DOI: https://doi.org/10.15407/techned2026.03.062

THERMAL STABILITY OF UNDERGROUND HIGH-VOLTAGE CABLE LINE UNDER EMERGENCY CONDITIONS OF OVERLOAD AND SHORT CIRCUIT

A.A. Shcherba[1]*, O.D. Podoltsev[1], I.M. Kucheriava[1], T.Yu. Antonetz[2]*****
[1] Institute of Electrodynamics National Academy of Sciences of Ukraine,
56, Beresteiskyi Ave., Kyiv, 03057, Ukraine, e-mail: podol@ied.org.ua.
[2] PJSC «Yuzhcable Works»,
7, Avtogennaya Str., Kharkov, 61099, Ukraine.

The paper proposes new knowledge in cable engineering by studying the operation of up-to-date high-voltage cable line under the non-nominal and emergency conditions to ensure its reliability and service life. The temperature conditions for operation of an underground 110 kV three-phase cable line with cross-linked polyethylene insulated cables in the nominal and emergency modes of short circuit and short-term overload of cables are studied by computer finite-element method. A number of practically important problems for designing such cable lines are solved. In particular, the computation of the three-phase short-circuit mode in the line is carried out taking into account its reconnection after short circuit with certain delay time (5, 10 or 15 s) and at different loads (50% and 100% of the nominal current). The results obtained allow determining the permissible operating time for the line operation with the temperature of the cable conductor not higher than the permissible limiting value. The nature of the increase in the temperature of the cables within the time of different current overloads varying from 120% to 200% is investigated. The results give a possibility to determine the permissible operating time of the line when the temperature of the cable conductor does not exceed 130°C. In the case of the double-circuit cable line, the computational results for non-stationary thermal process under emergency condition of one circuit failure and the transmission of double power through the other circuit are presented. It is shown that the limiting conductor temperature of 130°C is reached after 1.3 hours of line operation. The problems solved in the paper answer the questions regarding the thermal stability of the high-voltage cable line in emergency modes and are of interest to designers of such lines as well as organizations responsible for their safe operation and power companies for more efficient use of cable lines. References 36, figures 5, tables 2.

Keywords: cables with cross-linked polyethylene insulation, cable line, emergency mode, temperature conditions, safe operation.

Introduction. At present the cross-linked polyethylene (XLPE) insulated power cables, particularly cables of 110 kV and above are widely used in high- and extra-high-voltage power transmission lines This insulation has the high dielectric strength and plasticity as well as the low dielectric permettivity and dissipation factor. Its electrophysical characteristics can remain stable even when the temperature rises by 30% or more. However the reliability and service life of cable XLPE insulation depend largely on operating conditions [1, 2].

For underground cables, their layout, environmental conditions (backfill soil in the trench, natural soil around it) and compliance with electrical and thermal operating conditions are critical. The exceeding of reference temperature limits for cable components leads to accelerated degradation of the insulation that causes a decrease in its dielectric strength [1, 3]. This is particularly important to take into account for high-voltage cable lines. It should be noted that the XLPE insulated power cables rated for voltage up to 330 kV are predominantly used in Ukraine. They are produced by PJSC «Yuzhcable Works» (Kharkiv) [1, 4–7]. The detailed description of the features and characteristics of the cables are given in [6].

The standards and specifications are established for the electrical and thermal characteristics of power cables [2, 5], specifically: the permissible operating temperature of the conductors during continuous operation is 90°C; the maximum permissible temperature of the cable conductors during short circuit is 250°C; the maximum admissible temperature of the cable screen during short circuit is 350°C; the temperature of the conductors under overload conditions is up to 130°C; the duration of cable operation under overloading is no more than 8 hours per day and up to 1,000 hours over the service life. The nominal

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ORCID: *https://orcid.org/0000-0002-0200-369X; ** https://orcid.org/0000-0002-9029-9397;
*** https://orcid.org/0009-0007-2388-2252

cross-sections of conductors and screens are selected depending on current load and verified by the permissible current of the conductor and its current during short circuit [5]. In addition, the correction factors for practical cable laying are calculated and defined more exactly, for example, to recalculate currents depending on cable arrangement, ambient temperature and soil characteristics for underground cables [2, 5].

