Technical and Economic Model of the Conductor Cross-Section for Active-adaptive Electrical Networks

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Received: April 2022 Revised: May 2022 Accepted: June 2022

ABSTRACT:
There can be observed a gradual transition of the electric power industry to the innovative technology platform "Smart Grid" around the world; in Russia it is done on the platform of an intelligent electrical grid with an active-adaptive network, which becomes one of the most important subsystems. There are new elements of power transmission lines, among which new generation conductors (NGC) are being actively introduced. However, the high cost of innovations in the power grid complex makes their use quite slow. The conductor cross-section is the most significant parameter of the power transmission line; it determines its main technical and economic indicators. The problem of choosing economically reasonable conductor cross-sections stems from the need to ensure the required level of reliability of power transmission lines, determines the most effective way to invest money and reduce the cost of electricity transportation. Modern requirements for the feasibility study of design solutions increase the economic significance of the problem to determine the economically feasible conductor cross-sections for the power transmission lines. At the same time, there is no method for choosing the optimal conductor cross-sections of NGC. An incorrect choice of the conductor brand and its cross-section can lead to unjustified costs for the construction and reconstruction of power transmission lines and increase the cost of electricity transmission. In the article there is the analysis of existing methods of project decisions feasibility; it was taken as the basis to develop the technical and economic model of a conductor cross-section for active-adaptive electrical grids, taking into account the thermal model of the conductor and the random nature of the change of current running through the power transmission lines.

Keywords: Smart Grid, Active-Adaptive Electrical Networks, Conductor Cross-Section, Technical And Economic Model, Discounted Costs, Current Load.

1. INTRODUCTION

The development of the electric power industry is carried out on the basis of the Smart Grid technology platform which is widely recognized worldwide due to its advantages (Colak, Bayindir, & Sagiroglu, 2020). The United States and the EU countries chose this concept as the basis for the modernization of the national energy development policy (Campbell, 2018). In Russia, the concept of an intelligent electric power system with an active-adaptive network (IES AAN) has been adopted (The main regulations of the Concept for the Development of the Intellectual Power System of Russia with an Active Adaptive Network, 2012). The IES AAN is a fundamentally new electric power system. It is based on the multi-agent principle of organization, management and development for the effective use of all resources. This makes it possible to provide reliable, high-quality and efficient power supply to consumers due to flexible interaction of all types of generation, electric networks and consumers using modern technological means and a single intelligent hierarchical management system.

An active-adaptive electric network (Dorofeyev & Makarov, 2009) empowering the smart grid with fundamentally new functional properties becomes the basis of the technological infrastructure of this system (Varygina & Savina, 2018). A power transmission line (PTL) is a key element of the active-adaptive network. Now there are new technical solutions for the development of almost all elements of overhead PTL, but special attention should be paid to the conductors, since they explicitly or implicitly determine all the main parameters of the line, affecting the functional properties of the network.

Paper type: Research paper
DOI: https://doi.org/10.52547/mjee.16.3.27
How to cite this paper: Aleksandra O. Varygina, Natalia V. Savina, "**Technical and Economic Model of the Conductor Cross-Section for Active-adaptive Electrical Networks**", Majlesi Journal of Electrical Engineering, Vol. 16, No. 3, pp. 27-34, 2022.

In the design and construction of high-voltage overhead transmission lines (HV PTL), unified elements of classical structures are mainly used, which leads to a typical design and construction of overhead transmission lines based on a limited set of classic conductor grades and cross-sections. In European countries, the unification of power transmission line elements has led to a significant increase in conductor cross-sections and a significant reduction in their active resistances and, as a result, power losses during transmission. For example, in Germany, the use of ACSR 265/35 conductors for HV PTL 110 - 220 - 380 kV is a typical solution (Larina & Ryzhkov, 2017). In Russia, as a rule, sections of steel-cored aluminum conductors are used; they meet the minimum of the reduced costs for the construction and operation of power lines according to the method of economic current density, which is presented in the standard process documentation (Electrical installation rules (EIR), 7th ed., 2008). This approach restricts the range of grades and cross-sections for use in the construction of power lines and is not designed for new generation conductors. It does not correspond to the concept of the IES AAN due to the restriction of the use of new technical solutions and the use of outdated methodological approaches (Savina & Varygina, 2019), and can lead to significant economic risks.

