictions reflecting economic relations of the unified object are to be satisfied. Satisfying the conditions of distinguishability of two electric transmission variants with wires of different crosssections is considered to be one of such requirements. Thus, if we assume the existence of an economic interval of the i^{th} cross-section, the condition of equal economic efficiency is to be observed:

(2) $$C_{i+1/i} \big/ C_{i/i-1} \geq 1 + \varepsilon$$

where C_i – discount costs of OL; ε - a permissible value that defines the zone of equal economic efficiency.

Condition (2) is not only necessary, but also is a sufficient one for the *i-th* wire. Its non-fulfilment contradicts the condition of the existence of an economic power interval in terms of equal economic efficiency for the *i-th* cross-section (see Fig. 1).

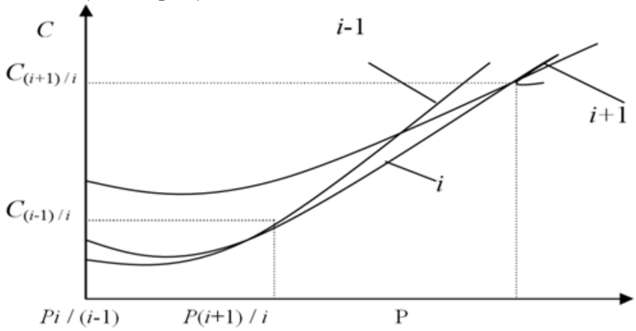

Fig. 1. Economic power intervals for the wires of F_i, F_{i+1}, F_{i-1} cross-sections

It is known that one of the main criteria of technical-economic relations is a minimum discount cost in the analysis of technical-economic OL indicators in TABM conditions [5]:

$$\mathrm{C}(x) \to \min, \quad x \in X$$

There is no generally accepted concept in the practice of constructing and implementing technical-economic models. In each specific case, the construction of a computational model and the method of its solution are closely interrelated. Moreover, in solving the general optimality problem, it is necessary to take into account the nature of initial information, reliability of which is sometimes rather low. This leads to the uncertainty of initial information [5 – 7].

Proceeding from the stated above, a computational model of the discount costs in 1 km of OL could be presented as

(3) $$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2 = (E + p)(a + вF) + (3I^2 \rho \tau \beta) \cdot F^{-1},$$

where C_1 – investment component of the technical-economic model of OL (investments); C_2 – technical component of the technical-economic model of OL (operation costs); E – bank rate, %; p – factor of allowances for depreciation, repair and maintenance of the line; a – constant component of the cost of 1km OL that depends on the type of poles, OL design solution, voltage class, currency units, (c.u.)/km; *F* – wire cross-section, mm^2; I – maximal current in the line, A; ρ – resistivity of the conductor material, Ω·mm^2/ km; τ – time of maximum losses, h/ year; *β* – unit cost of electric energy losses, c.u. per (KW h).

Investments in TABM conditions include the land cost in OL cost as well as loan payments, depreciation and taking into account inflation. For different voltage classes C_1, in a general form, could be presented as

(4) $$C_1 = \left(\frac{E_{nom} + 100}{\alpha + 100} - 1\right)\left(1 + \left[\left(\frac{E_{nom} + 100}{\alpha + 100}\right)^{T_{сл}} - 1\right]^{-1}\right) K_i$$

where E_{nom} – a nominal bank rate, %; *α* – inflation rate; T_s – normative service life, year; K_i – cost of 1 km OL of the i^{th} voltage class taking into account the cost of land, c. u./km [7].

Taking the above-mentioned into account, at point P_i the values of discount costs in OL made of wire with the i^{th} cross-section coincide with those in OL made of wire with the (*i*+1) cross-section (see Fig. 1) and the following expressions will be valid:

(5) $$C_{\frac{i+1}{i}} = p_л \frac{K_{i+1} r_i - K_i r_{i+1}}{r_i - r_{i+1}}$$
$$C_{\frac{i}{i-1}} = p_л \frac{K_i r_{i-1} - K_{i-1} r_i}{r_{i-1} - r_i}$$

The ratio of expressions (5) is given by:

(6) $$\frac{C_{\frac{i+1}{i}}}{C_{\frac{i}{i-1}}} = \frac{K_{i+1} r_i - K_i r_{i+1}}{K_i r_{i-1} - K_{i-1} r_i} \frac{r_{i-1} - r_i}{r_i - r_{i+1}} = \mathrm{idem}$$