The determination of cable temperature for specific practical applications requires the consideration of operating conditions and different modes (normal or emergency operation during overloading or short circuit), and is also a crucial factor to provide the reliability and expected service life of the cable lines, since their overheating can lead to insulation damage and cable failure. The temperature affects not only the permissible conductor current, but also power losses.

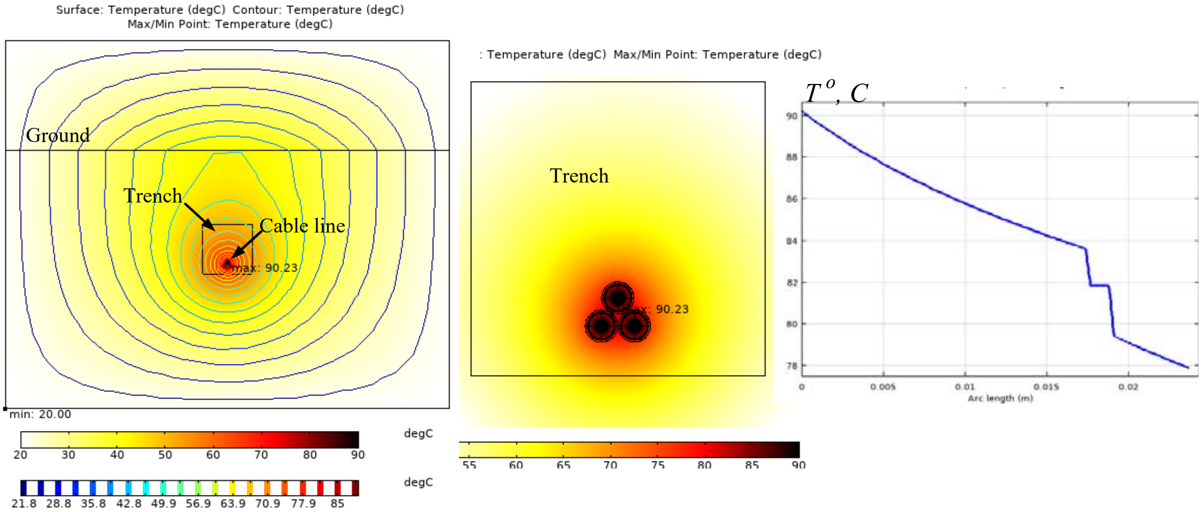
It follows that the task is to determine the permissible current load (maximum cable conductor current) when the cable operates without overheating under different conditions. The calculation of the permissible current and losses is regulated by the IEC international standard [8], which is also valid in Ukraine [9]. The approaches to computer modeling and solving the coupled electromagnetic and thermal field problems are presented in [10, 11].

The operational characteristics of each specific cable line under typical operating conditions, including emergency situations are revealed over a sufficiently long period of operation and require further study of the steady-state and transient thermal processes as well as consideration of cable temperature variations and consequently the development of practical measures to correct the current loads in order to ensure the stable and long-term operation of the cable line.

The objective of this paper is to obtain new data regarding the operation of high-voltage cables in emergency modes through a quantitative study by computer modeling of the thermal field and temperature characteristics of underground 110 kV cable line with XLPE insulation under the nominal condition, current overload, short circuit and then to compare them with existing standard specifications.

The problems solved were revealed during the long-term (10-year) operation of high-voltage cable lines in Ukraine and are of scientific-and-practical interest to both cable manufacturers and organizations responsible for cable operation.

The three-phase cable line under study consists of single-core cables of ПвЕгаПу 1 x 500 / 95(150) type with copper conductor (cross-section of 500 mm^2) and copper screen around the conductor, has the longitudinal and transverse screen sealing with water-blocking fabric and polyethylene shell [5]. According to manufacturer specifications, the cross-section of the copper screen can be 95 mm^2 or 150 mm^2. The cables are laid in a trefoil (triangle) configuration in the ground within a trench at specified depth of 1.5 m (Fig. 1, *a*). The three-phase cable system is modeled as an idealized system of three cables with balanced currents leaving out of account the cable accessories and joints.



a ***b*** ***c***

Fig. 1

The modeling is performed using the finite-element method by COMSOL Multiphysics software [12]. Depending on the specific aims, the two-dimensional steady-state or transient temperature field is numerically calculated and analyzed within the cable cross-section taking into account the mechanism of heat conduction. The convective and radiant heat transfer mechanisms do not considered. All cable characteristics and input data for the computations are set by the manufacturer and correspond to power cables which are in service for a long time (10 years).

