Nataliya Komenda[1], Vladyslav Volynets[2], Iryna Hrytsiuk[3], Irina Bandura[4],
Mykola Romaniuk[5]

Estimation of the total influence of methods for increasing the line natural load

Abstract: Studies aimed at the economically sound increase in the capacity of existing power lines and improvements in their design are relevant today. In addition to the well-known design methods of influencing the capacity of the transmission line, there are other meanings that can affect its natural capacity, which is directly related to the capacity. Therefore, the purpose of this study was to find possible methods of increasing natural power and evaluate their effectiveness in real configurations. The basis of the methodological approach applied in this study is a qualitative combination of methods of systematic analysis of ways to increase the capacity of power lines with the analytical investigation of the prospects for its impact on wave resistance to increase the natural power of the line. The conducted research determined the total influence of the analyzed factors on the in-

✉ Corresponding Author: Mykola Romaniuk; e-mail: mykolaromaniuk@ukr.net

[1] Department of Electrical Engineering, Lutsk National Technical University, Lutsk, Ukraine; ORCID iD: 0000-0002-5944-8665; e-mail: nataliyakomenda@outlook.com

[2] Department of Electrical Engineering, Lutsk National Technical University, Lutsk, Ukraine; ORCID iD: 0000-0002-9192-2785; e-mail: V.Volynets1973@outlook.com

[3] Department of Electrical Engineering, Lutsk National Technical University, Lutsk, Ukraine; ORCID iD: 0000-0003-4472-306X; e-mail: iryna_hrytsiuk@hotmail.com

[4] Department of Electrical Engineering, Lutsk National Technical University, Lutsk; ORCID iD: 0000-0003-2166-4909; e-mail: irina.bandura@hotmail.com

[5] Department of Electrical Engineering, Lutsk National Technical University, Lutsk, Ukraine; ORCID iD: 0000-0002-1039-1004; e-mail: mykolaromaniuk@ukr.net

crease in transmission capacity and identified the most optimal configuration from a technical and economic standpoint. Based on the results of the calculation of the natural capacity of the configurations, conclusions were made about the significance of the impact of each of the above factors, and the economic effect of their implementation in the integrated power system was established. Improvement of this methodology can, in the long run, serve as a tool for calculating configurations for economic and technical relevance, or serve as a foundation for further identification of factors affecting the transmission capacity of power lines.

KEYWORDS: electric field of power lines, mathematical model, power and electrical engineering, analytical investigation, transmission capacity

Introduction

The trend of increasing electricity consumption in the world has been reflected in many studies and is already a common reality (Zhang et al. 2023), which leads to a number of pressing issues related to the need for the continuous modernization of the existing energy system. The changes concern all stages of interaction with electricity: production, distribution, and consumption. Most items of Ukraine's energy strategy until 2030 (Law No. 605… 2017) are aimed at increasing generating capacity and improving electricity quality, but not much attention is paid to electricity transmission and distribution, and especially new means of increasing transmission capacity.

Currently, increasing the capacity transmitted over the network requires large investments. As electricity consumption increases, grid companies have to renovate existing networks with increasingly sizable wire cross sections and increasing wire mass (Kaplun et al. 2022). Eventually, companies will face the replacement of existing grid pylons with new alternatives designed for higher loads, or the construction of new transmission lines. The latter can be complicated, especially when the route of the overhead line (OHL) is located in densely populated areas and sparsely populated areas of private lands, such as national parks, reserves, and other areas where construction is prohibited (Deepak Selvakumar et al. 2023). Despite the extensive experience and research by scientists in this subject area, decision-making in the design of power systems and transmission lines is performed in the absence of clear comprehensive scientifically sound recommendations and methods. This limits the ability to assess the technical and economic performance of decisions at the design stage of OHL and leads to insufficient effectiveness of design decisions. As practice shows, the market relations that have developed between the subjects of design decisions require a new scientific approach, primarily in the strategy of the development of transmission lines and the power system in general.

Comprehensive, and scientifically sound recommendations and methods in designing power systems and transmission lines are crucial for several reasons. Power systems and transmission lines are critical infrastructure components. Reliable operation is essential to prevent blackouts,

ensure continuous power supply, and maintain public safety. Clear recommendations help in the designing of systems that meet these reliability requirements. The optimal design of power systems and transmission lines can result in cost savings, reduced energy losses, and increased efficiency. Scientifically sound methods can identify the most efficient configurations and technologies. The existing solutions may be insufficient because they may not adequately address the evolving challenges and opportunities in the energy sector. Rapid technological advancements, changing energy demands, and the need for sustainability require continuous research and development of updated guidelines and recommendations. The research aims to contribute to filling this gap by providing a systematic and up-to-date approach for designing power systems and transmission lines that considers both efficiency and economic factors. By offering clear and scientifically sound recommendations, our research aims to empower decision-makers with the tools and knowledge needed to design and operate resilient, efficient, and sustainable power systems that meet the demands of the modern world.

The main areas in improving the structure of the transmission line should primarily include increasing the capacity of transmission lines and reducing losses from environmental impact and utilities (Hasan and Agarwal 2023). However, the most urgent problem is the increase in transmission capacity. The search for the optimal solution can first create a significant economic effect in the process of the modernization of existing transmission lines and become a solid foundation for identifying shortcomings in transmission line designs, recent changes to which were made in the late twentieth century. After all, the proposed solutions can often be aimed at solving a single problem, rather than solving the problem comprehensively. A striking example is the attempt to use new types of wires in combination with old support structures, or the use of simple methods in relation to outdated OHLs, that do not have a significant economic effect. The solutions to increase throughput can be divided into two most commonly used areas: design (change in composition, shape of the wire layout, use of reactive power compensators, lines made of second generation superconductors) (Bondarenko and Lavrinovich 2007; Xiao et al. 2023); physical (direct impact on natural power through more optimal solutions from the standpoint of physics, for example, changes of the quantity of components in a phase, influence on sagging of a wire, use of ultra-long lines, influence on distance between phases) (Sadovoy et al. 2021; Song and Teh 2023). Investigating methods for increasing transmission capacity is significant within the context of existing energy challenges. As global populations and economies continue to expand, there is an ever-increasing demand for electricity. To meet this demand, it is essential to enhance the capacity of existing transmission systems to efficiently deliver electricity over long distances. Energy challenges such as extreme weather events, wildfires, and cyberattacks have highlighted the vulnerability of power grids. Enhancing transmission capacity can improve grid resilience by enabling power to be rerouted and distributed more effectively in the face of disruptions.

The objective of this study is to develop a systematic approach for identifying the most efficient and economically viable methods to enhance the transmission capacity of power lines. Additionally, the study aims to categorize and evaluate the primary methods that influence the inherent capacity of these lines. Tasks include the idemtification and compilation of a comprehensive list of methods and techniques used for increasing the transmission capacity of power li-

nes. This should encompass both conventional and innovative approaches. Determine how each method affects the inherent capacity factors mentioned above and establish a framework for quantifying this influence.

