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# Features of designing high-voltage overhead power lines in an underground collector

***Problem**. Protection of high-voltage (HV) overhead power lines (OPL) from external atmospheric and military influences and reduction of their hazardous electromagnetic radiation is possible if they are made in a compact form and placed in an underground collector. But to ensure high capacity and reliable operation of such compact HV OPL, it is necessary to improve the existing designs of their current-carrying elements. The **goal** of the work is to determine promising design parameters of busbars of compact high-voltage overhead power lines laid in an underground collector. The **methodology** for calculating permissible long-term currents of HV OPL laid in an underground collector is based on the analytical model proposed by the authors for describing the processes of mass and heat transfer in the air of an underground collector. **Scientific novelty**. For the first time, the possibility of efficient use of HV OPL in an underground collector conditions is substantiated and the conditions for their reliable transmission of electric energy with increased capacity are determined. This is achieved through the use of rectangular flat vertical conductive busbars with an increased surface area and providing better convective heat exchange compared to traditional round wire, as well as by determining the rated current for such overhead lines at a reduced ambient temperature (15 °C), which is typical for operating conditions in underground collectors (25 °C) adopted for overhead lines located outdoors. **Practical value**. The use of the proposed HV OPL laid in an underground collector should ensure reliable transmission of electrical energy, sufficient throughput and increased protection from external factors while reducing the electromagnetic impact on the environment (due to a significant reduction in the interphase distance from 3–4 m to 0.3–0.6 m for 110 kV HV OPL), and has advantages over SF6-insulated cable lines and cable lines characterized by an increased insulation cost).* References 36, table 1, figures 6.
*Key words:* **compact high-voltage overhead power line, underground collector, busbar conductor, thermal modeling.**

***Проблема.** Захист високовольтних повітряних ліній електропередавання (ПЛ) від зовнішніх атмосферних та військових впливів, та зменшення їх небезпечного електромагнітного випромінювання можливо при їх виконанні у компактному вигляді і розміщенні у підземному колекторі. Але для забезпечення високої пропускної спроможності та надійної роботи таких компактних повітряних ПЛ необхідно удосконалення існуючих конструкцій їх струмопровідних елементів. **Метою** роботи є визначення перспективних конструктивних параметрів струмопроводів компактних високовольтних повітряних ліній електропередавання, які прокладені у підземному колекторі (ПЛПК). **Методика** розрахунку допустимих тривалих струмів ПЛПК заснована на запропонованій авторами аналітичній моделі опису процесів масотеплоперенесення в повітрі підземного колектору. **Наукова новизна.** Вперше обґрунтовано можливість ефективного використання ПЛ в умовах підземного колектору та визначено умови надійної передачі ними електроенергії з підвищеною пропускною спроможністю. Це досягнуто завдяки застосуванню прямокутних плоских вертикальних струмопровідних шин, які мають збільшену площу поверхні та забезпечують кращий конвекційний теплообмін порівняно з традиційним круглим проводом, а також за рахунок визначення допустимого тривалого струму для таких ПЛ при зменшеній температури зовнішнього середовища (15 °С), що характерна для умов експлуатації в підземних колекторах і суттєво нижча за стандартну температуру (25 °С), прийняту для ПЛ, розміщених на відкритому повітрі. **Практична значимість**. Використання запропонованої ПЛПК має забезпечити надійне передавання електричної енергії, достатню пропускну спроможність і підвищену захищеність від зовнішніх факторів при зменшенні електромагнітного впливу на оточуюче середовище (за рахунок істотного зменшення міжфазної відстані з 3–4 м до 0,3–0,6 м для ПЛ 110 кВ), і має переваги над відомими підземними електромережами (лініями електропередавання з елегазовою ізоляцією та кабельними лініями, що характеризуються підвищеною вартістю ізоляції).* Бібл. 36, табл. 1, рис. 6.
*Ключові слова:* **компактна високовольтна повітряна лінія електропередавання, підземний колектор, струмопровід із плоских шин, моделювання теплового режиму.**

**Introduction.** Ensuring reliable power supply to consumers is the main task of the electric power industry. To achieve this, it is necessary to improve the technical and economic indicators of high-voltage (HV) power grids. Two main types of power grids are most often used to supply consumers with electricity: HV overhead power lines (OPLs) and HV underground cable lines (CLs). However, during the operation of OPLs and CLs, problems arise with ensuring their reliable functioning. This is due to the influence of natural atmospheric factors (ice, solar radiation, strong winds and rain, etc.), as well as the high vulnerability of these lines in the event of fighting using modern artillery and missile weapons.