The analysis of international and domestic best practices shows that the use of new generation conductors (NGC) is advisable in the construction of new and technical re-equipment of existing HV PTL (Li, Zhao &Yang, 2017). Often, their use allows solving the problem of transmission capacity without reconstructing other elements of the overhead transmission line, which dramatically reduces the cost of its reconstruction. There is a large variety of such conductors in the world market: compacted, high-temperature, with composite cores, with a gap, and others (Alawar, Bosze, & Nutt, 2005), (Chen, Geng, Fang & Dai, 2019), (Kenge, Dusane & Sarkar, 2016). All of them have excellent characteristics in comparison with classic steel-cored aluminum conductors, but at the same time, they are more expensive.

Thus, the problem of technical and economic justification of the use of a particular conductor for both classical and active-adaptive electrical networks is still relevant and has become even more important. The growing demands in the power industry, the introduction of technical solutions for individual design, and the constant change in economic conditions only confirm this fact. In addition, there is no method for selecting economically justified cross-sections of new-generation conductors.

2. METHODS

In general, the project feasibility study (PFS) serves as the basis for identifying its investment effectiveness. The erroneous PFS is the reason not only for its low investment efficiency, but also for losses. Technical and economic comparison of electric grid options in Russia is implemented taking into account the recommendations (Methodological recommendations for assessing the effectiveness of investment projects, approved by the Ministry of Economy of the Russian Federation, 1999), (Methodological recommendations for the design of the development of power systems, 2003). Currently, decision-making is based on the evaluation of the comparative effectiveness of options based on the criterion of the minimum of overall discounted costs. And the choice of the cross-section of classical conductors according to the approved industry document (Electrical installation rules (EIR), 7th ed., 2008) is based on the method with the minimum of the reduced costs. The task of selecting conductors for power transmission lines of active-adaptive power networks is complicated by outdated economic tools of existing methods to choose classical design conductors, by the lack of uniform industry guidelines and the method of choice of new generation conductors, and by the presence of numerous economic criteria of economic justification of projects investment attractiveness. There is also a high risk of an error by a designer who does not have the necessary tools to solve a technically complex problem.

The purpose of the article is to develop a technical and economic model of the conductor cross-section, which gives the grounds to choose the optimal conductor cross-sections for active-adaptive electrical networks, taking into account their functioning features.

To do this, the following tasks must be solved:

- The choice of a methodological approach to develop a technical and economic model of the conductor cross-section;
- The development of a technical and economic model of the conductor and implementation of its components;
- The study of the effectiveness and applicability of the developed model and its features.

Based on the prerequisites of the problem to be solved, it is reasonable to use a systematic approach to the development of a technical and economic model of the conductor. This approach will make it possible to combine the thermal model of the conductor taking into account its design features and environmental conditions, the laws of electricity transport along the transmission lines of the active-adaptive network, and modern economic criteria used to assess the investment efficiency of projects. As a result, the model will help to choose the optimal cross-sections of various design conductors to ensure new functional properties of the active-adaptive network, its reliability and efficiency of functioning. The fundamental difference of the proposed methodological approach is based on physical bases for the transfer of power through the conductor, construction of the conductor, environmental and economic parameters in the development of the model. This model is of a physical and technical nature, on the one hand, and is an economic model, on the other hand. Hence, the technical and economic model of the conductor cross-section has the following form: (see Fig. 1).

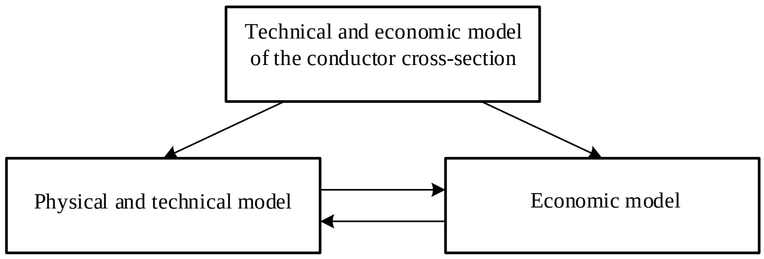

Fig. 1. General scheme of the model. *Source:* Compiled by the authors.

A technical and economic model that includes a variety of features is developed using the integrity predicate. The conductor cross-section model is generally represented by the expression:

$$F = \langle \psi_{tech}, \psi_{ec}, P(\psi_{tech}, \psi_{ec}) \qquad (1)$$

Where, ψ_{tech} is a physical and technical model that describes the physical characteristics and technical parameters of the conductor; and the conditions for current transfer through the conductor;

ψ_{ec} is an economic model that describes economic criteria and indicators and determines the choice of an economically optimal conductor cross-section;

$P(\psi_{tech}, \psi_{ec})$ is an integrity predicate.

This model helps to take into account the patterns of electricity transmission through the conductor.

