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RESEARCH INTO RELIABILITY ISSUES OF AN ELECTRIC POWER TRANSMISSION SYSTEM WITH A PHOTOVOLTAIC POWER PLAN

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Abstract. *The article provides a study of the reliability of the electric power transmission system with a photovoltaic power plant through a comprehensive analysis of the technical and economic characteristics of cable and overhead power lines. The choice of voltage class for the system under study, which has a radial electrical grid topology with an installed photovoltaic plant at the receiving substation, is justified. In accordance with the selected voltage class, the conductive part of the overhead and cable lines is determined, and the cross-sections of the wires and cable cores are checked for acceptable current load conditions. Based on the verifi-cation results, the current-carrying part of the overhead transmission line was selected using an ACSR 240/32 mm² conductor, while the cable line was designed with an APvEgP-110 1×240/95 mm² cable. The parameters of the overhead and cable transmission lines were determined, and a comparative analysis of the technological process of electric power transmission in a radial grid was performed using the PowerFac-tory software package, in particular with respect to voltage deviations in both transmission system vari-ants. It was shown that, in terms of technical performance indicators, the overhead and cable lines are equivalent. Taking this into account, an economic analysis was carried out to substantiate the optimal line option by calculating the cost component of the integral effect of total discounted costs. The results of this analysis indicate that the cable line is 59.4% more expensive than the overhead line. To further justify the feasibility of selecting the line type, a SWOT analysis was conducted, which demonstrated that the project incorporating a cable line is more attractive than the project based on an overhead line. The proposed com-prehensive analysis of the techno-economic characteristics of overhead and cable lines enables a well-grounded decision to be made regarding the selection of the appropriate facility to enhance the reliability of an electric power transmission system with a photovoltaic power plant, provided that the technical parame-ters of the electrical grid are equivalent.*

Key words: *renewable energy source, electrical grid, cable line, reliability, overhead line, electric power transmission system, techno-economic characteristics, photovoltaic power plant.*

ДОСЛІДЖЕННЯ ПИТАНЬ НАДІЙНОСТІ СИСТЕМИ ПЕРЕДАЧІ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ З ФОТОЕЛЕКТРИЧНОЮ СТАНЦІЄЮ

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Анотація. *В статті представлено дослідження надійності системи передачі електричної енергії з фотоеле-ктричною* *станцією шляхом комплексного аналізу техніко-економічних характеристик кабельної та повітряної ліній електропередавання. Обґрунтовано вибір класу напруги досліджуваної сис-теми, що має топологію радіальної електричної мережі з наявною фотоелектричною станцією на приймальній підстанції. Відповідно до обраного класу напруги визначено струмопровідну час-тину повітряної та кабельної ліній, виконано перевірку перерізів проводів і жил кабелю за умовами допустимого струмового навантаження. Визначено параметри повітряної і кабельної ліній еле-ктропередавання та в програмному комплексі PowerFactory здійснено порівняльний аналіз техно-логічного процесу передачі електричної енергії в радіальній мережі, зокрема відхилення напруги в обох варіантах системи передачі. Показано, що за технічними показниками повітряна й кабельна лінії є рівноцінними. З огляду на це проведено економічний аналіз для обґрунтування оптимально-го варіанта лінії шляхом розрахунку витратної складової інтегрального ефекту сумарних диско-нтованих витрат, за результатами якого встановлено, що кабельна лінія є на 59,4% дорожчою за повітряну. Для уточнення доцільності вибору типу лінії виконано SWOT-аналіз, за результа-тами якого проєкт із кабельною лінією виявився більш привабливим, ніж проєкт із повітряною лінією. Запропонований комплексний аналіз техніко-економічних характеристик повітряної та кабельної ліній дозволяє прийняти обґрунтоване рішення щодо вибору об'єкта для підвищення надійності системи передачі електричної енергії з фотоелектричною станцією за умови рівноцін-них технічних параметрів електричної мережі.*

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Ключові слова: *відновлюване джерело енергії, електрична мережа, кабельна лінія, надійність, по-вітряна лінія, система передачі електричної енергії, техніко-економічні характеристики, фотое-лектрична станція.*

List of Symbols and Abbreviations

RES — renewable energy sources

HV — high voltage

MV — medium voltage

LV — low voltage

EPS — electric power system

TL — transmission line

OL — overhead line

CL — cable line

EG — electrical grid

PVPP — photovoltaic power plant

Introduction. The current development vector of Ukrainian electric power systems (EPS) is focused on increasing the share of renewable energy sources (RES), which leads to the deployment of generating units with a nominal capacity of less than 20 MW connected to the busbars of electrical network substations. This approach is driven both by the need to comply with the requirements of European Union directives and by the necessity to compensate for the deficit of available generation capacity that has arisen as a result of targeted attacks on energy infrastructure facilities under martial law conditions [1].