In addition, the problem of improving the power supply of modern megacities with dense construction requires an urgent solution. The increase in load in cities leads to the need to find new methods for organizing their power supply.

One of the effective methods of increasing the reliability of power supply in cities and the protection of power grids from negative external man-made, natural and military influences is the placement of power grids in underground reinforced concrete tunnels (collectors), which is quite widespread in the world. Thus, in [1–11] examples of the development of pilot projects for the construction of underground power grids of different voltage classes with insulation from air, cross-linked polyethylene and SF6 are given.

In [1, 2] the issues of choosing insulation for underground lines and substations of various designs are considered, examples of their calculations are given. Work [3] is devoted to the analysis of the impact on the environment of OPLs and underground CLs. It is shown that underground lines have a significantly smaller number of external influence parameters and have a much smaller impact on the environment.

The works [12–14] are devoted to the comparison of the parameters of OPLs and underground CLs made of cross-linked polyethylene. It has been shown that CLs are more protected from external factors and have a compact design that reduces the electromagnetic impact on the environment and does not require the alienation of large land plots. However, with the same capacity, CLs are 2–10 times more expensive than overhead lines due to the high cost of HV insulation made of cross-linked polyethylene [13, 14]. It should also be noted that the repair work of OPLs and CLs can differ in cost by 5–10 times.

The works [4, 5] contain materials on the construction of a 500 kV underground line in California, made with a direct current cable. This decision is due to the impossibility of using AC CL in the required length. The choice of an underground line is due to the community's resistance to the construction of a ground OPL.

The works [6, 7] provide data on the implementation of a project to build a completely underground 220 kV substation in the Chinese city of Wuhan. Currently, no detailed information about this project is provided in open sources, but the fact that it is located in a shopping mall imposes additional requirements on its design.

The work [8] is devoted to the development in 2013 by the LLC Kharkiv Design Development Institute «Teploelektroproekt-Soyuz» of a project for an underground 220 kV substation with SF6 insulation.

The works [9, 10] show the possibility of building underground power networks, identify the advantages of such networks, but do not provide data on their design features.

The work [11] is devoted to the analysis of the use of SF6 insulation in power networks. The advantages and disadvantages of using SF6 as an insulating medium are given. Gas insulated transmission lines (GILs) are considered. Direct burial of the GIL system into the ground combines advantages of underground laying of cables with high throughput of ground OPLs of the corresponding power. It is shown that GILs have high reliability, high throughput, and low magnetic field levels. Such lines are similar in design to the so-called complete current conductors and have insulators inside the structure that limit the radius of rotation and the value of the permissible short-circuit currents. In addition, the GIL housings must be made hermetic, which significantly complicates their design. It is also worth noting the high cost and complexity of maintaining such a line compared to the OPL of the analog power.

In the works [15–18] it is shown that the magnitude of the magnetic field harmful to humans and the environment, created by OPLs and CLs, is proportional to the interphase distance of their current conductors. Therefore, the value of their magnetic field is significantly (by an order of magnitude) reduced in the compact design of electrical networks, which are characterized by an interphase distance of less than 1 m.

The main parameter that significantly affects the characteristics of electrical networks is the design of their phase power lines, including their material and geometry. Currently, the choice of current conductors of OPLs and CLs is regulated by regulatory documents [19]. It should be noted that their recommendations are more for different voltage classes. Thus, to determine the cross-section and number of wires in a phase for OPLs with a nominal voltage of up to 20 kV, it is necessary to exclude electrical calculations, and those parameters for a line with a higher voltage are performed without any technical or economic calculations in [19] in the form of Table 2.5.16. This necessitates the search for other approaches to the selection of material and design of current conductors in comparison with the traditional approach [20–23], and especially, given that the specified sources do not consider the issue of selecting the parameters of the current conductor for power networks located in underground collectors.

In the works [24–26], examples of the use and selection of so-called high-temperature wires are given. In the works [27, 28], information is provided and the advantages of wires with a composite core are highlighted, which can increase the mechanical characteristics and increase the length of OPL’s spans. The works [29, 30] describe the advantages of using wires made of aluminum alloys and provide examples of their use for OPLs.

It should be noted that the above advantages of the latest wire brands cannot be decisive for the choice of the design of current conductors of OPLs in an underground collector. It is necessary to take into account that the determination of the design of current conductors for OPLs located in an underground collector will be quite close to the choice of the design of phases of closed switchgear with air insulation in accordance with [19–23]. These sources provide tables with the values of wire and bus cross-sections and their maximum permissible continuous currents. However, it is not indicated under what conditions they operate.

The works considered above, which are devoted to the creation of compact underground electrical networks of various types and their structural elements, do not contain specific technical parameters of the completed or proposed projects.