Grounds for investigation. It is extremely important to ensure that the power cables operate within the temperature limits for safe operation. The permissible current of the cables can be calculated using the method described in detail in IEC 60287 [8]. However this standard provides only formulas for the rated current or maximum permissible current under stationary conditions and the maximum temperature rise, but does not take into account the heat transfer equations (unlike IEC 60287-2-1:2023 [13], which is applied to various cable installations, including underground laying cables up to 5 kV). Exactly the same is related to the IEC 60853 standard [14], which proposes the methods for determining the cyclic and emergency currents of power cables, but does not provide their temperature rise. The IEC 60986 standard [15] determines the temperature limits of cables at short circuit, provides the tables with maximum permissible temperature to limit the heating, but does not allow for determining the time-varying cable temperature.

The calculations of the rated current require the determining the temperature of the cable components or the permissible current for given cable temperature [16]. Such calculations involve the heat sources and their heat dissipation beyond the cables that depend on the current level, cable dimensions, installation and cable arrangement. With this approach, it is necessary to solve the heat conduction equations using numerical methods [16].

The two- and three-dimensional methods are widely used for numerical computations [17–20], which are a powerful and realistic approach to solving the electromagnetic and thermal problems for power systems [21]. For example, the international standard IEC TR 62095 [16] recommends to use the finite-element method when the methods presented in IEC 60287 (for steady-state conditions) and IEC 60853 (for cyclic conditions) cannot be applied.

In general, there are various approaches to calculate the temperature of power cables with XLPE insulation under nominal and emergency conditions. The most well-known approaches are the use of 1) analytical expressions [22], 2) thermal equivalent circuits (or electrothermal analogs) [10, 23–25] and 3) finite-element analysis [1, 10, 11, 26].

As noted above, the analytical methods do not allow for a detailed analysis of temperature variations as functions of the duration of emergency operation. The modeling of thermal processes in cable lines based on thermal equivalent circuits at three-phase short circuit in a load [10] involves the fairly complex MatLab/Simulink models and provides the computation of coupled electromagnetic and thermal processes in cable lines. The most widely used method for comprehensive steady-state and transient thermal processes based on the heat conduction equation is computer finite-element modeling which is chosen as a tool for this study.

The basic methods and approaches for determining the operational characteristics of high-voltage cable lines, including cable current load are presented in [27–29].

Further development and improvement of the methods for evaluation of cable thermal stability is of practical importance for the power industry.

Mathematical models for thermal processes in underground cables. The computer simulation of temperature field is carried out for 2D model under the assumption that the underground cables are long and laid parallel to the ground surface at specified depth. The installation conditions remain permanent along the entire length of the cable routing. In addition, it is assumed that the soil around the trench and the backfill soil in the trench are homogeneous throughout the depth. In a more general case, the physical properties of the soil are heterogeneous because they change during the operation of the underground cable as well as under the influence of weather factors.

The heat sources are the electric currents flowing in the conductors and induced in the cable screens.

Steady-state temperature field. The distribution of 2D temperature field in the cross-section of the cable line under steady-state conditions is described by heat conduction differential equation:

$$-\nabla \cdot (\lambda \nabla T) = Q, \tag{1}$$

where λ is the thermal conductivity; Q is the power density of the heat sources, including the Joule heat generated in the conductors of the cables and losses due to current in the copper screen of each cable (Fig. 2).

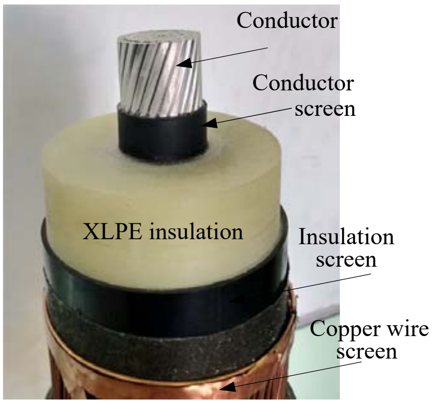


Fig. 2

The specific heat generation is calculated as follows:

$$Q = \begin{cases} J_c^2 / \sigma_c \ \ in\ conductors; \\ J_s^2 / \sigma_s \ \ in\ screens; \\ 0 \ \ in\ other\ elements. \end{cases} . \tag{2}$$

Here J_c, J_s are the current density in the cable conductors and screens, respectively; σ_c, σ_s are the electrical conductivity of the conductor and screen, which varies with temperature [30, p. 315].