According to [1], in the post-war period, the design and reconstruction of electric power transmission systems should be carried out in the following main directions:

- consideration of renewable energy sources (RES) at electrical network substations;
- development of ring electrical networks combined with deep 110 kV connections;
- preferential application of cable lines (CL) with cross-linked polyethylene (XLPE) insulation;
- use of compact (geometrically optimized) equipment at step-down substations.

Considering the above-mentioned development directions of electric power systems (EPS), it should be noted that the primary means of supplying consumers with electrical energy are overhead lines (OL) and cable lines (CL). The technologies used for the construction of OLs and CLs are based on the same fundamental physical laws (Ohm's law and Kirchhoff's laws), and both systems are technologically mature. However, this does not imply that one of them is "better" or "more technologically advanced" than the other. The current level of development of equipment and technologies enables the purposeful application of both types of lines.

At the same time, the technical feasibility of a particular solution does not necessarily imply its expediency. The criteria for selecting an overhead or cable line should not be determined by subjective opinions of network operators, policymakers, or experts, but rather by fundamental physical laws that define the key constraints. These factors include [2, 3]:

Voltage and current. The higher the voltage of a transmission line, the greater the required safety clearance. If such a clearance cannot be ensured (as in the case of cable lines), appropriate insulation is required to guarantee the safety of the line and the surrounding environment even at minimal distances.

Grid operating mode. This is another important factor affecting the feasibility of using overhead lines (OL) or cable lines (CL). In the arc-suppression (compensated neutral) operating mode, only a limited total length of cable can be installed; compliance with these length constraints (so-called *arc-suppression limits*) is critically important for the safe operation of transmission lines. In other operating modes of electrical grids, this limitation does not apply; however, additional interactions arise that must be taken into account when selecting the line type in an electric power transmission system, especially in the presence of RES at the substation.

Therefore, the selection of a particular line type in an electric power transmission system should be based on a comprehensive analysis of the techno-economic characteristics of OL and cable lines CL to ensure a well-founded decision regarding the choice of the facility, provided that the technical parameters of the electrical network are equivalent.

This issue has been addressed in numerous studies by both Ukrainian and international researchers. In [4], the specific aspects of ensuring operational reliability of electric power systems with decentralized generation based on renewable energy sources are identified. It is shown that an increase in the share of RES in the generation mix requires consideration of their static and dynamic characteristics, which significantly affect the operating modes of electrical grids. Consequently, this necessitates a comprehensive analysis when selecting the design of the supplying transmission line for a substation integrating RES.

Researchers [5, 6] compared the parameters of overhead lines (OL) and cable lines (CL) with cross-linked polyethylene (XLPE) insulation. They showed that cable lines are better protected against external factors and have a compact design that reduces electromagnetic impact on the surrounding environment and do not require the allocation of large land areas. However, a comprehensive techno-economic analysis was not provided.

Researchers [7–11] presented examples of pilot transmission line projects of various voltage classes employing XLPE and gas-insulated (SF_6) technologies, as well as overhead air-insulated solutions. In particular, researchers in [7] addressed the selection of cable lines for different operating conditions and reported successful implementations in foreign electrical grids. This experience may be valuable for the post-war design and reconstruction of electric power transmission systems in Ukraine, provided that it is appropriately adapted to domestic conditions.

In [8], researchers analyzed the environmental impact of overhead lines (OL) and cable lines (CL). It was demonstrated that cable lines have significantly fewer external impact parameters and exert a much lower impact on the environment; however, the study does not provide a comparison of the technical performance indicators of transmission lines. In [9], researchers addressed the issue of improving the efficiency of operating modes of overhead lines in electrical networks, but the possibility of applying cable lines was not considered.

In [10], the advantages and disadvantages of using sulfur hexafluoride (SF_6) as an insulating medium in electric power systems are discussed. Gas-insulated transmission lines (GILs) are considered. It was demonstrated that such lines employ internal insulators, which limit the route bending radius and the permissible short-circuit currents. In addition, the high cost and maintenance complexity of GILs compared to overhead lines with similar transmission capacity were highlighted.