According to the authors of the article, the greatest interest for practical use is HV compact OPLs with air insulation laid in an underground collector (OPLs in UC). But OPLs in UC in comparison with ground OPLs, underground CLs and underground GILs have not been studied enough to date. The rational design parameters of their current conductors, which at limited cost allow to realize increased throughput with increased protection from external factors and reduce electromagnetic impact on the environment, remain still not defined.

**The goal of the work** is to determine the promising design parameters of current conductors of compact high-voltage overhead power lines, which are laid in an underground collector.

The above analysis shows that OPLs in UC can be considered as a promising means of transmitting electrical energy under the conditions of ensuring their competitive technical and economic characteristics. Thus, OPL in UC has quite significant advantages over OPL, and primarily because in the underground collector there are no negative natural factors that affect OPLs, which are located in the open air. Therefore, OPLs in UC can be considered as an alternative to CLs and GILs, which have a more complex design of current conductor insulation and high cost.

Thus, the requirements for the structural elements of OPLs in UC will be very different from the known requirements for the structural elements of OPLs. This fact confirms the need to conduct research to determine the rational design of OPLs in UC elements, and primarily the design of their phase current conductor.

**Determination of the design of the phase current conductor of the OPL in UC**. One of the main design parameters of both the OPLs and the OPLs in UC is the cross-section of the current conductor. Based on the unambiguous recommendations of regulatory documents regarding the phase cross-section of the OPL with nominal voltage of 110 kV, a phase cross-section of 240 mm$^2$ was adopted, recommended in [19] for AC type wires. For phase current conductors of the OPLs in UC of busbars, the cross-section can be chosen the same as for the AC type wire. However, if we calculate the permissible continuous current of the 110 kV OPL wire based on its maximum natural power of 30 MW, we will obtain a current value in the phase of about 272 A. With an increase in power by 25 % (standard practice for using 110 kV lines), the current will increase to approximately 340 A. For such current values, it is possible to determine the cross-sections of AC wires of 95 mm$^2$ and 150 mm$^2$, respectively, from [19]. The choice of such wire cross-sections will lead to an increase in active power losses, but will reduce capital investment in the line. Therefore, to determine the rational wire cross-section, it is necessary to conduct a technical and economic comparison of the phase design, taking into account all the factors affecting it.

However, the conditions for using phase wires for OPLs in the open air and current conductors of the OPLs in UC, as noted above, are quite different. Regulatory documents recommend selecting phase wires based on the permissible continuous current. To determine it, it is necessary to calculate the heat transfer coefficient, which significantly depends on the design features of the phase current conductors and the air temperature in the underground collector.

Based on the current values (0.3–2 kA) that must be provided for the OPLs in UC, their creation does not require the use of special complex current conductor designs in the form of boxes, pipes, I-beams or several rectangular-section buses [19–23]. Therefore, the authors propose to consider using either a conventional AC type wire for OPLs or a rectangular busbar as a phase current conductor for OPLs in UC. This necessitates the performance of thermal calculations of rectangular busbars, which are widely used for low and medium voltages. This necessity is due to the fact that the nomenclature of busbars [19–23] does not meet the conditions of their use for power transmission lines. For OPLs in UC, completely different busbar sizes may be rational, which meet the requirements [19] for the cross-section of phase current conductors for different classes of rated voltage.

When determining the heat transfer coefficient and permissible long-term current of phase current conductors of the OPLs in UC, it is also necessary to take into account the specific conditions of their operation. The main difference from the OPLs is that for OPLs in UC, it is not necessary to take into account the strength and direction of the wind, as well as solar radiation, which affect the thermal mode at a given long-term permissible temperature of the current conductor of 70 °C [19–23].

The cooling efficiency of current conductors of the OPL in UC is estimated by their heat transfer coefficient [31], which determines the intensity of heat transfer from a solid surface to the air in the environment. For its calculation under conditions of laminarity and natural convection, the following relationship can be used [32]:

$$Nu = C\,(Gr \cdot Pr)^n \,, \tag{1}$$

where $Nu$ is the Nusselt criterion; $Gr$ is the Grashof criterion; $Pr$ is the Prandtl criterion; the coefficients $C$ and $n$ depend on the free motion mode and the surface washing conditions.

The Nusselt criterion $Nu$ [33] characterizes the intensity of heat transfer in the boundary layer between the gas and the surface of the body flown around it:

$$Nu = \alpha \cdot l / \lambda_p \,, \tag{2}$$

where $l$ is the characteristic size, m; $\lambda_p$ is the thermal conductivity of the gas, W/(m·K).

