doi: 10.5862/MCE.50.8

The capacity limitations of power transmission cable lines in the structure of civil and industry engineering networks

V.V. Titkov;
S.M. Dudkin;
P.D. Tukeev,
St. Petersburg Polytechnic University;
A.V. Kosorukov,
LLC "ELNAP"

Abstract. The present study analyses heat modes of high voltage cable lines typical for laying in the area of communications, different obstacles and engineering networks, such as, for instance, hot water supply lines.

It is well-known that the load capacity of modern high voltage cable lines with a plastic insulation is limited by the maximum permissible heating temperature of 90 °C. This study focuses on two typical cases of heating mains influence on heat exchange of a power cable line with surrounding ground: 1) the rapprochement of a power cable line with a heating main – the segment of a parallel disposal of a cable line and a heating pipe; 2) the intersection of a cable line and a heating main – the area where the cable line going above the heating main crosses it at the angle of 90 degrees.

We have proposed the model of a prolonged cylinder with inhomogeneous thermophysical and heat exchange parameters distribution along this cable for the temperature distribution along a power cable in terms of non-regular laying. The finite-element method has been used to solve the problem of cable line heating fields near heating main calculation. A quantitative analysis of the cases described above has revealed that the local cable temperature excess up to several tenths of degrees is typical for them. It leads to the transmission capacity decrease by 20–30 % and limits the cable line ability to cover peak loads occurring in industrial, natural or other disasters. Besides, cable line segment spillover out of permissible temperature mode leads to emergency, power shortage and further repairing efforts. While engineering and calculations of the cable lines modes, our proposed techniques allow avoiding critical temperature conditions which may lead to the consequences described above.

Key words: underground high voltage power cable; capacity limitation; specially developed math models

The appliance of power cables with paper-oil or plastic insulation in the power transmission technology is a commonly used approach in the power supply of major cities, industrial organizations and complexes [1, 2]. The high level of power consumption and high electrical power distribution density is typical for them. The most appropriate technical solution of the power supply by techno-economic criteria is the appliance of average and high voltage power cables with XLPE-insulation [3, 4]. A relatively small price and mass production of this cable type caused its vast application. These cables are also very workable at laying under different conditions [5]. The fast adaptation of a new type of cables with XLPE-insulation caused a number of problems associated with the lack of experience in diagnostics and reliability estimation [6] and also their insulation testing [7, 8].

The power cable insulation construction feature is high operating electrical field density. A relatively thin conductive shield is required for the proper field distribution sustenance in a polyethylene insulation. It guarantees the maximum field density limitation in the insulation and eliminates an electrical field outside the cable.

In this case a standard laying technology assumes shield grounding in several points along a cable line. Laying additional currents in shields cause significant additional heating which limits cable line capacity. These problems and possible solutions have been considered in [4]. For instance, the application of shield grounding in one point (one-side grounding) or shield transposition by means of a special box joints along the line has been proposed. Such a remarkable attention to the heat generation and cable line heating problems is concerned due to their influence on cable life-time and reliability [9, 10].

This study mostly focuses on an important aspect of the cable line heating mode typical for the cable line on 35 kV or higher voltage.

In this case the maximum cable temperature is the main reason of load-carrying limitation capacity, i.e. maximum line transmission capacity [11–14].

Unlike the cable line heating modes in regular laying area [12, 14–17] which have been thoroughly researched before, this study considers more complicated cases associated with local temperature excesses caused by the features of cable line laying next to the engineering networks and communication. In particular, a “breach” method is used to study cable line heating in case of its laying across the obstacles (roads, walls, rivers etc). In this case a cable line mechanical protection in the area of the “breach” complicates the heat exchange between the cable and the ground causing the local temperature excess.

However, even the local temperature excess becomes the reason for the cable line capacity limitation in general. In addition, local temperature excesses may appear in the case of its rapprochement or the intersection with heating mains.

Although different approaches to cable line heat mode estimation were described in the numerous publications, the particular qualities of a cable line temperature distribution field in terms of cable line uniformity breaches caused by the obstacles (”breaches” in places of crossings with pipelines, walls, water obstacles etc.), convergences or crossings with heat pipelines were not considered in details.