The energy losses in the insulation are not presented in (2). They can be evaluated by [31].

Transient temperature field is determined by the next equation:

$$C\rho \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = Q , \tag{3}$$

where C and ρ are the specific heat capacity and density of the corresponding material. The temperature dependencies $\lambda(T)$, $C(T)$ for polyethylene are given in [32]. The dependencies $\lambda(T)$, $C(T)$ and $\rho(T)$ for copper are presented in [33]. The heat generation rate Q in (3) is determined by (2).

Table 1. Characteristics of ПвЕгаПу 1 x 500 cable and the cable line based on it

Geometric characteristics	
Cable diameter, mm	74
Conductor diameter, mm^2	26.5
Thickness of XLPE insulation, mm	15.0
Thickness of conductor screen, mm	1.4
Thickness of insulation screen, mm	1.0
Layer of water-blocking fabric, mm	0.3
Thickness of screen, mm	1.13
Thickness of polyethylene shell, mm	4.5
Depth of cable laying in the ground, m	1.5
Electrical characteristics	
Cable with screen of 95 mm^2	
Current in conductor / electrical resistance, A /Ω/km	687 / 0.048
Current in screen/ electrical resistance, A / Ω/km	154 / 0.230
Cable with screen of 150 mm^2	
Current in conductor / electrical resistance, A /Ω/km	666 / 0.048
Current in screen / electrical resistance, A / Ω/km	226 / 0.148
Cable grounding	at both ends
Frequency, Hz	50
Thermal characteristics	
Specific thermal resistance of polyethylene (insulation, shell, screen), K·m/W	3
Thermal resistance of copper (conductor, screen), K·m/W	0.0025
Thermal resistance of water-blocking layer, K·m/W	50
Thermal resistance of backfill soil, K·m/W	1.0
Thermal resistance of soil around the trench, K·m/W	1.5

The dimensions of the computational domain are chosen to be significantly larger than the dimensions of the cables (Fig. 1, *a*), so the boundary conditions on all external boundaries are $T = T_O = 20\,^0$C (ambient temperature – 20°C). The initial temperature in the computational domain is equal to the ambient temperature – $T|_{t=0} = T_O$.

Computational results. The trench for cable laying is shown in Fig. 1, *a, b*. The computational domain contains a three-phase cable line in the trench with special backfill soil and natural soil around it.

The structure of the cables under study is shown in Fig. 2. The main characteristics of the cable line under consideration with different screen cross-sections (95 and 150 mm^2) are listed in Table 1. The cable screens in the line are grounded at both ends. The resistance of the grounding conductors does not taken into account.

Table 2. Calculated cable temperature for screens with different cross-sections

Screen cross-section S_S , mm^2	Current, A / resistance, Ω/km in conductor	Current, A / resistance, Ω/km in screen	Maximum temperature, $T_{\max}$
95	687 / 0,048	154 / 0,23	90,23
150	666 / 0,048	226 / 0,148	90,13

The cable and soil characteristics in Table 1 as well as the current values are the data of producer in accordance with IEC 60287 standard [8] and serve as initial conditions for the computations. The resistances of the cable conductor and screen in Tables 1 and 2 are given for 50 Hz frequency and maximum temperature of conductor (90°C). The changes in the soil characteristics around the cables are disregarded, although in reality the thermal resistance and heat capacity depend on the soil composition, moisture content, weather conditions and temperature variations in time [34].

1. Computer program verification by comparing the conductor temperature obtained with numerical calculation and IEC standard [8], regulating data by analytical methods. The results of the numerical calculation of the steady-state thermal process in the cable line with screen cross-section of 95 mm^2 are shown in Fig. 1, *a, b*, where the temperature field distribution (in color and by isolines) around the cables is given for conductor/screen current – 687/154 A, screen cross-section – 95 mm^2. The temperature variation along the radius of the upper cable from the conductor surface to the external point of the screen is given in Fig. 1, *c*. The highest temperature of the conductor is 90°C, it exactly complies with IEC standard [8].