The Prandtl criterion $Pr$ [33] determines the physical properties of the gas:

$$Pr = \mu \cdot C_p / \lambda_p = \nu_p / a \,, \tag{3}$$

where $\mu$ is the dynamic viscosity coefficient, N·s/m$^2$; $\nu_p$ is the kinematic viscosity coefficient of the gas at a given temperature of the medium $t_p$, m$^2$/s; $a$ is the coefficient of temperature stability of the gas at a given temperature, m$^2$/s; $C_p$ is the isobaric mass heat capacity of the gas, kJ/(kg·K).

The Grashof criterion $Gr$ characterizes the ratio of the lifting forces that arise in the gas during heating and the viscous forces [33]:

$$Gr = \frac{\beta \cdot g \cdot d^3 \cdot \Delta t}{\nu_p^2} \,, \tag{4}$$

where $\beta$ is the coefficient of volumetric expansion of the gas, 1/K; $g$ is the acceleration due to gravity, m/s$^2$;

$\Delta t$ is the temperature difference between the surface (wall) of size $d$ and the gas between which heat is exchanged, °C or K.

Let us use the relationships (1–4) to calculate the permissible long-term current of the current conductor of the OPLs in UC made of a round wire of type AC.

**Calculation of the permissible continuous current of the OPL in UC made of round wire.** The geometry of the current conductor of the OPL in UC made of round wire is shown in Fig. 1.

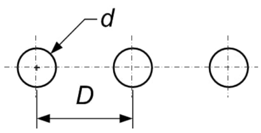



Fig. 1. To determining the heat transfer coefficient of a round wire of the OPL in UC

For the calculation, the recommended [19] design of a 110 kV phase with one AC type wire with cross section of 240 mm$^2$, which is used for overhead lines, was selected.

The calculation was performed under the following conditions.

The 110 kV OPL in UC is located in a reinforced concrete collector with minimum internal size of 3×4 m, which is located underground at a depth of at least 4 m. In this case, the calculated air temperature in the collector according to [34] will be 14–16 °C. Therefore, we will perform the calculation for the air temperature $t_p$ = 15 °C, and also for comparison for the temperature $t_p$ = 25 °C, which according to [19–23] is calculated for ground OPLs.

Long-term permissible temperature of the current conductor $t_{st}$ = 70 °C, thermal conductivity $\lambda$ = 0.0287 W/m·K; kinematic viscosity coefficient $v_p = 17.46 \cdot 10^{-6}$ m$^2$/s; Prandtl criterion for air $Pr$ = 0.698; volumetric expansion coefficient of air $\beta$ = 0.00343 1/K.

The following phase wire parameters were used in the calculation: diameter of the AC wire 240/32 $d$ = 21.4 mm; radiation coefficient of a completely black body $G_0 = 5.67 \cdot 10^{-8}$ W/m$^2$; blackness coefficient of the body $E_b$ = 0.4; active resistance of the wire $r_0$ = 0.1182 mΩ/m.

Taking into account the fact that the AC type wire is made of a bundle of wires of smaller diameter, the equivalent wire diameter increased by a factor of 1.33 was used [35]. The presence of collector walls was not taken into account in the calculation.

The Grashof criterion $Gr$ was calculated according to (4). Taking into account the value of the Prandtl criterion for air, the Nusselt criterion is defined as [33]:

$$Nu = 0{,}5\,(Gr \cdot Pr)^{0{,}25} . \quad (5)$$

The heat transfer coefficient from the wire is calculated using the formula:

$$\alpha = Nu \cdot \lambda / d . \quad (6)$$

The heat flux from the wire due to convection from 1 m$^2$ is equal to:

$$q = \alpha_2 \cdot (t_{st} - t_p). \quad (7)$$

Heat release from the wire due to convection from 1 m$^2$ of the surface of the wire AC 240/32 [33] is equal to:

$$Q_C = \alpha_1 (t_{st} - t_p) F , \quad (8)$$

where $F$ is the surface area of the wire.

Heat release from 1 m$^2$ of the surface of the AC240/32 wire due to radiation is [33]:

$$Q_R = \varepsilon_0 C_0 \left( (t_{st}/100)^4 - (t_p/100)^4 \right) \cdot F . \quad (9)$$

The total heat release in the channel is equal to:

$$Q_p = Q_C + Q_R . \quad (10)$$

The heat release from the flow of current $I$ is:

$$Q_e = I^2 R , \quad (11)$$

where $R$ is the electrical resistance of the conductor.