We have made an attempt to estimate the temperature excesses of cable lines in the proximity of sections mentioned before. The significance of this estimation is obvious assuming that the capacity of the high voltage cable lines is limited by their maximum temperature. Hereinafter three typical cases are considered: heat mode in a “breach” area, a heat pipeline and cable line crossing area and a heat pipeline and cable line proximity area.

In the area of natural obstacles (walls, roads etc) when steel or plastic tubes are used for the mechanical protection of cable lines a significantly more problematic heat mode, limiting cable line capacity, occurs in comparison with the uniform cable laying area [13, 18]. The presence of air in a protective tube significantly decreases heat exchange between the cable line and the ground. Besides, the steel tubes, if applied, are becoming the source of an additional heat generation caused by eddy currents. Thus such areas being relatively short still limit the cable line capacity in general.

In the paper [18] heat modes of cable lines laid in steel and polymeric tubes of different diameters with respect to long line segments have been analyzed. At the same time, as noted before, the obstacle length is mostly limited by 10 meters. Therefore cable heat mode in the area of obstacles will be formed not only by the heat exchange with surrounding soil (a transverse heat exchange) but also by the heat transfer along a cable line from a higher temperature area (a tube laying area) to the less heated ground laying area.

An exact analysis of a heat mode for the given conditions demands solving a three-dimensional problem with a number of terms which significantly complicates the given problem. They are the following: an air convection process inside the tube area of cable laying, a sophisticated eddy current distribution inside conductive construction elements (shields, tubes), very small ratio between transversal and lengthwise sizes of the cable line.. Therefore geometric parameters and the necessity to solve mutually dependent systems of electrodynamic and thermodynamic equations significantly complicates the problem. Thus, the application of standard software using a finite-element method seems to be ineffective.

We have considered an approach based on the representation of a cable line as an elongated object with uniform distributions of temperature and physical characteristics within each cross-section of this line calculated as mean values over the cross-sections of the real line. At the same time we have assumed that the mean values of the cross-section characteristics can change along the line. For instance, they will differ in the areas of the in-tube or in-ground cable laying. This approach has been implemented in several studies taking into consideration the analysis of temperature distribution along the current-carrying busbars with contact connections [19].

The paper considers the basis for averaged over the cable line cross-section characteristics calculation, for instance, in studies [12 ,13, 20]. It also deals with the model of plane parallel temperature fields and air flow due to convection, which finds usage in the analysis of long (theoretically infinite) cable line sections. Nowadays polymeric tubes are widely used in cable line laying. Let us consider a temperature field in a cross-section of a cable line laid in a polymeric tube of a big diameter (Fig. 1).

Let us also consider the shields of single-phased cables to be transposed and neglect the input of eddy currents in them in total heat generation. Although this approach does create slightly easier terms according to heating value, the implemented simplifications are not significant while estimating a “breach” influence on the lengthwise temperature distribution.

It’s convenient to take a round cross-section limited by a protective tube as the computation cross-section of the cable line with equivalent averaged parameters. Then the equivalent cross-section will exactly match the cross-section of the protective tube. In the area of in-ground laying air space will be replaced by ground in calculating the averaged parameters. The results of the finite-element analysis by means of the models mentioned before are used as distributions for the averaging by the cross-section of the equivalent line. Table 1 shows mean characteristics calculation formulas.