1. Materials and methods

The study was conducted in three main stages.
In the first stage:
✦ A number of existing solutions were analyzed to increase the transmission capacity, methods of influencing the impedance and phase stress, which became the basis for further configuration and derivation of methods to assess their effectiveness.
✦ An analysis of each factor was performed to determine the level of capacity to influence the line capacity.
✦ The results of researches on the use of isolation in high-voltage wires, constructive changes in resistance and use of wires with the increased thermal stability and conductivity were considered.
✦ The type of wire with the highest transmission capacity for further use in configurations is singled out.
✦ Means of synchronous compensation as a potentially promising means of increasing natural capacity were analyzed.
At the second stage:
✦ A detailed analytical investigation of the method of increasing transmission capacity by introducing a layer of insulation for high-voltage wires was carried out.
✦ In addition to the main properties, for which this method was considered, other quite significant properties were identified that would give preference to the thermal component of the process of impact on natural power.
✦ The method of determining the optimal insulation thickness based on the heat balance equation was considered.
✦ The level of influence of line insulation on phase capacitance was determined.
At the third stage:
✦ Modelling of line configurations, different in phase placement and number of components, was performed. To do this, the method of mirror mappings was adapted to calculate the line voltage, and based on it, a number of simulation programs were built, which allowed calculating and generating the data necessary for further analysis.
✦ The most optimal design options were identified and the dependences of natural power on the above factors were constructed.
In addition, at this stage, three characteristic configurations based on the analyzed means are synthesized. To determine the effectiveness of increasing their capacity, an equation for calcula-

ting the line impedance was derived, which is considering most of the accepted factors and used to calculate natural power and compare with the standard version of high-voltage power lines. An analytical comparison of the natural power of the configuration with the existing insulation layer (presented in the form of a coaxial wire), with the line in the standard for modern design activities.

In the last stage, based on the results obtained during the modelling, the final conclusions of the study were formulated, which serve as a final reflection of the importance of compiling the optimal configuration of power lines in design to increase maximum line capacity. In general, the results and conclusions obtained show the effectiveness of combined solutions to increase line capacity and to provide a simple and cost-effective means of modernising existing lines; it can also serve as a scientific basis for further improvement of performance measurement methods and configuration in terms of natural power.

2. Results

A scientific study to assess the total impact of methods of increasing the natural power of the transmission line gave the following results. Based on equation (1), it is determined that the effect on natural power can be carried out only through the wave resistance (zhv) because the voltage U in the grid is, conditionally, a constant. Then, according to equation (2), it becomes clear that the methods of influencing the natural power of the line are reduced to a direct effect on the parameters that make up the impedance: capacitance and inductance of the lines.

However, it was found that the common equation (2) for calculating the wave resistance of transmission lines does not objectively assess the value of the impact of certain methods of influence. Therefore, a number of decisions were made to evaluate the proposed methods and the transition to equation (3); lines are represented by the ratio of the sum of the resistivity with the specific inductance of the line to the sum of the conductivity and capacitance of the line:

$$P_n = 3U_{ph.n}I_n = 3\frac{U_{ph.n.}^2}{z_w} = \frac{U_{nom.}^2}{z_w} = 3\frac{U_{ph.n.}^2}{v_w L} = 3U_{ph.n.}^2 v_w C =$$
$$= 3U_{ph.n.}^2 q v_w = 6\pi\varepsilon_0 v_w r_0 U_{ph.n.}E \tag{1}$$

where:

P_n – natural power,
$U_{ph.n.}$ – nominal phase voltage,
I_n – nominal current,
z_w – wave resistance,
$U_{nom.}$ – nominal linear voltage,
L – line inductance,

v_w –   wave conduction,
C –   line capacity,
q –   charge at the beginning of the line,
ε_0 –   the value of the electrical constant ($8.8541878128 \cdot 10^{-12}$),
r_0 –   radius of a single wire.

$$Z_w = \sqrt{\frac{L}{C}} \tag{2}$$

where:

Z_w –   wave resistance,
L –   line inductance,
C –   line capacity.

Because the equation of wave resistance, which expresses it as the root of the ratio of the inductance of the line to its capacitance, does not sufficiently reflect all the influencing factors, turn to the record given in (Leenders 2007):

$$Z_w = \sqrt{\frac{r_0 + jx_0}{g_0 + jb_0}} \tag{3}$$

where:

$x_0 = \omega L_0$ –   specific inductive resistance of wires (phases) of the line [Ohm/km],
$b_0 = \omega C_0$ –   specific capacitive conductivity of wires (phases) of the line [cm/km],
r_0 –   specific active resistance of wires (phases) of the line [Ohm/km],
g_0 –   active transverse conductivity of wires (phases) of the line [cm/km], determined by the expression: $g_0 = \dfrac{\Delta P_{cr.av}}{U_{nom}^2}$, where $\Delta P_{cr.av}$ – average annual loss per crown.

Since the phases are split in the analyzed transmission lines, the Mayer's formula is used to calculate the corona losses:

$$P_k = k \cdot n \cdot f \cdot r_0^2 \cdot E_e \left(E_e - E_k \right) \cdot \left(2.31 lg \frac{1350 E_e}{f \cdot r_0} - 1 \right) \cdot 10^{-5} \tag{4}$$

where:

n –   the number of wires in phase,
f –   frequency [Hz],
r_0 –   radius of a single wire,

E_k – corona intensity [kV/cm],
E_e – equivalent tension [kV/cm],
k – weather ratio.

The equivalent voltage is found by the equation:

$$E_e = \frac{E_{max} - E_{av}}{2} \qquad (5)$$

Average voltage for split wire:

$$E_{av} = \frac{U_{av}}{n \cdot r_0 \cdot ln \dfrac{S}{r_{eq}}} \qquad (6)$$

Maximum tension:

$$E_{max} = k_y \cdot E_{av} \qquad (7)$$

where:

$k_y = 1 + (n-1) \cdot \dfrac{r_{eq}}{r_s}$; $r_{eq} = \sqrt[n]{n \cdot r_0 \cdot r_s^{n-1}}$ – equivalent radius of a single wire having the same capacitance as the split phase,

r_s – split phase radius,
S – wire section.

The disadvantage of Mayer's formula is that all the variety of weather conditions is reduced to two groups of weather: "good" weather ($k = 44$; $E_k = 17$ kV/cm) and "bad" weather ($k = 31.5$; $E_k = 11$ kV/cm). To determine the loss on the crown during the year, energy losses are calculated for each weather group and then summed according to the duration of the group during the year:

$$\sum P_k = \sum_{i=1}^{4} P_{ki} \cdot \psi_i \qquad (8)$$

where:

ψ_i – relative duration of the weather group,
P_{ki} – average annual power losses of i-the weather group.