The permissible value of the current flowing in the conductor under the condition $Q_e = Q$ is equal to:

$$I = (Q_p / R)^{0{,}5} . \quad (12)$$

The results of calculating the permissible continuous current for the AC 240/32 wire, which is made in accordance with (5–12) by (1–4), are presented in Fig. 3 and allow us to compare it with the tabular one given in [19]. The calculation error was 2.6 % (tabular value 505 A, calculated value 518.13 A). This confirms the correctness of the developed calculation method and the possibility of its use for determining the permissible continuous currents of current conductors placed in an underground collector. At the same time, the operating conditions of current conductors in the collector are practically the same as the conditions of their operation in the room.

**Calculation of the permissible continuous current of the current conductors of the OPL in UC of busbar.** It is proposed to perform the phase current conductor of the OPL in UC in the form of one busbar of rectangular cross-section. This design of the phase current conductor was chosen taking into account the simplicity of its installation and operation. When analyzing the busbar cross-section, we take it equal to the wire cross-section for AC 240 110 kV OPL, which is recommended in [19]. It should be noted that with an equal cross-section with an AC type wire, busbar, unlike AC, may have a different design.

For the calculation, variants of the busbar with the geometry corresponding to the following dimensions $h/d$ ratio (Fig. 2) were selected: 240/1, 120/2, 80/3, 60/4, 48/5, 24/10, 20/12, 12/20, 12/24, 5/48, 4/60, 3/80, 2/120, 1/240.

The calculation of the permissible continuous current of the busbar is based on the relationships (1–4), which are also used for round wire. The geometry of the current conductor with the busbar is shown in Fig. 2.

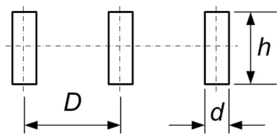



Fig. 2. To determining the heat transfer coefficient of a current conductor of the OPL in UC of busbars

In busbars, the heat release process is different because of presence of clearly expressed busbar vertical and horizontal surfaces for which, in presence of natural convection, heat transfer conditions are another. This difference is taken into account by different coefficients in (1).

Relation for the determination of the Nusselt criterion for the busbar horizontal part is [32]:

$$Nu = 1{,}18 \cdot (Gr \cdot Pr)^{0{,}125}\,. \tag{13}$$

For the vertical part of the busbar [32]:

$$Nu = 0{,}75 \cdot (Gr \cdot Pr)^{0{,}25}\,. \tag{14}$$

Calculation of the heat transfer coefficient due to natural convection is carried out in accordance with (6). The calculation conditions are similar to those specified above for the round wire of AC type.

Let us calculate the Prandtl and Grashof similarity criteria necessary to determine the Nusselt criterion by (3) and (4), respectively. The Nusselt criterion is determined for horizontal and vertical busbar surfaces.

The heat transfer coefficient of the busbar from the horizontal surface is:

$$\alpha_1 = Nu \cdot \lambda / d\,, \tag{15}$$

where $d$ is the thickness of the rectangular busbar.

The heat transfer coefficient from the vertical surface is:

$$\alpha_2 = Nu \cdot \lambda / h\,, \tag{16}$$

де $h$ is the height of the rectangular busbar.

The area of the busbar horizontal surface (Fig. 2) is:

$$F_1 = 2 \cdot d \cdot L\,, \tag{17}$$

where $L$ is the length of the rectangular busbar.

The area of the busbar vertical surface (Fig. 2) is:

$$F_2 = 2 \cdot h \cdot L\,. \tag{18}$$

The heat flow due to convection from the horizontal busbar surface is:

$$q_{C1} = \alpha_1 \cdot (t_{st} - t_p)\,. \tag{19}$$

Heat release due to convection from the busbar horizontal surface is:

$$Q_{C1} = q_{C1} \cdot F_1\,. \tag{20}$$

The heat flow due to convection from the vertical busbar surface is:

$$q_{C2} = \alpha_2 \cdot (t_{st} - t_p)\,. \tag{21}$$

Heat release due to convection from the busbar vertical surface is:

$$Q_{C2} = q_{C2} \cdot F_2\,. \tag{22}$$

Heat release due to convection is determined as:

$$Q_C = Q_{C1} + Q_{C2}\,. \tag{23}$$

The heat release from busbars due to radiation is determined by (9), and total one by (10).

The permissible continuous current for busbars is determined in accordance with (12). The results of its calculation in accordance with (12–23) are presented in Fig. 3.