In [11], scientific developments of high-voltage compact air-insulated lines installed in underground collectors are presented. As opposed to transmission line projects of various voltage classes reported in [7–10], these solutions have not yet been implemented in practice. Transmission lines with uninsulated conductors installed in collectors are extremely hazardous, as the installation of uninsulated current-carrying parts in confined spaces may lead to short circuits, fires, electric shock, and, consequently, damage to the entire electric power transmission system.

For safe installation in collectors and other confined spaces, only insulated current-carrying parts may be applied [5–8, 10], since any accidental contact of an uninsulated conductor with collector walls, other structural elements, or personnel may result in a fault condition. An additional risk is the lack of natural ventilation: in the event of a short circuit or fire, this leads to the rapid accumulation of toxic gases and makes safe evacuation impossible.

Thus, a systematic assessment of the selection of a transmission line for an electric power transmission system with a photovoltaic power plant, based on a comparison of OL and CL under equivalent technical parameters of the electrical network, constitutes a relevant scientific and practical task.

Purpose of the Article. The purpose of this article is to investigate the reliability of an electric power transmission system with a photovoltaic power plant through a comprehensive analysis of the techno-economic characteristics of overhead and cable transmission lines, in order to make a well-founded decision regarding the selection of the appropriate facility under equivalent technical parameters of the electrical grid.

Research Materials and Methods

Input Data of the Electric Power Transmission System

The electric power transmission system with a photovoltaic power plant is located in the Eastern region of Ukraine and has a radial electrical grid topology, which is shown in Fig. 1.

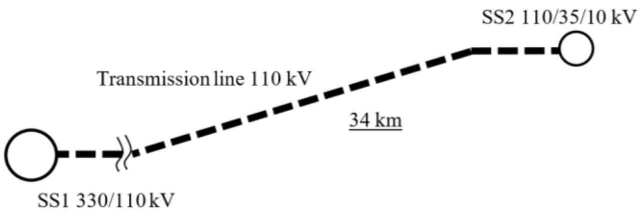

Fig. 1. Diagram of a radial electrical grid

The power supply center of the electrical grid (Fig. 1) is substation SS1 with a voltage level of 330/110 kV.

The length of the supplying TL is L=34 km.

At SS2 (Fig. 1), a photovoltaic power plant is installed and connected to a common switchgear together with the load, which is supplied through a power transformer.

The load of the power transformer at SS2 (Fig. 1) under the maximum load condition of the electrical grid is as follows: on the low-voltage (LV) side, S_{LV}=20 MVA with a power factor cosϕ$_{LV}$=0.93; on the medium-voltage (MV) side, S_{MV}=15.5 MVA with a power factor cosϕ$_{MV}$=0.89.

The short-circuit current is Isc=35 kA. The relay protection at SS2 clears the short-circuit current within t=0.3 s.

Load Calculations of SS 2

Considering the current state of the electrical grid, it can be stated that the integration of renewable energy sources (RES) has the greatest impact on the operational performance of power transformers compared to its impact on transmission lines. However, for the development of substation reconstruction projects with integrated photovoltaic power plants, in accordance with [1], it is critically important to take into account the operating mode of the supplying transmission line and the magnitude of power delivered to the power transformer from the electric power system.

For this purpose, during the analysis of the technological process of electric power transmission supplied from the electric power system, it is necessary to separately consider the active (P) and reactive (Q) power components on all voltage sides of the power transformer under the maximum load condition of the electrical grid. These quantities are calculated according to the following relations [12, 13]:

$$P_{LV} = S_{LV} \cdot cos\,\varphi_{LV} \qquad Q_{LV} = S_{LV} \cdot sin\,\varphi_{LV}; \tag{1}$$

$$P_{MV} = S_{MV} \cdot \cos\varphi_{MV} \qquad Q_{MV} = S_{MC} \cdot \sin\varphi_{MV}; \tag{2}$$

$$S_{HV} = S_{LV} + S_{MV};\ P_{HV} = P_{LV} + P_{MV}; Q_{HV} = Q_{LV} + Q_{MV} \tag{3}$$

where S_{LV}, S_{MV}, cosφ$_{LV}$, cosφ$_{MV}$ are taken from the input data

From calculations (1) – (3), the power was determined as follows:

- on LV side of the power transformer –

S_{LV} = (17,8 + j9,12) MVA;

- on MV side of the power transformer–

S_{MV} = (14,42 + j5,69) MVA;

- on HV side of the power transformer–

S_{HV} = (32,22 + j14,81) MVA.