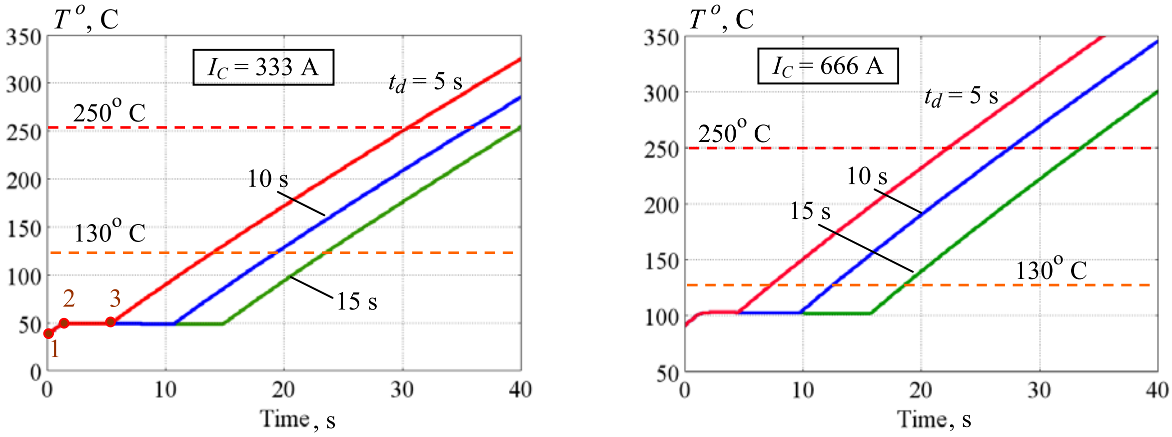
Below we consider a number of problems that arose due to a long-term (over 10 years) operation of high-voltage power lines in Ukraine and are important for cable manufacturers and designers.

2. Evaluation of current-carrying capacity of the cables as the screen cross-section increases. The computations are carried out for cables with screens of 95 mm^2 and 150 mm^2. The numerical results are listed in Table 2. The table shows that as the screen cross-section increases, the current in the screen increases (from 154 to 226 A) and the losses in it increase too. Consequently to keep the conductor temperature at 90°C, the current in the conductor should be reduced (in this case, from 687 to 666 A). The ratio of these values is equal to 666/687 = 0.97 and corresponds exactly to the recommended correction factor [9]. Thus the numerical results in Table 2 confirm the correction factor (0.97) at the transition to screen cross-section of 150 mm^2.

The problems 1 and 2 conform to the steady-state heating of cables. The problems 3–5 involve the study of transient temperature field in the cable.

3. *Thermal stability of cables to three-phase short-circuit currents at the output of cable line, when the automatic recloser (AR) operates, in a practical scenario of relay protection against cable short circuit under different current loads.* It is assumed that the relay protection clears the external short circuit and after a certain delay time the AR operates and then the line is reconnected to the power source. In this case, two scenarios are possible: either the line subsequently operates under normal conditions, or the repeated short circuit occurs. Such emergency conditions of the cable line in power network require the study of cable thermal stability. This is important for both designers and companies responsible for the maintenance of cable lines.

Fig. 3 shows the time-dependent conductor temperature of the upper cable in the line with screen cross-section of 150 mm^2 and for different delay times t_d (5, 10, 15 s) after one-second short circuit and the automatic reconnection of the cable line after such delay period, when the short circuit occurs again. The computational results are presented for two values of current in the cable conductors: *a)* 50% of conductor current (333 A); *b)* 100% of conductor current (666 A). Fig. 3, *a* shows the characteristic red points: 1 – short-circuit emergence, 2 – line disconnection after 1 second, 3 – reconnection of the cable line operating at short-circuit condition. The specified current values (333 and 666 A), the conditions both for short-circuit and connection of the cables shown in Fig. 3 are stated by the cable producer and found to be practically significant for the cable under investigation.



a ***b***

Fig. 3

The thermal stability of the cable line within the relevant time interval is evaluated by data in Fig. 3, taking into account the exceeding of the specified maximum conductor temperature of 130°C under overloading and 250°C at short-circuit mode [2, 5]. The results in Fig. 3 allow determining the permissible operating time of the cable line when the conductor temperature does not exceed the limiting values.