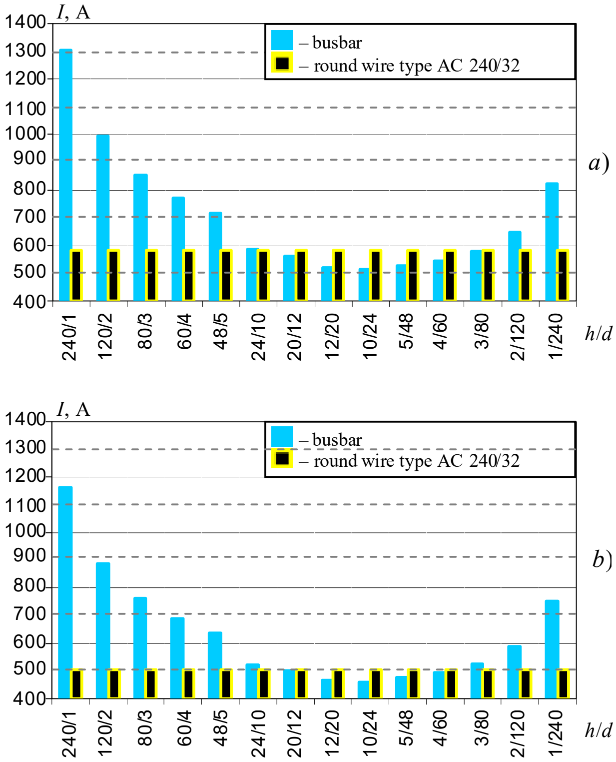



Fig. 3. Results of calculation of permissible continuous current of the OPL in UC with different design of the phase current conductor with cross-section of 240 mm$^2$ and different air temperatures: *a*) at $t_p$ = 15 °C; *b*) at $t_p$ = 25 °C

**Analysis of the results of calculation of permissible continuous currents and choice of design of the phase current conductor of the OPL in UC.** The analysis of the results obtained shows that busbars of the OPL in UC in comparison with round wire of the same cross-section have greater values of permissible continuous currents.

In Fig. 3, the abscissa axis shows the ratio $h/d$ for different geometries of the busbars considered. Therefore, at an air temperature of 15 °C in the collector, the limiting values of currents for the OPLs in UC with busbars compared to temperature of 25 °C can be increased. Thus, for the OPLs in UC 110 kV with busbars 240/1, the permissible continuous current will increase by 12 % (from 1164 A to 1302 A), which will allow increasing the power of the power grid by 15 MW. At the same time, when performing the OPL in UC from the AC 240/32 wire, a change in air temperature from 25 °C to 15 °C leads to an increase in the permissible continuous current by only 9 %.

The results of calculations of permissible continuous currents for busbars with different $h/d$ ratios allow us to determine the most rational designs of phase conductors of OPLs in UC with busbars. Such designs should be taken into account in the feasibility study when implementing a specific OPL in UC project, taking into account other technical parameters such as the line route, the presence of man-made influences, the presence of a rated voltage network, the impact on the environment, the costs of operation and repair, the required throughput, mechanical strength, reactive and active resistance, etc.

Determining rational designs of OPLs in UC with busbars will allow us to reduce the number of options for a more detailed technical and economic analysis.

OPLs in UC with busbars have greater permissible continuous currents which is connected with increase in the current conductor heat transfer surface $P$ (Fig. 4).

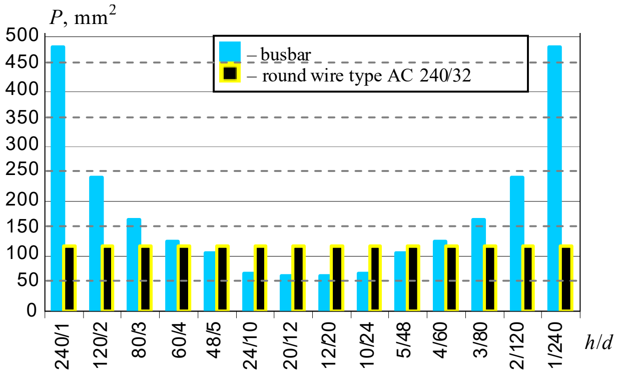



Fig. 4. Heat transfer surface area $P$ of different designs of current conductors of the OPL in UC with cross-section of 240 mm$^2$

Analyzing the results shown in Fig. 3, 4, we can conclude that there are designs ofbusbars that have a smaller surface area or perimeter than the AC wire (with the same length) and have higher permissible continuous currents. With equal lengths of the compared conductors, their area is proportional to the perimeter of the conductor. At the same time, the perimeters of current conductors with busbars differ significantly from the perimeter of the AC 240/32 type wire. This confirms that the permissible continuous currents for OPLs in UC with busbars will be greater than the current for a round wire. This is also confirmed by Fig. 5, which shows the ratio $k$ between the perimeters of different designs of busbars and a round wire and the ratio $k$ for permissible continuous currents of busbars and a round wire.