The use of ACCC, ASSR, ZTACIR, and Aero-Z (the abbreviations ACCC, ASSR, ZTACIR, and Aero-Z refer to specific types of composite wires or materials) composite wires as a method for influencing the resistivity. The main advantage is the use of alloys that significantly improve

the throughput of the line due to their thermal and electrical performance (Selvakumar et al. 2023). This is conditioned by the use of alloys such as aluminum-zirconium or invar, which have a much lower specific cross section at the same cross section, and improved mechanical properties. This wire can improve throughput up to 2.5 times. It was found that the implementation of Z-shaped wire weaving leads to improved natural cooling of the wire. Of great interest is the use of insulated wires in high voltage lines. Among the advantages are increased thermal stability and line capacity. The factor affecting the capacitance is changes in the distribution of field strength, which increases the capacitance and leads to a decrease in impedance. Some studies confirm this effect, which provide the results of the calculation to determine the electric field strength in wires with existing and absent insulation (High temperature low… 2008). The field strength on the electrode surface is determined by the calculated charge density $E_i = \dfrac{\sigma_i}{\varepsilon_0}$ and for the distribution limits of dielectric media:

$$E_i = \frac{\sigma_i}{2\varepsilon_0}\left(1 + \frac{1}{\alpha}\right) \tag{9}$$

where:

α – parameter related to the dielectric constant of adjacent media: $\alpha = (\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + \varepsilon_1)$.

True density σ′ charges on the surface of the core, which is insulated by a dielectric with relative dielectric constant ε_2, more than ε_2 times (Bezprozvannych and Naboka 2012). The required capacitance is defined as the ratio of the true charge to a given phase voltage. The wire is in the air with dielectric constant $\varepsilon_1 = 1$. The results of the calculation are shown in Figure 1. Curve 1 – optimal insulation thickness (3.2 mm) and Curve 2 – 33% less than optimal (2.3 mm) for shielded wire made of cross-linked polyethylene insulation: (relative dielectric constant) $\varepsilon_2 = 2.3$. Curve 3 – wire with oxide insulation 100 nm thick (relative dielectric constant $\varepsilon_2 = 9$: for a continuous oxide film obtained, for example, by the method of high-voltage oxidation, the value of the relative dielectric constant is $\varepsilon = 8$–10 on the frequency 50 Hz). Section I (0–0.04) is the stress distribution on the core surface, Section II (0.04–0.11) is on the insulation surface. It can be concluded that the insulation has a really positive effect on the voltage distribution, and hence, on the capacitance of the line and on its natural power.

Having determined the presence of on influence of insulation on natural power, it is necessary to assess its real value, creating a configuration based on the presented method and comparing it with the value of natural power of the standard configuration of power lines. To do this, it is necessary to determine the impedance, and equation (3) is not able to take into account the changes, because it is not intended for the calculation of insulated wires. To solve this problem, the study considers the physical content of the problem. The current configuration is a coaxial wire model (Fig. 2). The calculation of the impedance for the coaxial wire was presented in previous work (Bezprozvannych and Naboka 2012).
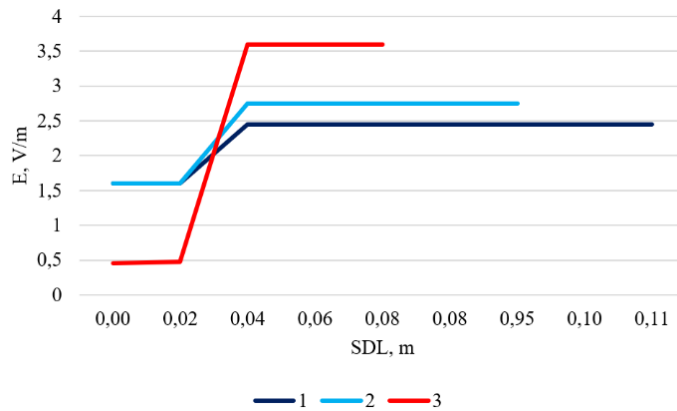
Fig. 1. Influence of relative dielectric constant and thickness on the distribution of electric field strength
on the surface of the wire
Note: SDL corresponds to the abbreviation "sum of DL" – the sum of many sections of short length

Rys. 1. Wpływ względnej stałej dielektrycznej i grubości (SDL odpowiada skrótowi "sum of DL" – suma wielu
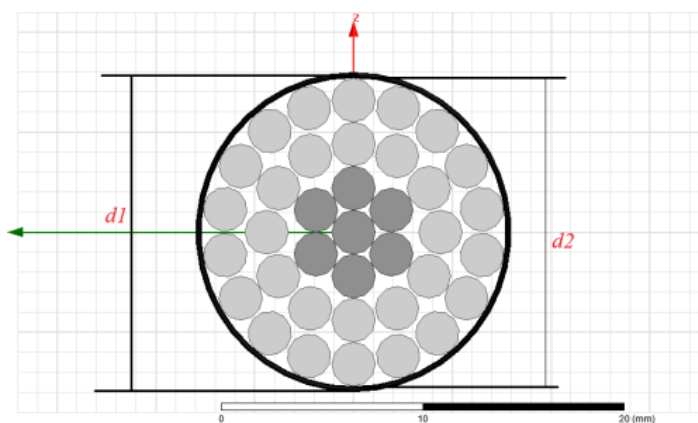odcinków o niewielkiej długości) na rozkład natężenia pola elektrycznego na powierzchni drutu

Fig. 2. Model of coaxial wire

Rys. 2. Model przewodu koncentrycznego

$$Z_w = \frac{138}{\sqrt{k}} log \frac{d_1}{d_2}$$

(10)

where:

    k –   dielectric constant of the insulating layer,

    d_1, d_2 –   outer and inner diameter of the coaxial wire.

According to the above equation, the natural power for the configuration of power lines where the wire is insulated is 14.9% more than for a similar line without insulation. However, for the above reasons, it is difficult to accurately estimate its impact on natural line power. Its complexity lies in the absence of an equation that would accurately describe the interaction of metal-insulation and insulation-air, and therefore, there is no possibility of the objective reflection of reality. An unobvious effect was revealed: the creation of conditions for maximum convergence of phases, which is one of the factors influencing the natural power of the line. This effect allowed shifting the vector of research towards the design features of the supports. To investigate the impact of changes in the design features of transmission lines, the method of mirror images was adapted and a program for modelling and configuration of transmission lines was developed based on identified influencing factors. These include: phase distance, number of components in the phase, and the splitting step. Modelling is performed and regularities are revealed, according to which, the line capacity changes depending on the change of the above parameters. The convergence of phases was found, reducing the number of components and increasing the step of cleavage. The simulation results for the 330 kV line is shown in Table 1.