We use expression (6) in relation (2):

(7) $$\frac{K_{i+1} r_i - K_i r_{i+1}}{K_i r_{i-1} - K_{i-1} r_i} \frac{r_{i-1} - r_i}{r_i - r_{i+1}} \geq 1 + \varepsilon$$

or

(8) $$\frac{K_{i+1} r_i - K_i r_{i+1}}{K_i r_{i-1} - K_{i-1} r_i} \geq \frac{r_{i-1} - r_i}{r_i - r_{i+1}} (1 + \varepsilon)$$

The obtained criterion reflects not only the technical, but also the economic basis for the construction of unified OL.

The above considerations could be used for elaborating restriction methods based on the existing unification. Observing the criteria results should be noted in obtaining the most correct solution.

The condition for distinguishability of the two OL variants, determined by the boundaries of equal economic efficiency, depends, to a certain extent, on the scale of wire cross-sections with which those lines are made. On the other hand, if restrictions on equal efficiency conditions are not taken into account, two variants, formed by neighboring wire cross-sections, will be equally efficient since the scale growth factor in this case is inadequately low.

Feasibility of such a solution depends on the method used, mathematical apparatus as well as the nature and accuracy of the object description. In conditions of absence of full initial information for the analysis of electric network objects, it is necessary to use generalization methods based on the theory of similarity, mathematical programming and simulation. One of such methods is a criteria method with the elaborated algorithms, enabling quantitative description of optimal technical and economic relations of the object in both cases: availability and unavailability of full initial information.

The given method was used as a research tool, making it possible to substantiate parametric series of wire cross-sections. Besides, a mathematical model of OL, applicable in TABM conditions, was used. It is distinguished mainly by the difference in analytical relation between the investments in OL and wire cross-section. Formulation of the problem is sufficiently accurate, physical meaning of the object being preserved [5].

Thus, a mathematical model of the discount costs in OL can be presented as:

$$\text{(9)}\quad \mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2 = (A-1)\left(1+\left[A^{T_{sl}}-1\right]^{-1}\right)\mathrm{K}_{110} + (3I^2\rho\tau\beta)\cdot F^{-1}$$

where $A = \dfrac{E_{nom}+100}{\alpha+100}$.

With a certain error, (9) could be presented as a single general model:

$$\text{(10)}\quad C = A_1F^{0,25} + A_2F^{-1}$$

The criteria method for analyzing the generalized technical-economic model (10) has shown that at the point of minimum

$$\text{(11)}\quad C_0 = \left(\frac{A_1}{\pi_1}\right)^{\pi_1}\left(\frac{A_2}{\pi_2}\right)^{\pi_2}$$

where π_1 and π_2 are similarity criteria, π_1=4/5, π_2=1/5, which can be obtained from systematic procedures of the criteria method.

The values of parameters of function (10), expedient in terms of economic efficiency, are determined from the condition

$$\text{(12)}\quad F_0 = \left(\frac{\pi_1A_2}{\pi_2A_1}\right)^{0,8}$$

Let us perform the following transformations: introduction of a generalized constant $A'_2 = A_2/p^2$ and writing (11) in a relative form provided that basic value of the generalized constants coincides with the real value of these constants A_i, i.e. $A_1 = A'_2 = 1$. Then

$$\text{(13)}\quad \underset{*}{C} = (\underset{*}{A_1})^{\pi_1}(\underset{*}{A_2}\,\underset{*}{P}^2)^{\pi_2}$$

or

$$\text{(14)}\quad \underset{*}{C} = \underset{*}{P}^{0,4}$$

Similarly, for (12)

$$\text{(15)}\quad \underset{*}{F} = \left(\frac{\underset{*2}{A}\cdot\underset{*}{P}^2}{\underset{*1}{A}}\right)^{0,8}$$

or

$$\text{(16)}\quad \underset{*}{F} = \underset{*}{P}^{1,6}$$

From (14) and (16) it could be written

$$\text{(17)}\quad \underset{*}{F} = \underset{*}{C}^4 .$$

In a general case, formation of the permissible solution existence region depends on the initial information error *δ,* the accuracy of which will be determined by the value of *ε*. The results of such estimation are as follows:

δ, %	±1	±2	±3	±4	±5	±6	±7	±8	±9	±10
F	1.14	1.28	1.45	1.56	1.66	1.77	1.89	2.05	2.20	2.60

Thus, the error of operational characteristics plays an essential role in the scale growth factor substantiation. From practice it is known that the accuracy of engineering calculations is at least 10%. Therefore, the most appropriate scale growth factor of wire sections in this case should not be less than 2 – 2.5. The easiest way to get this growth factor is to eliminate intermediate standard values of the wire cross-section scale.