4. The overload of a double-circuit cable line with screen cross-section of 150 mm². The cable line consists of two circuits similar to those in Fig. 1, *b*. It is assumed that the emergency takes place in one of the circuits and then all power is transmitted through the other circuit that is the conductor current increases 2 times. For this case, Fig. 4 shows the time-varying temperature of the conductor of the upper cable in the overloaded circuit with current of 2 × 666 A. As can be seen from Fig. 4, the conductor temperature of 130°C that corresponds to the permissible level under overload conditions is achieved after 1.3 hours of cable line operation. This means that the double-circuit cable line with one disconnected circuit can operate and transmit the total rated power in an emergency within 1.3 hours.

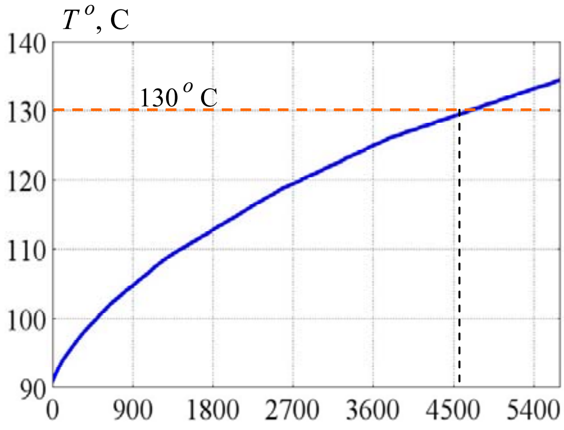


Fig. 4

5. Temperature of overloaded cable line. This problem corresponds to the case when the cable line operates with power transformer. It is known that the power transformer at the output of the power line can withstand the overloads for a given period of time, for example, 110–120% overload – for an indefinite period, 130% – for up to 6 hours, 150% – for half an hour, and 200% – for 5 minutes. The designers of the power line should be confident that the cables in the line can take the possible overloads.

The computed data for time-dependent conductor temperature at given overloads are presented in Fig. 5. As assumed, the initial conductor current is 666 A, the cross-section of the screen is 150 mm² and the initial temperature of all cable components is equal to steady-state temperature. The dotted lines in Fig. 5 indicate the permissible operating time of the power transformer. It can be seen that during this time the conductor temperature increases, but does not exceed the admissible temperature (130°C). Moreover even if the current increases up to 2 times during the specified operating intervals, there is still a load reserve.

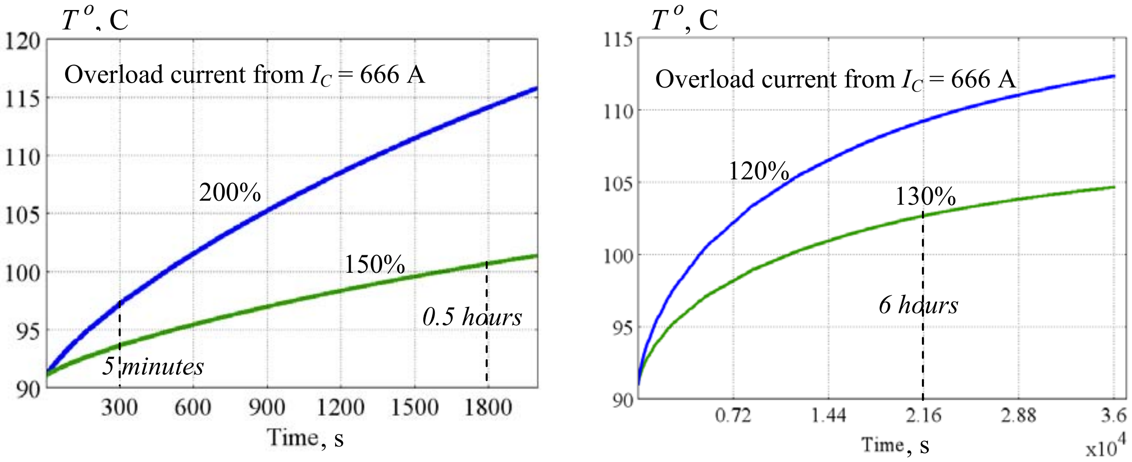


Fig. 5

The problems 4 and 5 take into account the temperature variation along the thickness of XLPE insulation of the cables as shown in Fig. 1, *c*. This is particularly important for cyclic heating of cables, as it is associated with the thermal aging of the insulation and the electrothermal stresses inside the cable [35, 36].

It should be noted that this work stipulates the further study with consideration of cable joints, grounding connections, current state of polyethylene insulation and so on.