Justification of the Rated Voltage of the Analyzed Electric Power Transmission System

Since the electric power transmission system has a radial electrical grid topology (Fig. 1), an active power of P_{HV}=32.22 MW flows through the transmission line.

The justification of the nominal voltage of the electrical grid is performed using a formula that provides satisfactory results over the entire range of nominal alternating-current voltage levels from 35 to 1150 kV [12, 13]:

$$U_{nom} = 1000/\sqrt{(500/L + 2500/P_L)}, \tag{4}$$

where L – length of the line, km; $P_L = P_{HV}$ – power transmitted through the line, MW.

The results of the calculations for the justification of the rated voltage of the electrical grid according to (4) yield U=104.17 kV. This indicates that electric power transmission is carried out at a nominal voltage level of 110 kV. The determination of the nominal voltage class is necessary for selecting the current-carrying component of the transmission line.

Selection of the Current-Carrying for a 110 kV Transmission Line

The selection of the current-carrying component of the 110 kV transmission line “SS1–SS2” is carried out in accordance with the Electrical Installation Regulations (PUE) [14] and SOU-N MEV 40.1-37471933-49:2011 [15].

According to [14] and [15], the current-carrying components of the transmission line are recommended to be implemented as follows:

- for the OL 110 kV: using an ACSR 2(240/32) mm² conductor;
- for the CL 110 kV: using an APvEgP-110 1×240 mm² cable laid in a trench.

The short-circuit current through the cable screen (Iscr) for this cable type, assuming a short-circuit duration of t=1s, is determined by the following expression [15]:

$$I_{scr} = I_{scr} \cdot \sqrt{t}\,. \tag{5}$$

According to the input data and Eq. (5), the screen short-circuit current is Iscr=19.2 kA. For this short-circuit current, a copper screen with a cross-sectional area of 95 mm² is required [15]. Thus, the current-carrying component of the 110 kV cable line should be implemented using an APvEgP-110 1×240/95 cable.

Verification of the Current-Carrying Component of the 110 kV Transmission Line

110 kV Overhead Line. According to [12], the verification of the current-carrying component of the 110 kV overhead line is performed based on the permissible continuous current-carrying capacity using the following expression:

$$I_{calc.TL} \le I_{perm}, \qquad (6)$$

where $I_{\text{calc TL}}$ is the calculated current flowing through the overhead line under the maximum operating condition; I_{perm} is the permissible continuous current-carrying capacity of the conductors for the temperature range from +25∘C to 70∘C.

The calculated current ($I_{\text{calc TL}}$) for verifying the conductors of the 110 kV TL is determined by the following expression [13, 14]:

$$I_{calc.TL} = S_{HV(max)}/(\sqrt{3} \cdot U_{nom}), \qquad (7)$$

where $S_{HV(msx)}$is the load on the HV side of the power transformer located at SS 2 (Fig. 1).

Based on the results of calculation (7), the calculated current $I_{calc.TL}$=186.5 A.

The permissible continuous current-carrying capacity (I_{perm}) for verifying the conductors of the 110 kV overhead line is determined by the following expression:

$$I_{perm} = I_{max} \cdot k_{\theta}, \qquad (8)$$

where k_θ is the temperature correction factor for ambient air temperature in the given region during the maximum load period, determined in accordance with [14], and for the Eastern region of Ukraine, it equals k_q = 1,24.

For the conductors of the 110 kV overhead line with a cross-sectional area of 240/32 mm², the maximum current-carrying capacity (I_{max}) is Imax=605 A [12, 13]. Accordingly, the permissible continuous current (I_{perm}) is determined as follows:

$$I_{perm} = 605 \cdot 1{,}24 = 750{,}2 \ A.$$

Thus, the ACSR 240/32 mm² conductor is capable of ensuring the technological process of electric power transmission for the OL 110 kV n terms of permissible current-carrying capacity under heating conditions.