TABLE 1. The simulation results obtained in the program

TABELA 1. Wyniki symulacji uzyskane w programie

d_0	a	n	iq	$Q_{\max}$	iE	$E_{\max}$	Ca	Cb	Cc	Co	Zv	Pn
1	2	3	4	5	6	7	8	9	10	11	12	13
5	40	2	3	$1.649 \cdot 10^{-6}$	3	27.485	11.295	12.242	11.295	11.611	295.969	$3.679 \cdot 10^5$
5	40	3	5	$1.309 \cdot 10^{-6}$	5	21.816	13.227	14.569	13.227	13.674	251.3	$4.333 \cdot 10^5$
5	40	4	7	$1.114 \cdot 10^{-6}$	7	18.56	14.807	16.532	14.807	15.382	223.406	$4.875 \cdot 10^5$
5	40	5	7	$9.895 \cdot 10^{-7}$	7	16.49	16.207	18.316	16.207	16.91	203.218	$5.359 \cdot 10^5$
5	40	6	9	$9.027 \cdot 10^{-7}$	9	15.043	17.498	20	17.498	18.332	187.453	$5.809 \cdot 10^5$
5	45	2	3	$1.671 \cdot 10^{-6}$	3	27.855	11.433	12.407	11.433	11.758	292.266	$3.726 \cdot 10^5$
5	45	3	5	$1.337 \cdot 10^{-6}$	5	22.285	13.481	14.88	13.481	13.947	246.383	$4.42 \cdot 10^5$
5	45	4	7	$1.144 \cdot 10^{-6}$	7	19.071	15.188	16.987	15.188	15.774	217.852	$4.999 \cdot 10^5$
5	45	5	7	$1.023 \cdot 10^{-6}$	7	17.042	16.671	18.918	16.671	17.42	197.265	$5.52 \cdot 10^5$
5	45	6	9	$9.378 \cdot 10^{-7}$	9	15.629	18.067	20.754	18.067	18.963	181.219	$6.009 \cdot 10^5$
5	50	2	3	$1.692 \cdot 10^{-6}$	3	28.195	11.56	12.558	11.56	11.893	288.946	$3.769 \cdot 10^5$
5	50	3	5	$1.363 \cdot 10^{-6}$	5	22.722	13.716	15.171	13.716	14.201	241.98	$4.5 \cdot 10^5$

By combining the above parameters, the configurations of power lines were created, which allowed estimation of the total impact of changes in their design made on the basis of these parameters. The results of calculations according to equations (1) and (3) are summarized in Table 2. As a result of the calculation, values of impedance will be obtained, which can be used to determine the natural voltage. However, a prerequisite for configuration is: $\dfrac{P_{nat.n.conf}}{P_{nat.stand.}} > 1$.

	Configuration 1	Configuration 2	Configuration 3
Wire type	ZTACIR	AS	AS
Splitting step [m]	0.4	0.4	–
Interfacial distance [m]	0.4	3	4
Phase layout	Triangle	Triangle	Triangle
Presence of insulation	cross-linked polyethylene (CLP)	–	–
The number of components in the phase	3	2	1
Profile [mm^2]	40	60	120
Wave resistance	323.37	423.06	495.12
Natural power	37.43	28.60	24.44
Compliance with the condition	1.53	1.17	1

The tabular data indicate that the implementation of methods in OHL's configurations can significantly (more than 1.5 times) increase the efficiency of power transmission lines. Furthermore, it is proposed to consider, fragment by fragment, the features of the influence of each parameter on the performance of the lines.

3. Discussion

The methods considered in the study enabled the creation of effective configurations that significantly increase the natural power of the line, and hence, its capacity. However, the technical and economic performance of these configurations has not been evaluated. The results of calculations shown in Table 1 suggest that Configuration 1 significantly increases the natural power of the transmission line compared to standard (Configuration 3) and upgraded configurations. This is conditioned by the improvement of the following parameters: lower active resistivity of the wire, which is significantly different in design from the widely used brand of AS, reduced interfacial distance (implemented due to the insulating layer), the presence of splitting and the number of components in phase. As a result, it is seen that Configuration 1 is 53% more efficient than Configuration 3, and 30.7% more efficient than Configuration 2.

All these configurations were built primarily in terms of economics and trends. Thus, the method of synchronous compensation is considered. AC transmission systems are conditioned upon the lack of investment that has existed in many electricity grids for many years, which is forcing

more attention to intensifying the use of existing transmission lines, improving the quality of electricity transmitted. As a result, there is a sharp increase in interest in both new and conventional technical solutions, which include flexible AC transmission systems (FACTS – Flexible AC Transmission Systems), such as SVC, SVC Light, TCSC. An example of such tasks could be to increase the capacity of any power line. An attractive solution is to install in the corridor of the power transmission line additional capacitors included in the series compensation circuit (Hrechko et al. 2023). The series-connected capacitor reduces the reactance of the power line at an industrial frequency (50 Hz), while giving the network reactive power. This scheme has the following advantages:

✦ Increase of phase stability: to ensure the transmission of electricity it is necessary to have a certain difference of voltage phases at each end of the transmission line. This phase shift increases with increasing transmitted power, and the series-connected capacitor maintains it within safe limits. In other words, the presence of a capacitor ensures that the phase shift does not exceed the level at which a dangerous loss of phase stability is possible.

✦ Increase the voltage stability of transmission lines.

✦ Optimal power distribution between both parallel circuits: the absence of series capacitors will be the first to enter the saturation mode and will be a transmission line with lower transmission capacity, not allowing any further increase to the power supplied to the system, despite the fact that the second circuit could receive it. In the presence of series capacitors, the power is redistributed between the circuits, which increases the efficiency of the system.

Capacitors connected in series are fully integrated into the power system and use its control, protection and control mechanisms (Bondarenko et al. 2012). Additionally, they are completely isolated from the ground. SVC Light technology is the brand name of ABB's static synchronous compensator based on insulated gate bipolar transistors (IGBT). This technology, based on the use of voltage converters (VSC), also provides the necessary means to maintain the required voltage in the main networks (Korzhyk et al. 2017). The VSC platform is configured as a high-voltage direct current (HVDC) transmission line with a counter-parallel circuit in which priority is given to voltage support using dual SVC Light systems. Of particular importance in this regard is the fact that the ability to transmit active power using HVDC Light inserts or in certain areas, or included in the counter-parallel scheme provides both bidirectional transmission of the active power component and the dynamic reactive power component. This not only maintains the stability of the power transmission regime, but also opens up great opportunities to maintain voltage at the expense of reserve capacity (Gritsyuk et al. 2022).