Conclusions. This paper presents new data on the operation of 110 kV power cables under emergency conditions. They are important for improving the reliability and stability of cable lines in power supply systems.

Using the finite-element method, the temperature conditions of underground three-phase cable line with 110 kV XLPE insulated cables are investigated under normal operation and under the emergency conditions such as short circuit and transient cable overloads.

A number of the problems practically important for the designing of such cable lines are solved. In particular, the computations are fulfilled for three-phase short-circuit condition, taking into account the automatic reclosing of the line after short circuit with different delay times (5, 10, and 15 s) and under different loads (50 and 100% of the rated current). The results allow determining the operating time of the line when the cable conductor temperature does not exceed the permissible limiting values.

The cable temperature variations under different current overloads (ranging from 120 to 200%) are studied. The results give a possibility to find the operating time of the line when the cable conductors do not heat up above the admissible temperature of 130°C.

For the double-circuit cable line, the computation of the transient thermal process in an emergency of one circuit is carried out. As shown, the maximum conductor temperature of 130°C is achieved after 1.3 hours of cable line operation.

The developed methodology and the obtained data regarding the thermal stability of high-voltage cable lines at the overload and short-circuit conditions are of interest to the cable designers, organizations responsible for the safe operation of power cables and can show the ways to use the cable lines more efficiently.

The paper was realized within the framework of state fundamental program «Elres», state registration number 0123U100693, KPKVK 6541030.

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УДК 621.315.2:004.94

ТЕРМІЧНА СТІЙКІСТЬ ВИСОКОВОЛЬТНОЇ ПІДЗЕМНОЇ КАБЕЛЬНОЇ ЛІНІЇ В АВАРІЙНИХ УМОВАХ ПЕРЕВАНТАЖЕННЯ І КОРОТКОГО ЗАМИКАННЯ

А.А. Щерба[1*] академік НАНУ, **О.Д. Подольцев**[1**], докт. техн. наук, **І.М. Кучерява**[1], докт. техн. наук,
Т.Ю. Антонець[2***], канд. техн. наук

[1] **Інститут електродинаміки НАН України,**
пр. Берестейський, 56, Київ, 03057, Україна,
e-mail: podol@ied.org.ua.
[2] **ПАТ «Завод «Південкабель»,**
вул. Автогенна, 7, м. Харків, 61099, Україна.

Роботу присвячено отриманню нових даних у галузі кабельної техніки шляхом вивчення роботи сучасної високовольтної кабельної лінії в аварійних режимах задля забезпечення надійності і ресурсу функціонування. З використанням скінченно-елементного аналізу досліджено температурні режими підземної трифазної кабельної лінії з кабелями зі зшито-поліетиленовою ізоляцією напругою 110 кВ в номінальному режимі та в аварійних режимах короткого замикання і короткочасного перевантаження кабелів. Розв'язано ряд практично важливих задач, що виникають під час проектування таких кабельних лінії, зокрема проведено розрахунок режиму трифазного КЗ в лінії з урахуванням її повторного включення після КЗ з певним часом витримки (5, 10 та 15 с) та за різного навантаження – 50% і 100% від номінального струму. Результати дають змогу визначити допустимий час роботи лінії з температурою жил кабелів не вище допустимого граничного значення. Досліджено характер зростання у часі температури кабелів за різного струмового перевантаження, що змінюється в діапазоні від 120% до 200%. Результати дають змогу визначити допустимий час роботи лінії, коли температура жили кабелів не перевищує 130°С. У випадку дволанцюгової кабельної лінії наведено результати розрахунку нестаціонарного теплового процесу у разі аварійного режиму пошкодження одного ланцюга та передаванні подвійної потужності по іншому ланцюгу. Показано, що гранична температура жили 130°С досягається після 1,3 години роботи такої лінії. Розв'язані в роботі задачі дають можливість отримати відповіді на питання щодо термічної стійкості високовольтної кабельної лінії в аварійних режимах і представляють інтерес для проектувальників таких ліній, організацій, відповідальних за їхню безпечну експлуатацію, електроенергетичних компаній для більш ефективного використання кабельних ліній. Бібл. 36, рис. 5, табл. 2.

Ключові слова: кабелі зі зшито-поліетиленовою ізоляцією, кабельна лінія, аварійний режим, температурні режими, час роботи кабелю в безпечному режимі.

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Received 11.09.2025
Accepted 13.10.2025