110 kV Cable Line. According to [15, 16], the verification of the current-carrying component of the CL laid in a trench is performed based on the permissible continuous current-carrying capacity using the following expression:

$$I_{calc} \le I_{perm}, \qquad (9)$$

where I_{calc} is the calculated current corresponding to the average half-hour maximum current, the highest value among the average half-hour currents of a given grid element; I_{perm} is the permissible continuous current for the corresponding cable conductor cross-section.

The calculated current ($I_{calc\ CL}$) for verifying the 110 kV cable is determined by the following expression [15]:

$$I_{calc\ CL} = S_{HV(max)}/(\sqrt{3} \cdot U_{nom}), \qquad (10)$$

where $S_{HV(\text{нб})}$ is the load on the HV side of the power transformer located at SS 2 (3).

According to the results of calculation (10), the $I_{calc\ CL}$=186.5 A. The permissible continuous current (I_{perm}) for the conductor cross-section of the APvEgP-110 1×240/95 cable, taking into account the correction factors (k_Σ), is determined in accordance with the methodology described in [15] using the following expression:

$$I_{perm\ CL} = I_{perm\ table} \cdot k_{\Sigma}, \qquad (11)$$

where $I_{\text{perm.table}}$ - permissible continuous current for 110 kV cables with cross-linked polyethylene (XLPE) insulation and a nominal conductor cross-section of 240 mm² is 422 A [15].

It should also be taken into account that the permissible continuous current of the cable line $I_{\text{perm CL}}$ must be adjusted to account for cable laying and operating conditions using correction factors [15, 16].

The values of the correction factors (k_Σ) for the Eastern region of Ukraine were determined in accordance with [14, 15].

The permissible current for the given conditions of cable installation in a trench was calculated using expression (11) and, taking into account the correction factors [14, 15], amounts to $I_{\text{perm CL}}$ = 383,0 A. This confirms the adequacy of the 240 mm² conductor cross-section under the selected installation conditions.

Thus, the XLPE-insulated cable of type APvEgP-110 1×240/95 is capable of ensuring the technological process of electric power transmission for the CL 110 kV in terms of permissible current-carrying capacity under heating conditions.

Parameters of the 110 kV Transmission Line

110 kV Overhead Line. The calculation of the parameters of the 110 kV overhead line is performed using the expressions given in [13]:

$$R_{TL} = r_0 \cdot L;\ X_{TL} = x_0 \cdot L;\ B_{TL} = b_0 \cdot L; Q_{ch} = q_0 \cdot L, \qquad (12)$$

where r_0, x_0, b_0, q_0 – parameters per 1 km of line length with an ACSR 240 mm² conductor [13].

The results of the calculations using expressions (12) are as follows:

R_{TL} = 4,08 Ohm; X_{TL} = 13,77 Ohm;

B_{OL} = 95, 54 10^{-6} cm; Q_{ch} = 1,28 MVar.

110 kV Cable Line. The calculation of the parameters of the 110 kV cable line (Fig. 3) is performed using the expressions given in [13]:

$$R_{CL} = r_0 \cdot L;\ X_{CL} = x_0 \cdot L;\ B_{CL} = b_0 \cdot L; Q_{ch} = q_0, \cdot \qquad (13)$$

where r_0, x_0, b_0 are the specific parameters of the APvEgP-110 1×240/95 cable [13]; q_0 is the specific charging current, defined as $q_0 = b_0 \cdot U_{\text{ном}}^2$.

The results of the calculations using expressions (13) are as follows:

R_{TL} = 5,37 Ohm; X_{TL} = 6,53 Ohm;

B_{OL} = 1611,6 10^{-6} cm; Q_{ch} = 19,5 MVar.

In addition, for the 110 kV cable line, dielectric losses (ΔP_d) are calculated using the following expression:

$$\Delta P_d = \Delta P_{d.0} \cdot L_{TL}, \qquad (14)$$

where ΔP_{d0} - specific dielectric losses

$$\Delta P_{d.0} = g_0 \cdot U^2, \qquad (15)$$

where g_0 is the specific active conductance of the 110 kV cable line, S/km:

$$g_0 = b_0 \cdot \tan\delta, \qquad (16)$$

where $\tan\delta$ = 0,006 the dielectric loss tangent of the insulation at phase voltage [15].

The dielectric losses in the 110 kV cable line calculated using expressions (14)–(16) are as follows:

$$\Delta P_d = 0{,}1168 \text{ МВт}.$$

The parameters of the overhead and cable lines are used in the analysis of the technological process of electric power transmission and voltage levels in the studied electrical grid.