The process of developing the proposed conductor cross-section model contains several stages:

- selection of a single economic criterion for conductors of traditional construction and NGC in correspondence with modern economic conditions;
- identification and formulation of mathematical regularities linking the main economic criteria and physical and technical parameters that characterize the conductor and its cross-section.
- development of a physical and technical model based on the thermal model of the conductor and the stochastic nature of the change in the current transmitted over the power line;
- synthesis of a technical and economic model;
- study of the applicability of the model to conductors of any design;
- comparison of the results of the study of the obtained model with the result of experience to verify its compliance with the object of research and to prove its applicability.

3. RESULTS

3.1. Economic Model

Choosing the correct economic criterion is an important step in the process of developing a technical and economic model. It is its significance that will determine the applicability of the project in the future. The main principles used to evaluate the effectiveness of the project are the following: analysis of the project throughout its life cycle; modeling of cash flows, including all project-related cash receipts and expenditures for the billing period with the possibility of using different currencies; comparability of the conditions for comparing different projects (project options); the principle of positivity and maximum effect; time factor; accounting for only costs and income, comparison study of "with the project" and "without the project"; accounting for the effects of inflation; the uncertainty and risk of the project (Methodological recommendations for assessing the effectiveness of investment projects, approved by the Ministry of Economy of the Russian Federation, 1999), (Methodological recommendations for the design of the development of power systems, 2003).

The currently used methods for selecting an economically feasible conductor cross-section are based on the static indicator of finding the minimum of the reduced cost function, which does not correspond to modern economic conditions and design conditions. It is important to understand that at present, the methods of feasibility studies and economic criteria have become more numerous (Rakhlina, 2015), (Biryukov, 2017), which complicates the task of choosing the right solution. Table 1 systematizes the methods of the feasibility study, taking into account the classification of economic indicators.

Table 1. Systematization of Feasibility Study Methods.

PFS methods	
using static metrics	*using dynamic metrics*
Economic impact	Total discounted costs
Reduced costs	Net present value
Profit indicator	Internal rate of return
Profitability indicator	The profitability index
Simple payback period	Discounted payback period
	Modified internal rate of return

Source: Compiled by the authors.

In general, all these methods not including the time factor do not correspond to the principles reflected in (Methodological recommendations for assessing the effectiveness of investment projects, approved by the Ministry of Economy of the Russian Federation, 1999) and are not suitable for the feasibility study of the choice of conductor cross-section of power transmission lines.

Modern time-factor methods use the concept of discounting cash flows to obtain a more accurate assessment of the effectiveness of investment. Table 2 shows the characteristics of the dynamic indicators.

Table 2. Characteristics of Dynamic Indicators

Indicator	Characteristics
Total discounted costs	These are the costs given for a certain year, including capital investments in the project, costs over the entire life cycle of the project, and tax payments. They are a special case of NPV.
Net present value (NPV)	This is the most frequently used indicator (Wetekamp, 2011) which represents the difference between the discounted inflow (result: sales revenue) and the discounted cash outflow (costs).
Internal rate of return (IRR)	It is the discount rate at which the inflow of funds is equal to the outflow of funds for the project, i.e. NPV = 0. The indicator characterizes the "economic stability of the project". But, based on the solution of the equation NPV = 0, it is not clear what should be taken as IRR and how to work with this value.
The profitability index (PI)	It is similar to NPV and is the sum of elements of a monetary stream from operational activity to absolute size of the sum of the elements of the cash flow from investing activities
Discounted costs profitability index	It is the ratio of the amount of discounted cash inflows to the amount of discounted cash outflows.
Discounted investments profitability index	It is equal to the ratio of the NPV to the accumulated discounted investment volume increased by one.
Discounted payback period	It is the duration of the period from the initial moment to the "payback period with discounting".
Modified internal rate of return	It is calculated in the case of an extraordinary cash flow. If the investment project has an ordinary cash flow, then the criterion does not apply.

Source: Compiled by the authors.

The analysis of the methods and indicators of economic justification has shown that the tools have been greatly expanded to date, but most of the criteria are either directly related to NPV (for example, IRR, PI) or complement it (discounted payback period), and some criteria may not be applied depending on the conditions (modified internal rate of return). But despite all the advantages of NPV, the total discounted costs for solving the problem of choosing the optimal cross-section are more applicable as an economic criterion. The selected criterion does not require forecasting tariffs and revenues in comparison with NPV. It makes it possible to escape the uncertainty of tariff forecasts for a long period and simplify the calculation. In addition, the total discounted costs in fact show the part of the calculation of NPV, characterized by the outflow of funds for the period under review.