The benefits of synchronous compensation are obvious, but global trends in electricity indicate a demand for self-compensating power lines, as the same capacitor banks or motors are another link that reduces the reliability of the system and their cumbersomeness necessitates additional infrastructure (Rubino and Rubino 2016). With regard to insulation, there is a difficulty with regard to considering its impact on the natural power of the line. Its complexity is the lack of an equation that would accurately describe the interaction of metal-insulation and insulation-air, and therefore, there is no possibility of an objective reflection of reality. Thus, in the work of J.S.A. Sarmiento and M.C. Tavares (Sarmiento and Tavares 2018) a lot of data on the same

phase capacity is provided, but no equations are given by which they could be obtained and estimate the real impact of insulation. However, its presence is an important tool in another method of increasing natural power and provides an additional margin for thermal stability. Moreover, additional research requires the effectiveness of thermal insulation. F. Song et al. (2019) present graphs of bandwidth efficiency depending on weather conditions (Fig. 3).
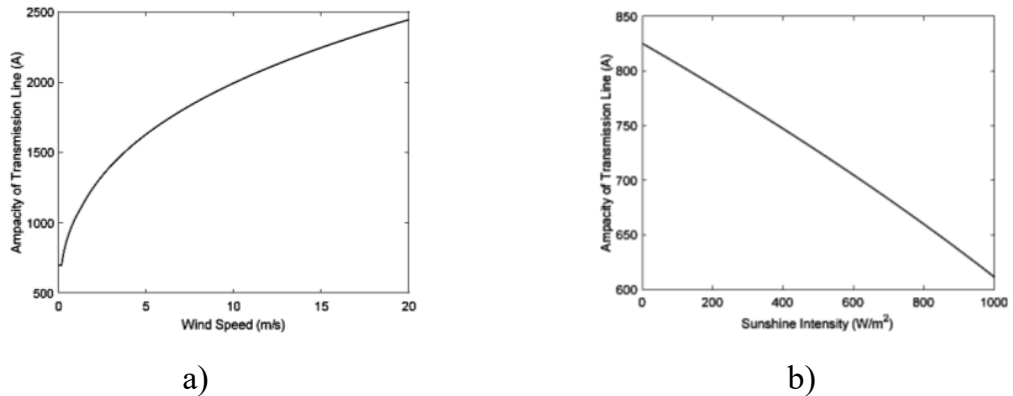

Fig. 3. Influence of a) wind speed and b) sunshine intensity on ampacity of transmission line
Source: Song et al. 2019

Rys. 3. Wpływ a) prędkości wiatru i b) natężenia promieniowania słonecznego na obciążalność prądową linii przesyłowej

The conclusions of these studies indicate that natural factors, such as the intensity of solar radiation and wind speed, have a significant impact on the leading qualities of the transmission line (Hingorani and Gyugyi 1999). When insulating the wire, the influence of these factors will completely change its nature, which will significantly change the thermal characteristics of the line. However, the disadvantage of the considered approach is that when drawing up impact graphs (Fig. 3), self-compensation for the benefits of natural cooling from wind by intense exposure to solar radiation is obtained. Under these conditions, peak values in wind gusts will not give significant advantages against the background of improving the constancy of the temperature regime through insulation by levelling the direct effect of solar radiation on the conductor. As the radius of the wires, the splitting step and the number of components in the phase increase, the charge on the wire increases, which leads to an increase in the electric field strength of the line. ?Furthermore, due to the increase in the magnitude of the charge on the wire there is an increase in the capacity of the line, which leads to a decrease in its impedance and increase the natural power (Yang 2011).

Excluding the parameters that can be influenced in the design of the support to increase the natural power, it was found that increasing the height of the wire suspension and line size leads to a decrease in wire charge and line voltage, but at the same time, decreases electrical capacity,

and consequently, impedance loading. The only factor that is analyzed, and the change of which simultaneously leads to an increase in the natural power of the line and a decrease in electric field strength is the distance between the centers of the phases d_o. According to the scheme, it is necessary to provide changes of three parameters in various combinations. To analyze them, graphs were constructed that better reflect the impact on the parameters of the line (Fig. 4).
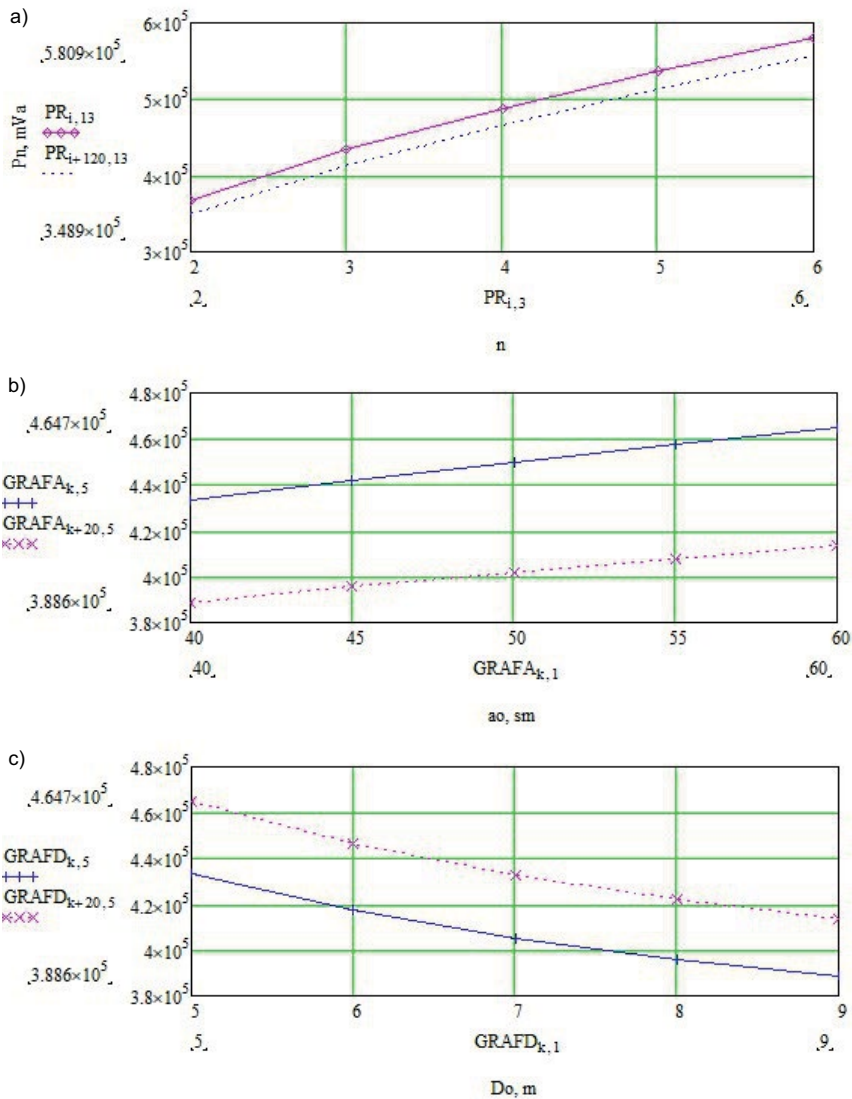

Fig. 4. Dependence of the natural power of the line of a) the number of components in phase n and b) on the splitting step a and c) on the distance between the phases d_o

Rys. 4. Zależność mocy naturalnej linii a) od liczby składowych w fazie n i b) od kroku podziału a i c) od odległości między fazami d_o

As can be seen from the figure, as the number of components in the phase increases, the value of the capacitors (phases A, B, C, and working capacity) and, accordingly, the power of the line increases. This is conditioned by the decrease in impedance. Furthermore, there is a decrease in the value of the maximum voltage on the wire and the impedance. This is conditioned by the increase in the equivalent radius of the wire. Convergence of wires (reduction of distance d_o) causes an effect similar to an increase in the number of components in the phase. That is, increasing the value of capacities (A, B, C, and working capacity) and, accordingly, the power of the line. This is conditioned by the fact that when the wires come together, the capacitance between them increases due to the reduction of air gaps, reducing the value of the maximum voltage on the wire and the impedance (Wang et al. 2019).