Analysis of the Technological Process of Electric Power Transmission

Since the repair of a damaged cable line takes more time than that of an overhead line, the analysis of the technological process of electric power transmission for the cable line is performed for a single cable circuit.

The investigated electric power transmission system is implemented with a radial electrical grid configuration (Fig. 1), which, for the analysis of the technological process under the maximum load condition of the electrical grid, is represented in Fig 2.

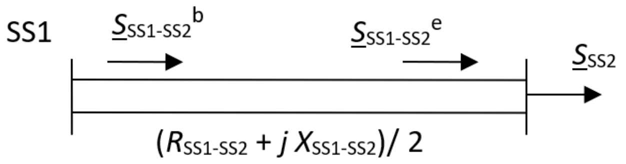

Fig. 2. Electrical grid diagram for the analysis of the technological process

The analysis of the technological process of electric power transmission under the maximum load condition of the electrical network, based on expressions (1)–(3) and the scheme shown in Fig. 2, was performed using the PowerFactory software package and is presented in Fig 3.

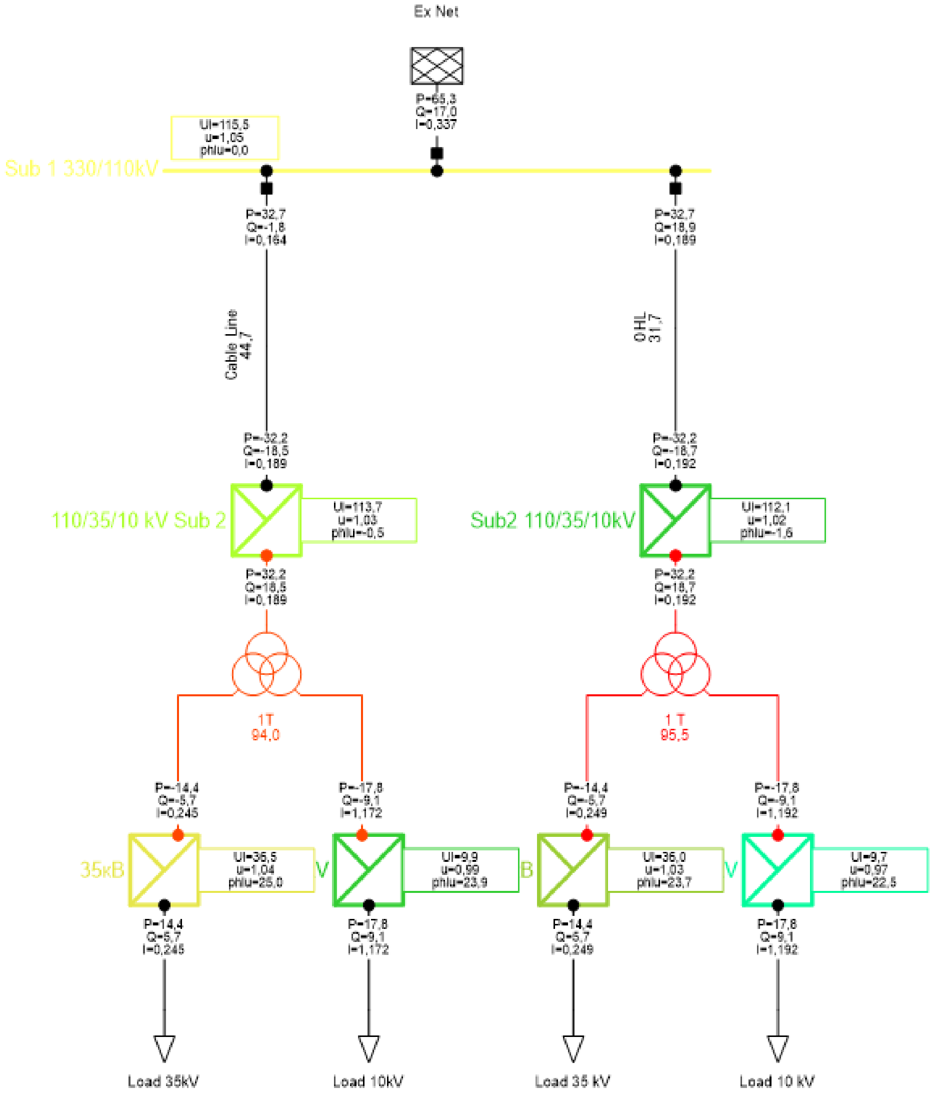

Fig. 3. Graphical representation in PowerFactory of the electrical network maximum operating conditions for the overhead line (right) and the cable line (left)