The canonical formula for the discounted costs of the investment period of the PTL has the form:

$$C_{disc} = \sum_{t=0}^{T} (CE_t + OC_t + TP_t) \cdot (1+E)^{-t} \qquad (2)$$

Where, CE_t is capital expenditures per year, rub.; OC_t represents operating costs, rub.;

TP_t is tax payments per year of the object period;

E is a discount rate;

t is any year of the object period;

T is the last year of the object period.

Based on the above, the economic model of the conductor is presented in the form of discounted costs per unit and is described by the following expression:

$$C_{disc} = \sum_{t=0}^{T} [CE_t \cdot (1+\alpha_{dd}+\alpha_{drm}) + c \cdot (3 \cdot I^2 \cdot R \cdot T + 8760 \cdot \Delta P_{cor} + \frac{U_n^2 \cdot T_{ww} \cdot N_{is}}{3 \cdot N_{in} \cdot R_{in}})] \cdot (1+E)^{-t} \qquad (3)$$

Where α_{dd} is the rate of deductions for depreciation, 1/year;

R is specific line resistance, Ohm/km;

α_{drm} is the rate of deductions for repairs and maintenance, 1/year;

U_n is nominal line voltage, kV; c is an electricity rate, rubles/kWh;

ΔP_{cor} is specific losses of power to the crown in the conductors of overhead lines, kW/km;

N_{in} is the number of insulators in the string, pieces;

N_{is} is the number of insulator strings per 1 km of overhead lines, piece/km;

R_{in} is the resistance of the single suspension insulator in the string, Ohm;

T_{ww} is the average number of hours of the wet weather a year, h.

Thus, discounted costs per 1 km of the constructed overhead line are accepted as a universal economic criterion, since they meet all the economic requirements for ensuring the efficiency of capital investment in a particular investment project, and their use makes it possible to simplify the calculation in comparison with other criteria.

3.2. Physical and Technical Model

To make a physical and technical model, the current load of the active-adaptive network line is represented by a random process of the form (Savina, 2008):

$$I(t) = I_{av}(t) + I_S(t) + \varepsilon(t) \qquad (4)$$

Where, $I_{av}(t)$ is the average value of the current load (mathematical expectation);

$I_S(t)$ is a stationary ergodic process with zero mathematical expectation;

$\varepsilon(t)$ is noise describing the non-stationary random component of the process.

The value $I_{av}(t)$ is determined by the thermal model of the conductor taking into account its physical characteristics and design features. The remaining components are described in (Savina, 2008).

Based on the thermal model of the conductor and the model of the current transmitted along the line, represented by a random process, it is possible to obtain an engineering implementation of the physical-technical model in the following form:

$$I_e^2 = I_{pc}^2 \cdot K_{ff}^2 \cdot K_{sf}^2 \qquad (5)$$

Where, I_e is an equivalent value of the current transmitted along the line, A;

$K_{sf} = \sqrt{1+\gamma^2}$ is a shape factor determined with the help of the coefficient of variation γ depending on the type of random process (Savina, 2008);

K_{ff} is the fill factor of the line current load graph;

I_{pc} is permissible current determined by the thermal model of the conductor, A.

A universal mathematical model of long-term permissible current for conductors of classical design and new-generation conductors has the form:

$$I_{pc} = \sqrt{\frac{(\alpha_c+\alpha_r) \cdot F \cdot (T_{av}-T_a) - \varepsilon_a \cdot k_H \cdot D \cdot W_t \cdot \sin\psi_c - P_i}{k_M \cdot k_j \cdot R_{20} \cdot (1+\beta_r(T_{av}-20))}} \qquad (6)$$

Where, α_c is the coefficient characterizing the process of heat transfer when heat is transferred by convection, W/(m^2·°C);

α_r is a coefficient characterizing the process of heat transfer in radiant heat transfer exchange, W/(m^2·°C);

F is the heat transfer area, m^2;

T_{av} is conduct temperature, °C;

T_a is air temperature, °C;

ε_a is the absorption coefficient of the wire; D is the conductor diameter, m;

k_H is a coefficient that takes into account the influence of altitude above sea level;

W_t is the intensity of the direct and reflected radiation (total), and is calculated depending on the time of year by the formulas for the different air pollution level, W/m^2;

ψ_c is active tilt angle of solar rays which depends on the time of day and year;

R_{20} is DC resistance at 20 °C, Ohm;

β_r is a temperature coefficient of resistance, 1/°C;

k_j is a coefficient taking into account the increase in resistance due to skin effect;

k_M is a factor of magnetic losses for conductors with a steel core.

A detailed description of the model of the long-term permissible current is given in (Varygina & Savina, 2020).