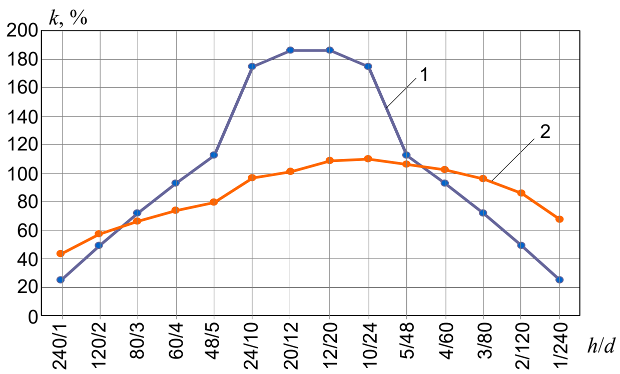



Fig. 5. Ratio $k$ between wire parameters:
1 – ratio of the area of heat transfer surface for the wire type AC 240/32 for different busbar designs with cross-section of 240 mm$^2$;
2 – ratio of permissible continuous currents for the wire type AC 240/32 or different busbar designs

As shown above, the cooling efficiency of the current conductors of the OPLs in UC and the intensity of natural convection are determined by their heat transfer coefficient $\alpha$ according to (1–4, 6, 15, 16). At given air temperatures in the collector and the limiting temperature of the current conductor, $\alpha$ significantly depends on its geometry, which determines the surface area, as well as on the spatial orientation of the conductor, which is illustrated in Fig. 3.

Thus, the greatest cooling efficiency and the greatest values of permissible continuous currents are provided by current conductors with busbars (Fig. 2) with the maximum ratio of its height $h$ to its width $d$. Theoretically, such structures include busbars with an side ratio $h/d$ of 240/1, 120/2, 80/3, 48/5 with a vertical busbar installation (at $h > d$) in accordance with Fig. 2. However, taking into account ensuring the necessary mechanical strength of the busbars, when designing an OPLs in UC it is advisable to limit oneself to a vertical current conductor with thickness of at least 2 mm.

In case of horizontal installation of busbars ($h < d$) the cooling efficiency and values of permissible continuous currents decrease (Fig. 3) due to worsening natural convection.

**Determination of the interphase distance and the length of the spans for OPLs in UC with busbars.** The geometric dimensions of OPLs in UC with busbars are determined by their minimum interphase distance $D$ (Fig. 2), which depends on the insulating properties of air. For closed switchgear 110 kV, the smallest interphase distance between their buses according to [36] is 250–450 mm, which can also be accepted for OPLs in UC.

Another important issue is the determination of the minimum length of the spans of the OPLs in UC with busbars at the accepted interphase distance, which depends on the electrodynamic forces that arise when a short-circuit shock current flows through the current conductors of the OPL in UC. In such an emergency mode, phase current conductors should not approach the adjacent phase at a distance at which insulation breakdown is possible.

To study this issue, calculations of the minimum allowable value of the span between supports of the OPL in UC when using busbars were performed. The analysis assumed that the busbar can be represented as a beam supported by several supports. Under this assumption, the allowable breaking force $\sigma$ of the aluminum busbar can be defined as [35]

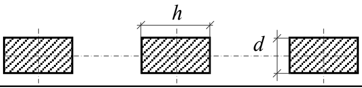
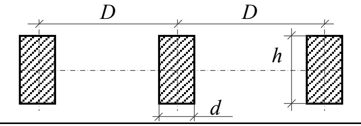
$$\sigma = \sqrt{3} \cdot 10^{-8} \cdot \frac{i_y^2 \cdot l^2}{W \cdot D}, \quad (24)$$

where $i_y$ is the short-circuit current, kA; $l$ is the span length; $D$ is the interphase distance, m; $W$ is the moment of resistance of the busbar relative to the axis perpendicular to the force action, m$^3$.

The minimum span length of the OPL in UC is determined from the following relationship, obtained according to (24) and Table 1, limiting the allowable force $\sigma$ for the aluminum busbar to a value of 40 MPa:

$$l = \left((\sigma \cdot W \cdot D)/(\sqrt{3} \cdot 10^{-8} \cdot i_y^2)\right)^{0,5}. \quad (25)$$

Table 1
Determination of moment of inertia and moment of resistance of the busbars of the OPL in UC

| Busbar location | Moment of inertia | Moment of resistance |
|---|---|---|
|   | $d \cdot h^3/12$ | $d \cdot h^2/6$ |
|   | $h \cdot d^3/12$ | $h \cdot d^2/6$ |

The results of calculating the length of spans for different designs of OPLi in UC with busbars under the action of different short-circuit shock currents, which are performed in accordance with [35] for the minimum possible under the conditions of air insulation breakdown the interphase distance of 300 mm for the PL in UC 110 kV [36] are presented in Fig. 6.