As EN form a complex dynamic system, the issue of unification of such networks should, to a certain extent, solve the problems of reconstruction. The issue of OL unification has a significant influence on reconstruction time that includes the time for replacing the wires of a certain crosssections with bigger ones in order to increase OL bandwidth and to improve the electric energy quality [5, 6, 8, 9].

Let us show that reconstruction time is connected with the wire cross-section scale used for network construction. The law of power variation is known in a relative form:

$$\text{(18)}\quad \underset{*}{P} = \underset{*}{P_0}(1+q)^t$$

where *q* is an average value of the load increment.

Using expressions (16) and (18), we can write

$$\text{(19)}\quad \underset{*}{P}(1+q)^t = \underset{*}{F}^{0,625}$$

The obtained expression shows the rate of the wire cross-section, changing for a given nature of the load. It should be noted that if a wire cross-section value $F_б$, in the year when OL was constructed and put into operation is taken as a basic one and cross-section of the wire at the period of OL reconstruction is taken as the following cross-section, the ratio

$$\text{(20)}\quad \frac{F_2}{F_б} = \underset{*}{F}$$

will represent the cross-section scale growth factor.

Let us assume that we have two different cross-section scales characterized by factors F_1 and F_2.

The load growth rate we assume to be equal both in the first and in the second case. Then, in accordance with (20)

$$\text{(21)}\quad \underset{*}{P}(1+q)^{t_1} = \underset{*}{F}^{0,625}$$

and

$$\text{(22)}\quad \underset{*}{P}(1+q)^{t_2} = \underset{*}{F}^{0,625}$$

Relations (21) and (22) could be written in the form of

$$\text{(23)}\quad \frac{t_2}{t_1} = \frac{\ln \underset{*}{F_2}}{n\,\underset{*}{F_1}} = \text{idem}$$

In this expression time *t* defines the interval from the beginning of operation life to the first reconstruction. The obtained expression does not depend on the load growth rate and is determined only by the chosen scale of wire cross-sections. Besides, from (22) and (23) we can determine the reconstruction time, depending on OL bandwidth and given load growth rate *q*. We assume that $P_0 = 1$ as it is related to the beginning of OL operation. Then:

$$\text{(24)}\quad t_0 = 0,625\frac{\ln \underset{*}{F}}{\ln(1+q)}$$

As a result of calculation of the reconstruction terms for wire cross-section scales with the factor $F_2 = 2$, an average value of time ratio was determined to be equal to 2.

Thus, as a basis for OL unification, it is necessary to use a standardized cross-section scale that makes it possible to minimize the number of reconstructions.

The obtained characteristics of OL cross-section scale unification give scientific substantiation for the basis of unification procedure. In this case from several OL options we should choose the one that will satisfy the condition of economic feasibility of the selected object with regard to reliability, maintainability, additional investments in the reconstruction, etc. The task will be simplified if the analysis of various options is performed purposefully. For this it is necessary to choose a basis. E. g., OL cross-section from the unified scale, which is the most common among the existing OL, could be used as a basic one.

The task of forming the unification basis is confined to the investigation of OL wire cross sections depending on climatic and load conditions. A number of design institutions conducted research in order to obtain relative frequencies of OL loads on the basis of statistical processing. The obtained results have shown that the growth factor of the wire cross-section scale, that is close to 2, is the most acceptable one [5]. This information taken as a basis, wire cross-section values for different voltage classes were obtained.