According to Fig. 3, the power transmitted via the 110 kV overhead line to the power transformer located at SS 2 is as follows:

– on the high-voltage (HV) side of the power transformer S_{HV} = (32,22 + j18,7) MVA;

– on the medium-voltage (MV) side of the power transformer – S_{MV} = (14,4 + j5,7) MVA;

– on the low-voltage (LV) side of the power transformer S_{LV} = (17,8 + j9,1) MVA.

According to Fig. 3, the power transmitted via the 110 kV cable line to the power transformer located at SS 2 is as follows:

– on the high-voltage (HV) side of the power transformer S_{HV} = (32,22 + j18,5) MVA;

– on the medium-voltage (MV) side of the power transformer S_{MV} = (14,4 + j5,7) MVA;

– on the low-voltage (LV) side of the power transformer S_{LV} = (17,8 + j9,1) MVA.

Based on the results of the maximum operating condition analysis of the electrical grid performed in PowerFactory (Fig. 3), it follows that the technological performance indicators of electric power transmission for the overhead and cable lines are equivalent. The difference between the analytical calculations (1)–(3) and the simulation results (Fig. 3) is less than 3%, which confirms the reliability of the obtained data.

Analysis of Electric Power Quality Parameters

One of the main reliability indicators of an electric power transmission system is the voltage deviation ((ΔU), which is regulated in accordance with [17, 18]. Using the calculation results (Fig. 3), the voltage drop is determined as a function of the electric power transmission method using the following expression [13]:

$$\Delta U^b_{SS1-SS2} = (P^b_{SS1-SS2} \cdot R_{SS1-SS2} + Q^b_{SS1-SS2} \cdot X_{SS1-SS2})/U_{SS1}, \qquad (17)$$

where $P^b_{SS1-SS2} + jQ^b_{SS1-SS2}$ - the power transmitted through the TL (Fig. 3);$R_{SS1-SS2} + jX_{SS1-SS2}$ – the parameters of the OL (12) and the CL (13)

The percentage voltage deviation is calculated according to the following expression [13]:

$$\Delta U_* = \left(\frac{\Delta U}{U_b}\right) \cdot 100 = \left(\frac{PR+QX}{U_b^2}\right) \cdot 100. \qquad (18)$$

The results of the calculations using formulas (17)–(18) are presented in Table 1.

As follows from Table 1, the voltage deviation under the maximum operating condition of the electric power transmission system for both transmission line options lies within ±5%, which confirms compliance with power quality requirements [17, 18] and the equivalence of the analyzed alternatives.

Table 1. Voltage parameters of the electric power transmission system for overhead and cable lines

Parameters	OL	CL
U_{SS1}, kV	115,5	115,5
U_{SS2}, kV	112,1	113,7
$\Delta U_{SS1\text{-}SS2}{}^b$, kV	3,4	1,8
ΔU, %	3,01	1,64

Economic Justification of the Electric Power Transmission System

For problems that do not require the determination of overall evaluation efficiency, it is possible to calculate the cost component of the integral effect of total discounted costs (C). This indicator is recommended to be used as the main criterion for tasks in which the construction of energy facilities extends over more than one year and the operating parameters change throughout the calculation period [19, 20].

In the calculations, monetary symbols are treated as monetary units (m.u.).

In static problems, the indicator (C) is determined by the expression given in [20].

$$\mathrm{C}_{constTL} = C_{OL} + C_{OL}/\mathrm{E}\,;\; C_{constCL} = C_{CL} + C_{CL}/\mathrm{E}, \qquad (19)$$

where $C_{const\mathrm{TL}}$, $C_{const\mathrm{CL}}$ the construction cost of the line, which is determined based on aggregated cost indicators of electrical grid elements; C_{OL}, C_{CL} annual costs, which are determined without taking into account depreciation charges for renovation, m.u; E is the real (net) discount rate, which is adopted in accordance with the recommendations of the Ministry of Economic Development and Trade of Ukraine, as specified in the Letter on the preparation of state investment projects, and is equal to 12% [21].