The constructed dependences of the calculated characteristics on the magnitude of the splitting step a allow distinguishing the following regularities. As the splitting step increases, there is a slight increase in the value of the maximum voltage on the wire. In addition, with increasing value of a there is a significant increase in capacity (A, B, C, and working capacity) and, accordingly, the value of power, which is associated with a decrease in air gap, with increasing capacity, and thus, with decreasing impedance (Sarmiento and Tavares 2016). Analyzing these dependences, it can be stated that reducing the maximum value of voltage on the wire and increasing the line power can be done by providing the maximum number of components in the phase, the maximum value of the splitting step, and the minimum distance between phases. At the same time, under conditions of actual operation, there are a number of objective limitations that provide these conditions. In particular, increasing the number of components in the phase will complicate the design of the phase, which will necessitate an increase in the mechanical strength of the support structure, which, in turn, affect its cost (Bondarenko and Galich 2014).

When the phases converge, it is obligatory to consider the possibility of wire collisions, which is a limiting factor regarding the variation of the value of the splitting step, when the wires converge in phase. However, the presence of an insulating layer will allow the phases to converge to much shorter distances than uninsulated, which will completely change the picture in the calculation. The proposed configurations are an advanced subspecies of controlled self-compensating overhead lines (SCOHL) (Fortescue 1918). Comparing traditional OHLs with controlled self-compensating OHLs, when regulating the phase shift between systems of circuit voltage vectors in the SCOHL, power is transferred between its circuits, as a result of which, circuits are loaded with different active and reactive powers. This is conditioned by the presence of capacitive and inductive connections between the circuits of the line, due to which, the mutual currents and induced EMF from one circuit change the magnitude of the current and voltage of the adjacent circuit, which is equivalent to the transmission and reception of power (Bence et al. 2022). The main distinguishing features of the calculation of technical and economic indicators between traditional OHL and SCOHL are as follows. In determining the costs based on the fact that the charging capacity of the SCOHL is equal to the sum of the charging capacities of two separately operating circuits (its components) in the case when the angle of displacement of the voltage systems between the circuits $\theta = 180^0$, that is, in the mode of the maximum throughput. If $\theta = 0^0$, and this can be achieved by means of FR in the modes of low loads and idling, which

requires the connection of a shunt reactor (SR), the charging power of the SCOHL is much smaller and on average can be determined by equation:

$$Q_{SCOHL}^{char\,0^0} = 0.55 Q_{SCOHL}^{char\,180^0} = 0.55\left(2Q_{OHL}^{char}\right)$$ (11)

where:

$Q_{SCOHL}^{char\,0^0}$ – charging power of SCOHL at $\theta = 0^0$,

$Q_{SCOHL}^{char\,180^0}$ – charging power of SCOHL at $\theta = 180^0$,

Q_{OHL}^{char} – charging power of OHL.

When determining the cost of compensation for electricity losses in the KSPL considers the possibility of reducing losses on the crown to regulate the parameters of the EP with the help of FR. The total electricity losses in the SCOHL can be determined by the following equation (Carslaw and Jaeger 1986):

$$\Delta\,Э_{\Sigma} = \left(\Delta\,Э_{cr}^{180^0} + \Delta\,Э_{load}\right)\left(\frac{100 - K_{reg}}{100}\right)$$ (12)

where:

$\Delta\,Э_{cr}^{180^0}$ – electricity losses to the crown in SCOHL at $\theta = 180^0$ (maximum),

$\Delta Э_{load}$ – loading losses of the electric power in SCOHL,

K_{reg} – the coefficient of reduction of total power losses in the SCOHL by adjusting the shear angle between the systems of vectors of circuit voltages when changing the amount of transmitted power, and reducing the component of losses per corona compared to traditional OHL ($K_{reg} = 6–10\%$).

Savings in electricity losses are thus achieved by regulating the phase shift between the circuits of the SCOHL and thereby, reducing losses on the crown. The cost of SCOHL is assumed to be equal to 70–80% of the cost of a two-chain traditional OHL. Thus, for SCOHL, the cost is defined as (Hunter and Fowle 1956):

$$K_{SCOHL} = 2\cdot K_{OHL}^{trad}\cdot\left(0.7 - 0.8\right)$$ (13)

where:

K_{OHL}^{trad} – the cost of traditional OHL lines.

The savings in investment are also evident due to the reduction in the number of circuits and the use of a large number of double-chain power supply, and the reduction in investments in the linear part is complemented by savings on SR, which are much smaller for SCOHL by charging power. The increase in investment in SCOHL compared to traditional OHL significantly affects the overall efficiency due to the installation of FR (Fernandez et al. 2016). The width of the

exclusion band for SCOHL is taken to be equal to the sum of twice the width of the single-chain support and twice its height. It should also be noted that SCOHL create lower levels of electrical voltage and magnetic fields in the surrounding space, which reduces the alienation band compared to the alienation band of traditional OHLs per unit of transmitted power. Therefore, the transmission capacity of SCOHL is very effective in comparison with standard OHL and can be considered as one of the perspective methods for the transmission of electrical power, features of implementation of intersystem communications.

Increasing the natural power or power-handling capacity of a transmission or distribution line is a critical aspect of electrical engineering. Replacing traditional aluminum conductors with higher conductivity materials like aluminum-steel composite conductors (ACCC) or aluminum-carbon fiber composite conductors can increase power capacity by reducing resistive losses. This method is highly effective and commonly used (Wu et al. 2020). Replacing existing conductors with larger cross-sectional area conductors can reduce resistance and increase power-carrying capacity. However, it may require tower modifications and might not be cost-effective in all cases (Waswa et al. 2021). Raising the voltage level of the transmission line can significantly increase the power transmission capacity. This method is effective but requires substations and equipment upgrades (Horowitz et al. 2020). Effectiveness evaluations would require a detailed analysis of the specific configuration, including line length, existing infrastructure, environmental factors, budget constraints, and more. The choice of method often depends on a trade-off between cost, effectiveness, and environmental impact. Engineers and grid operators typically conduct feasibility studies and cost-benefit analyses to determine the most suitable method for a given situation.

Research may face limitations that may affect its scope and results. Estimating the effect of different methods on line loading requires access to a large amount of data on real transmission lines. The restriction is limited access to this data due to a variety of reasons, for example, commercial confidentiality.