4. DISCUSSION

Combining the developed economic and physical-technical models into a single whole, a technical-economic model of a universal nature is obtained, which allows determining the optimal cross-section of the conductor of any design, the use of which is possible both for an active-adaptive network and for a network of classical design.

Based on the obtained technical and economic model, an algorithm for determining the optimal conductor cross-section is proposed, shown in Fig. 2.

For calculations, it is recommended to use any convenient computer mathematics system, for example, MathCad or MATLAB.

The technical and economic model obtained using the criterion of specific discounted costs per 1 km of HV PTL allows determining the current value at which it is advisable to make a transition from one conductor cross-section to another. The construction of a family of dependencies for a number of cross-sections makes it possible to obtain a series of parabolic curves, where the intersection points are the boundaries of the ranges of the appropriate application of a particular cross-section.

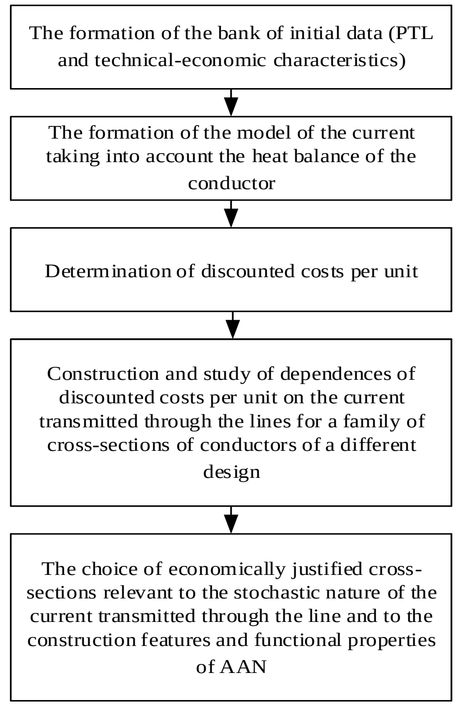

Fig. 2. Algorithm. *Source:* Compiled by the authors

As an example, Fig. 3 shows the construction of a family of dependencies for a 110 kV single-chain overhead line using the brand of a new generation of SENILEK AT3P/S conductor (General information about the conductor, 2020), reinforced concrete supports and the location of the object in the Moscow region.

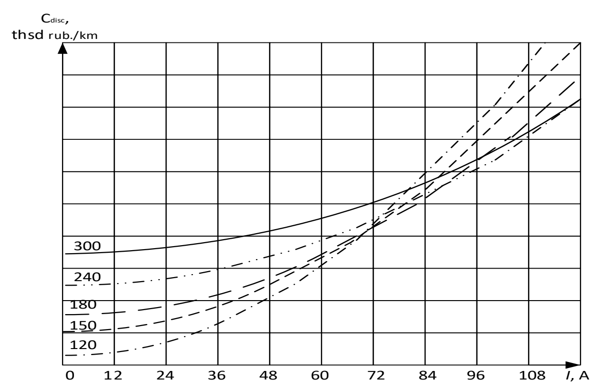

Fig. 3. The family of dependences of the unit discounted costs on the current. *Source:* Compiled by the authors.

With the introduction of additional data on the required current load, it will not be difficult to determine the optimal cross-section.

It is important to notice that the conducted studies have shown a tendency to increase the optimal cross-section of conductors of any design in comparison with the values determined by existing methods.

5. CONCLUSION

As a result of the conducted researches there was established the correlation between physical and technical parameters and the current economic criteria and parameters that have an influence on the choice of conductor cross-sections of PTL of any design taking into account the conditions of its functioning. The features of the influence of the innovative elements of the new technological platform for the formation of the model were also analyzed. The proposed model is universal, since it allows choosing an economically reasonable cross-section of conductors of any design, taking into account the special functioning of the electrical power grid and in the future, during operation, to provide flexible loading of HV PTL.

When studying the applicability of the technical and economic model to the calculation of the NGC, it was revealed that the approaches to evaluate the components of the model will differ from the traditional ones. So in the application of technical and economic model of NGC, it is recommended to consider the whole system "support – conductor – suspension strand – steel reinforcement – concrete", taking into account the additional costs which include the cost of warning lights, anti-icing activities, transportation, construction works, means of protection of personnel against falls from heights when climbing on a support, and others.

The expected effect of using the proposed model when choosing the conductor cross section is as follows:

- providing specialists with a tool for justifying complex technical decisions that meets modern conditions and trends and takes into account the features of the physical transfer of power over the conductor;

- reducing the costs of electric grid companies for the entire period of operation of the overhead transmission line;

- reduction of the cost of new construction of overhead transmission lines;

- effective investment in power grid facilities and, as a result, reduction in the cost of electricity transmission.

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