Based on the above, K_{OL} is calculated using the following expression [20]:

$$C_{TL} = \mathrm{K}_0 \cdot L_{TL}, \qquad (20)$$

where κ_{o} is the cost per 1 km of the 110 kV transmission line, determined in accordance with [15, 17]; L_{TL} is the line length.

The annual costs for operation and maintenance TL (B_{OMTL}) are calculated using the expressions given in [20]:

$$C_{OMOL} = \alpha_{OMTL} \cdot C_{OL}; \quad C_{OMCL} = \alpha_{OMTL} \cdot \mathrm{K}_{CL}, \qquad (21)$$

where α_{OMTL} = 0,012 for 110 kV lines – the annual operation and maintenance and repair costs of transmission lines expressed as a percentage of the fixed asset value of the transmission line, m.u.

The results of the calculations using formulas (19) – (21) are presented in Table 2.

Table 2. Economic indicators of the electric power transmission system for power transmission via overhead and cable lines

Indicators	OL	CL
C_{TL}, m.u.	1 394 000	2 346 000
C_{OMTL}, m.u.	16 728	28 152
C, m.u.	1 533 400	2 580 600

Since, in [19], the construction cost values of 110 kV electrical networks are given in U.S. dollars and were adopted in the calculations as monetary units (r.u.) (Table 2), conversion to the national currency is performed using the official exchange rate of the National Bank of Ukraine (NBU) at the time of the calculations. Using the coefficient κ_{NBU}=42.02 UAH per 1 m.u. as of July 2025, the cost component of the integral effect of total discounted costs (19), without taking inflation into account, is as follows:

- for OL 64 433 468 UAH;
- for CL 108 436 812 UAH.

As follows from the calculations, the cost component of the integral effect of total discounted costs for the 110 kV cable line is 59.4% higher compared to the corresponding value for the 110 kV overhead line.

The obtained results of the calculations of technical performance indicators and the cost component of the integral effect of total discounted costs for the overhead and cable lines necessitate conducting a SWOT analysis of the project in order to substantiate the selection of the most appropriate transmission line option.

SWOT Analysis

Using the SWOT analysis components of a project presented in [22], a comparison of electric power transmission systems with overhead and cable lines was performed.

Project 1. Electric Power Transmission System with a 110 kV Overhead Line

Strengths

1. Maximum separation from populated areas;
2. Low project implementation cost.

Weaknesses

1. A large number of crossings with road infrastructure;
2. Complexity of crossing railway lines;
3. The need to coordinate land acquisition and right-of-way along the line route with landowners.

Opportunities

1. Accelerated project implementation.

Threats

1. A low level of operational safety during line operation;
2. Issues related to adverse weather conditions;
3. Problems associated with force majeure events caused by third parties.

Project 2. Electric Power Transmission System with a 110 kV Cable Line

Strengths

1. Minimal impact on the environment;
2. Significant improvement in safety;
3. Ensured uninterrupted operation of critically important infrastructure even under adverse weather conditions;
4. Low maintenance costs during the operational period and, consequently, a long-term economic advantage.

Weaknesses

1. A large volume of approvals required from various organizations;
2. High capital cost (59.4% higher compared to the overhead line).

Opportunities

1. Comprehensive resolution of technical, operational, environmental, land-use, and social issues.

Threats

1. The risk of extending the project implementation timeline by 1–1.5 years.

Conclusion of the SWOT Analysis

As follows from the above, based on the conducted SWOT analysis, Project 2 is more attractive, whereas Project 1 is less attractive.

Conclusions

A study of the reliability of an electric power transmission system with a photovoltaic power plant was carried out through a comprehensive analysis of the techno-economic characteristics of overhead and cable transmission lines. This approach enables a well-founded decision to be made regarding the selection of the appropriate facility under conditions of equivalent technical parameters of the electrical grid.

Based on the research results, it was established that: the overhead and cable lines have the same current-carrying conductor cross-section of 240 mm²; the overhead and cable lines are characterized by equivalent technical performance indicators; the cable line is 59.4% more expensive than the overhead line; according to the conducted SWOT analysis, the project employing a cable line is more attractive compared to the project based on an overhead line.

Thus, in order to enhance the reliability of an electric power transmission system with a photovoltaic power plant, under conditions of equivalent technical parameters of the electrical network and taking into account the combined indicators of the comprehensive techno-economic analysis, the application of a cable line is more reasonable than the use of an overhead line.

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