Conclusions

A scientific inquiry into the potential for assessing the overall impact of methods aimed at augmenting the inherent power capacity of transmission lines has yielded the following findings. The most efficient approaches for enhancing the natural power of power lines include modifying wire design, applying an insulating layer to the conductor's surface, altering the design of resistance to manipulate phase spacing, the number of components within phases, and splitting step configurations. In contrast, technologies involving synchronous reactive power compensation and second-generation superconductors exhibit limited potential in the current stage of energy development. Moreover, during the evaluation of wave resistance calculations, it became evident that the existing equation fails to account for insulation presence. The research corroborated that the alumina film also serves as an insulating material, underscoring the need for an

enhanced equation. Nonetheless, equation (4) implies that the insulating effect factors into the computation of losses due to corona discharge in the line, which is an issue that warrants detailed investigation in forthcoming studies.

The proposed configurations show significant promise as methods for boosting the natural power of power lines without necessitating substantial alterations to the power transmission system's visual appearance. The collective influence of factors amplifying the natural power of power lines has been ascertained. In Configuration 1, which incorporates all identified methods, the natural power increase was 53% relative to Configuration 3, representing the standard line configuration. Configuration 2, on the other hand, holds paramount interest from both technical and economic perspectives. Although it boasts 30.8% less transmission capacity efficiency than Configuration 1, it surpasses the standard configuration by 17% while incurring minimal economic costs.

The analytical methodologies employed to assess influencing factors in this study can be effectively applied in the design of high-voltage power lines, serving as a comprehensive tool for evaluating the technical and economic attributes of the proposed projects. This approach has the potential to substantially reduce expenditures related to further upgrades within the electricity transmission system. The challenge of rigidity is a common characteristic of energy systems, exemplified, for instance, in the Ukrainian context. This research establishes a robust scientific and technical foundation for future modifications of impedance calculation equations, prompting the consideration of the insulating layer's impact and raising questions concerning the redistribution of electric field strength along the conductor in coaxial wire configurations.

References

Bence et al. 2022 – Bence, N., Lengyel, A. and Tarics, Z. 2022. A simple model for describing the minimum differential cross-section of elastic proton scattering on protons at high energies. *Scientific Herald of Uzhhorod University. Series "Physics"* 51, pp. 30–38, DOI: 10.54919/2415-8038.2022.51.30-38.

Bezprozvannych, A.V. and Naboka, B.G. 2012. *Mathematical models and methods for calculating electrical insulating structures*. Kharkiv: National Technical University "Kharkiv Polytechnic Institute".

Bondarenko et al. 2012 – Bondarenko, I.N., Galich, A.V., Slipchenko, N.I. and Troitski, S.I. 2012. Cone-shaped resonator the high-order mode oscillation transducers. *CriMiCo 2012–2012 22nd International Crimean Conference Microwave and Telecommunication Technology, Conference Proceedings* 1, pp. 565–567.

Bondarenko, I.N. and Galich, A.V. 2014. Microstrip resonant sensors. [In:] *CriMiCo 2014–2014 24th International Crimean Conference Microwave and Telecommunication Technology, Conference Proceedings*, pp. 984–985, DOI: 10.1109/CRMICO.2014.6959725.

Bondarenko, I.N. and Lavrinovich, A.A. 2007. Investigation of the thin-film high-temperature superconductivity coplanar line. *Telecommunications and Radio Engineering* (*English translation of Elektrosvyaz and Radiotekhnika*) 66(7), pp. 597–605.

Carslaw, H.S. and Jaeger, J.C. 1986. *Conduction of heat in solids*. Oxford: Oxford University Press.

Deepak Selvakumar et al. 2023 – Deepak Selvakumar, R., Wu, J., Ding, Y. and Alkaabi, A.K. 2023. Melting behavior of an organic phase change material in a square thermal energy storage capsule

with an array of wire electrodes. *Applied Thermal Engineering* 228, DOI: 10.1016/j.applthermaleng.2023.120492.

FERNANDEZ et al. 2016 – FERNANDEZ, E., ALBIZU, I., MAZON, A.J., ETXEGARAI, A., BUIGUES, G. and ALBERDI, R. 2016. Power line monitoring for the analysis of overhead line rating forecasting methods. [In:] *2016 IEEE PES PowerAfrica,* pp. 119–123, DOI: 10.1109/PowerAfrica.2016.7556583.

FORTESCUE, C.L. 1918. *Method of symmetrical co-ordinates applied to the solution of polyphase networks*. New York: The American Institute of Electrical Engineers.

GRITSYUK et al. 2022 – GRITSYUK, V., NEVLIUDOV, I., ZABLODSKIY, M. and SUBRAMANIAN, P. 2022. Estimation of eddy currents and power losses in the rotor of a screw electrothermomechanical converter for additive manufacturing. *Machinery & Energetics* 13(2), pp. 41–49, DOI: 10.31548/machenergy.13(2).2022.41-49.

HASAN, S. and AGARWAL, V. 2023. A voltage support scheme for distributed generation with minimal phase current under asymmetrical grid faults. *IEEE Transactions on Industrial Electronics* 70(10), pp. 10261–10270.

High temperature low sag conductors 2008. [Online] https://www.entsoe.eu/Technopedia/techsheets/high-temperature-low-sag-conductors-htls [Accessed: 2023-08-20].

HINGORANI, N.G. and GYUGYI, L. 1999. *Understanding FACTS: Concepts and technology of flexible AC transmission systems*. Hoboken: Wiley-IEEE Press.

HOROWITZ et al. 2020 – HOROWITZ, K.A.W., JAIN, A., DING, F., MATHER, B. and PALMINTIER, B. 2020. A techno-economic comparison of traditional upgrades, volt-var controls, and coordinated distributed energy resource management systems for integration of distributed photovoltaic resources. *International Journal of Electrical Power & Energy Systems* 123, DOI: 10.1016/j.ijepes.2020.106222.

HRECHKO et al. 2023 – HRECHKO, Y., SEREDA, I., BABENKO, I. and AZARENKOV, M. 2023. Thermionic coating method with preliminary bombardment of the substrate surface with a stream of low energy ions. *Scientific Herald of Uzhhorod University. Series "Physics"* 53, pp. 9–8, DOI: 10.54919/physics/53.2023.09.

HUNTER, M.S. and FOWLE, P. 1956. Natural and thermally formed oxide films on aluminium. *Journal of the Electrochemical Society* 103(9), DOI: 10.1149/1.2430389.

KAPLUN et al. 2022 – KAPLUN, V., OSYPENKO, V. and MAKAREVYCH, S. 2022. Forecasting the electricity pricing of energy islands with renewable sources. *Machinery & Energetics* 13(4), pp. 38–47, DOI: 10.31548/machenergy.13(4).2022.38-47.