Table 1. Variants of distributing OL lengths for OL cross-sections of 70mm^2, 120mm^2, 240mm^2 and discount costs in accordance with the variants

No. of a research variant	Distribution of OL lengths in accordance with cross-sections, %			C ,%
	70 mm^2	120 mm^2	240 mm^2	
1 (basic)	38	35	27	100
2	38	21	41	99,5
3	38	0	62	99,9
4	24	0	76	99,6
5	9	0	91	99,9
6	**0**	**0**	**100**	**100**
7	24	49	27	98,1
8	9	64	27	97,0
9	0	73	27	96,6
10	24	35	41	97,6
11	9	29	62	97,2
12	0	24	76	98,0
13	0	9	91	99,8
14	0	38	62	96,8
15	0	58	42	96,1
16	9	49	42	96,5
17	24	14	62	98,3
18	9	14	77	98,5

Let us illustrate the above by the example of the cross-section scale formation for OL 110 KV. It is known that wide-scale electrification was carried out in the 70s of the last century and the selection criteria were somewhat different. This factor was taken into consideration when basic variant for the research was formed. The cross-section scale is built assuming that $K_n \geq 2$ and a single cross-section is used for a given voltage class. The table presents possible optimal solutions for this statement of the problem taking into account redistribution of OL lengths.

From the table it is evident that all the options are equally efficient. At the same time, variant 6 is the optimal one in terms of reconstruction, increasing of OL bandwidth, reduction of electric energy losses and improvement of OL reliability [4].

Conclusions

The paper considers one of overhead lines' development trends in TABM conditions: optimization of parametric series of wire cross-sections. An optimality criterion of the parametric series of wire cross-sections is elaborated and recommendations on overhead lines unification are proposed. This will make it possible to minimize the number of reconstructions, to increase overhead lines bandwidth, to reduce electric energy losses and to improve reliability of EN.

***Authors**: prof. dr hab. inż. Petro D. Lezhniuk, Department of Electrical Stations and Systems, Vinnytsia National Technical University, 95 Khmelnitskoye Shose, Vinnytsia, 21021, Ukraine, E-mail: lpd@inbox.ru; dr inż. Mykola M. Cheremisin, Department of electricity supply and energy management, Kharkiv Petro Vasylenko National Technical University of Agriculture, 44 Artyoma St., Kharkiv 61002, Ukraine; dr inż. Veronika V. Cherkashyna, Department of transmission of electrical energy, National Technical University "Kharkiv Politechnic Institute", 21, Frunze St., Kharkiv 61002, Ukraine; mgr inż. Natalia Denisova, D. Serikbayev East Kazakhstan state technical university, 070004, Ust-Kamenogorsk, 69 Protozanov Street, Kazakhstan, e-mail: kanc_ekstu@mail.ru; dr hab. inż. Andrzej Smolarz, Instytut Elektroniki i Technik Informacyjnych, Nadbystrzycka 38A, 20-618 Lublin, E-mail: a.smolarz@pollub.pl; mgr inż. Samal Abdreshova, Instytut Elektroniki i Technik Informacyjnych, Nadbystrzycka 38A, 20-618 Lublin.*

REFERENCES

[1] Law of Ukraine on the principles of the electricity market of Ukraine, *http://zakon4.rada.gov.ua/laws/show/663-18*.
[2] Kyrylenko O.V., Blinov I.V., Parus E.V., Balancing electricity market and its mathematical model. *Technical electrodynamics,* 2 (2011), 36 - 43
[3] Russia's Energy Strategy to 2030, *http://minenergo.gov.ru/aboutminen/energostrategy/*.
[4] Rules for Electrical Installation, *Publishing House "Fort"*, 2009
[5] Budzko I.A., Astakhov N.Y., Cheremisin N.M., Unification of overhead power lines, *Elektrychestvo*, 2 (1982), 1 - 11
[6] Faibisovich D.L., Offers for the unification of sections of overhead lines with voltage wires 110 - 750 kV, *Energetik,* (2003) nr3, 21 - 22.
[7] Cheremisin N.M., Cherkashyna V.V., The choice of priority in the design of overhead power lines in the conditions of market relations, *Proceedings of the VI All-Russian scientific and technical conference with international participation "Energy: management, quality and efficient use of energy" - Russia. Blagoveshchensk: AUG – 2011,* vol 1 (2011), 105 - 110
[8] Rzepecki A., State estimation in the highest voltage power system networks, *IAPGOS*, 2 2012; nr 2, 45-48
[9] Dechnik M., Moskwa S., Benchmarking of power distribution systems, *IAPGOS*, 5 2015, No 1, 37-44