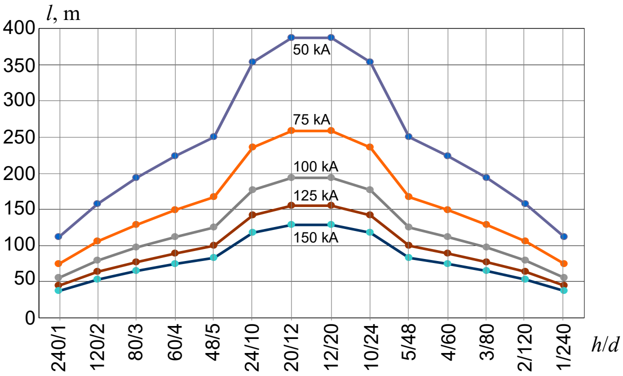


Fig. 6. Results of calculation of the length of the spans $l$ of the OPL in UC depending on the design of the busbars with cross section of 240 mm2 ($h/d$) at different currents

Analysis of the obtained results (Fig. 6) shows that the permissible span length of the OPL in UC with busbars depends quite significantly on its design parameters. The values of the span lengths obtained during the calculations indicate the possibility of constructing OPLs in UC with busbars for almost all busbar structures considered in the work. This indicates that the OPLs in UC with busbars, even for the smallest span values (50 m), will be cheaper than a conventional OPL due to the absence of traditional supports, which in our case are replaced by cheaper garlands of insulators, or support insulators. Therefore, the OPLs in UC, even when its spans are reduced to the minimum value (50 m), are competitive in comparison with OPLs.

Thus, OPLs in UC proposed by authors, in comparison with ground OPLs, as well as with underground OPLs of the same power, allow for reliable transmission of electricity with high throughput, the increase of which compared with ground OPLs 110 kV is from 3 % to 230 % (depending on the design of the busbars) with the same cross-sections of their current conductors. At the same time, the proposed OPLs in UC provide high protection from negative external atmospheric and military factors while reducing the electromagnetic impact on the environment.

At voltages of 20–110 kV, the proposed OPLs in UC are competitive with underground lines with SF6 insulation, since with similar technical characteristics they have a simplified design of current conductors, which requires lower capital and operating costs.

**Conclusions.**

1. The technical and economic advantages of using OPLs in UC when placed in an underground collector are substantiated based on a comparative analysis of the characteristics of OPLs, CLs, and lines with SF6 insulation.

2. A method for calculating permissible continuous currents of OPLs in UC is proposed, which is based on the analytical model developed by the authors for describing mass and heat transfer processes in the air of an underground collector and allows justifying the rational design of phase current conductors made of busbars.

3. It is shown that the implementation of the current conductors of the OPLs in UC from vertical busbars with side ratio of 240/1, 120/2, 80/3, 48/5, which are characterized by an increased surface area and increased natural convection heat transfer compared to a round wire of the same cross-section, as well as taking into account the decrease in air temperature in the underground tunnel to 15 °C compared to the external environment (25 °C), allows to significantly increase the throughput of the OPLs in UC compared to OPLs.

4. Based on the analysis of thermal, electromagnetic, electrodynamic processes in the OPLs in UC and literature sources, the possibility of significantly reducing the interphase distance for OPLs in UC compared to OPLs (for 110 kV OPLs from 3–4 m to 0.3–0.6 m) is substantiated, which allows to design the OPLs in UC in a compact design with a reduced level of electromagnetic fields.

5. For the first time, the technical and economic advantages of using the OPLs in UC in comparison with ground OPLs, as well as underground OPLs and underground CLs with SF6 insulation are substantiated, and conditions are determined to ensure reliable transmission of electricity by the OPLs in UC with high throughput, the increase of which is from 3 % to 230 % (depending on the design of the busbars) compared to 110 kV OPLs in the open air with the same cross-sections of their conductors.

6. The proposed OPLs in UC are competitive with underground lines with SF6 insulation for voltage of 20–110 kV, since with similar technical characteristics they have a simplified design of current conductors, which requires lower capital and operating costs.

7. The design and construction of the proposed OPLs in UC will ensure reliable transmission of electrical energy, sufficient throughput capacity and increased protection from negative external atmospheric and military factors while reducing the electromagnetic impact on the environment.

8. Further research is planned to focus on developing scientific foundations for regulatory documents on the design of OPLs in UC, which are currently absent in Ukraine.

**Conflict of interest.** The authors declare no conflict of interest.

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