KORZHYK et al. 2017 – KORZHYK, V.N., KULAK, L.D., SHEVCHENKO, V.E., KVASNITSKIY, V.V., KUZMENKO, N.N., LIU, X., CAI, Y.X., WANG, L., XIE, H.W. and ZOU, L.M. 2017. New equipment for production of super hard spherical tungsten carbide and other high-melting compounds using the method of plasma atomization of rotating billet. *Materials Science Forum* 898 MSF, pp. 1485–1497, DOI: 10.4028/www.scientific.net/MSF.898.1485.

Law No. 605 *"On the approval of the Energy strategy of Ukraine for the period until 2035 «Safety, energy efficiency, competitiveness»"*. 2017. [Online] https://zakon.rada.gov.ua/laws/show/605-2017-%D1%80#Text [Accessed: 2023-08-18].

LEENDERS, J.P.A. 2007. *Upgrading overhead lines with high temperature, low sag conductors*. Eindhoven: Eindhoven University of Technology. 59 pp.

Net electricity consumption worldwide in select years from 1980 to 2021. 2023. [Online] https://www.statista.com/statistics/280704/world-power-consumption [Accessed: 2023-08-18].

RUBINO, L. and RUBINO, G. 2016. Electrical Power Center with energy management capability for aeronautical applications. [In:] *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2016*, pp. 940–945, DOI: 10.1109/SPEEDAM.2016.7525944.

SADOVOY et al. 2021 – SADOVOY, O., AVDIEIEVA, E., VAKHONINA, L. and SHEBANIN, V. 2021. Comparison of the Active Parts of Single-Phase Transformers with Twisted and Laminated Magnetic Circuits. [In:]

Proceedings of the 20ᵗʰ IEEE International Conference on Modern Electrical and Energy Systems, MEES 2021, DOI: 10.1109/MEES52427.2021.9598597.

SARMIENTO, J.S.A. and TAVARES, M.C. 2016. Enhancement the overhead transmission lines' capacity by modifying the bundle geometry using heuristics algorithms. [In:] *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 646–650, DOI: 10.1109/APPEEC.2016.7779583.

SARMIENTO, J.S.A. and TAVARES, M.C. 2018. Methodology for optimizing the capacity and costs of overhead transmission lines by modifying their bundle geometry. *Electric Power Systems Research* 163(Part B), pp. 668–677, DOI: 10.1016/j.epsr.2017.10.005.

SELVAKUMAR et al. 2023 – SELVAKUMAR, R.D., WU, J., AFGAN, I., DING, Y. and ALKAABI, A.K. 2023. Melting performance enhancement in a thermal energy storage unit using active vortex generation by electric field. *Journal of Energy Storage* 67, DOI: 10.1016/j.est.2023.107593.

SONG et al. 2019 – SONG, F., WANG, Y., ZHAO, L., QIN, K., LIANG, L, YIN, Z. AND TAO, W. 2019. Study on thermal load capacity of transmission line based on IEEE Standard. *Journal of Information Processing Systems* 15(3), pp. 464–477, DOI: 10.3745/JIPS.04.0114.

SONG, T. and TEH, J. 2023. Dynamic thermal line rating model of conductor based on prediction of meteorological parameters. *Electric Power Systems Research* 224, DOI: 10.1016/j.epsr.2023.109726.

WANG et al. 2019 – WANG, R., TIAN, J., WU, F., ZHANG, Z. AND LIU, H. 2019. PSO/GA combined with charge simulation method for the electric field under transmission lines in 3D calculation model. *Electronics* 8(10), DOI: 10.3390/electronics8101140.

WASWA et al. 2021 – WASWA, L., CHIHOTA, M.J. and BEKKER, B. 2021. A probabilistic conductor size selection framework for active distribution networks. *Energies* 14(19), DOI: 10.3390/en14196387.

WU et al. 2020 – WU, W., LIU, J., LIU, M., RAO, Z., DENG, H., WANG, Q., QI, X. and WANG, S. 2020. An innovative battery thermal management with thermally induced flexible phase change material. *Energy Conversion and Management* 221, DOI: 10.1016/j.enconman.2020.113145.

XIAO et al. 2023 – XIAO, F., CAO, K., TANG, J., LIU, D., RAO, Y. and XIONG, P. 2023. Study on coordinated multi-objective reactive control system of AC/DC power grid based on new-generation synchronous condenser. *Energy Reports* 9, pp. 2140–2148, DOI: 10.1016/j.egyr.2022.12.084.

YANG, B. 2011. *Study on heat capacity of power grid transmission components*. Jinan: Shandong University.

ZHANG et al. 2023 – ZHANG, Y., ZHAO, X., WANG, X., LI, A. and WU, X. 2023. Multi-objective optimization design of a grid-connected hybrid hydro-photovoltaic system considering power transmission capacity. *Energy* 284, DOI: 10.1016/j.energy.2023.128683.

Nataliya Komenda, Vladyslav Volynets, Iryna Hrytsiuk, Irina Bandura, Mykola Romaniuk

Oszacowanie całkowitego wpływu metod zwiększania obciążenia naturalnego linii

Streszczenie

Badania mające na celu ekonomicznie uzasadnione zwiększenie przepustowości istniejących linii elektroenergetycznych i ulepszenia w ich projektowaniu są obecnie aktualne. Oprócz dobrze znanych metod projektowania wpływających na przepustowość linii przesyłowej, istnieją inne znaczenia, które mogą wpływać na jej moc naturalną, która jest bezpośrednio związana z przepustowością. Dlatego celem niniejszego badania było znalezienie możliwych metod zwiększenia mocy naturalnej i ocena ich skuteczności w rzeczywistych konfiguracjach. Analizowane czynniki obejmują: zastosowanie przewodów o ulepszonych parametrach, wpływ liczby komponentów w fazie, odstęp fazowy, obecność warstwy izolacyjnej na przewodach. Podstawą podejścia metodologicznego w tym badaniu jest jakościowe połączenie metod systematycznej analizy sposobów zwiększenia przepustowości linii elektroenergetycznych z analitycznym badaniem perspektyw ich wpływu na opór falowy w celu zwiększenia mocy naturalnej linii. Przeprowadzone badania pozwoliły określić łączny wpływ analizowanych czynników na zwiększenie zdolności przesyłowych oraz wyznaczyć najbardziej optymalną konfigurację z technicznego i ekonomicznego punktu widzenia. Na podstawie wyników obliczeń mocy naturalnej konfiguracji, sformułowano wnioski dotyczące istotności wpływu każdego z powyższych czynników oraz określono efekt ekonomiczny ich implementacji w zintegrowanym systemie elektroenergetycznym. Udoskonalenie tej metodyki, w dalszej perspektywie, może posłużyć jako narzędzie do obliczania konfiguracji pod kątem przydatności ekonomicznej i technicznej lub stanowić podstawę do dalszej identyfikacji czynników wpływających na zdolności przesyłowe linii elektroenergetycznych.

Słowa kluczowe: pole elektryczne linii elektroenergetycznych, model matematyczny, energetyka i elektrotechnika, badania analityczne, zdolność przesyłowa