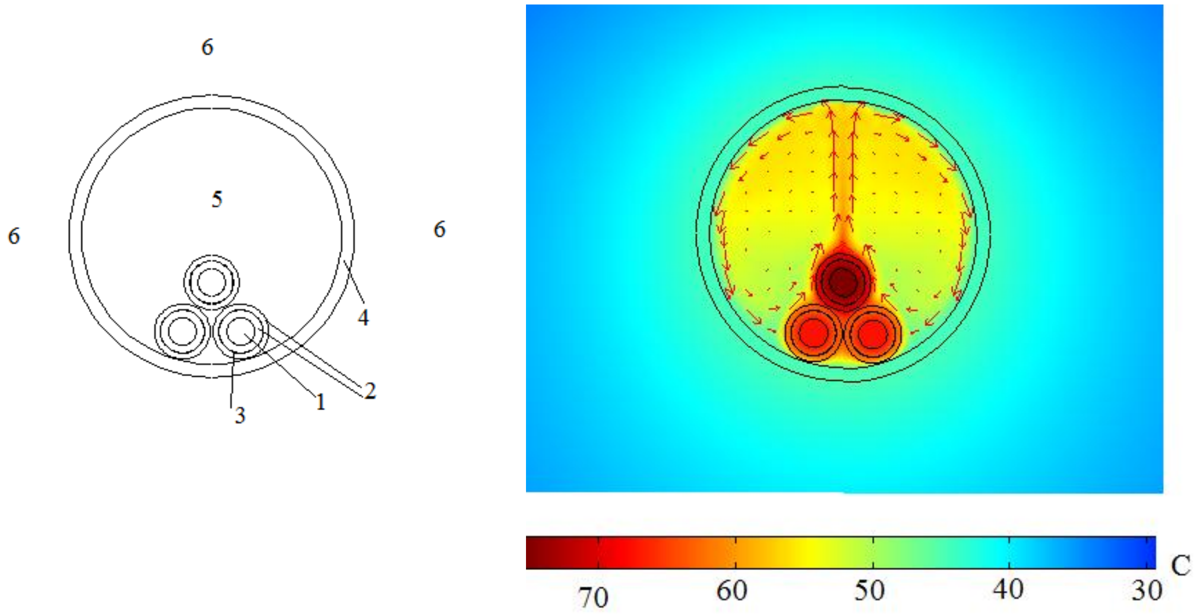


Figure 1. Temperature field and convective air flow scheme of 35 kV cable line laid in a polymeric tube: 1 – cable conductor, 2 – insulation layers, 3 – conductive shield, 4 – tube, 5 – air, 6 – ground

It seems to be rational to take round cross-section limited by the protective tube diameter as the computation cable cross-section with the equivalent averaged parameters. Then the equivalent cable line cross-section will perfectly match to the protective tube cross-section. In case of regular cable laying the air space and the protective tube will be replaced by ground in the calculation of averaged parameters. The results of a finite-element analysis by means of the models mentioned before are used as distributions for averaging across the equivalent cable line cross-section S. Formulas for averaged characteristics calculation are given in the table below.

Table 1. Formulas and numerical values of the averaged parameters for the cable line of 35 kV with phase load of 850 A in polymeric tubes of big and small diameters

Averaged values	Formulas	Units of measure	Small tube		Big tube	
			Ground	Tube	Ground	Tube
Thermal conductivity along the line	$\tilde{\lambda} = \frac{1}{S} \int\limits_S \lambda dS$	W/m*K	53	54	12.8	13.3
Volume heat generation power in the cable line cross-section	$\tilde{q} = \frac{1}{S} \int\limits_S q dS$	W/m^3	2700	2700	630	630
Temperature of a distant perimeter L of a computation area	$\tilde{T}_e = \frac{1}{L} \int\limits_L T_e dL$	° C	10	10	10	10

Averaged values	Formulas	Units of measure	Small tube		Big tube	
			Ground	Tube	Ground	Tube
Temperature in the cable line cross-section	$\tilde{T} = \frac{1}{S}\int_S T\,dS$	$^\circ$C	83	116	69	89
Coefficient of a heat generation from equivalent line surface	$\tilde{\alpha} = \frac{\tilde{q}S}{(\tilde{T}-\tilde{T}_e)p}$	W/m^2 *K	0.74	0.51	0.9	0.67
Equivalent line cross-section perimeter	p	m	0.5	0.5	1.02	1.02
Equivalent line cross-section	S	m^2	0.02	0.02	0.086	0.086

The computation model for a cable line with averaged parameters is based on the solution of the equation given below according to Figure 2:

$$\tilde{\lambda}\frac{d^2\tilde{T}}{dx^2} + \dot{q}_+ - \dot{q}_- = 0,$$

where x – the coordinate along the line; $\dot{q}_+ = \tilde{q}$ – averaged heat generation power (Table 1);

$$\dot{q}_- = \frac{\tilde{\alpha}p}{S}(\tilde{T} - \tilde{T}_e) \ –$$

the volume power density of a transverse heat generation from the equivalent line surface to the ground, where p – the equivalent line cross-section perimeter; $\tilde{\alpha}$, $\tilde{T}_e$ – the effective coefficient of the heat source from the equivalent line surface and the temperature of the ground distant from the cable line laying area (Table 1). Using the designations

$$\theta = \tilde{T} - \tilde{T}_e,\ k^2 = \frac{\tilde{\alpha}p}{S\lambda},\quad w = \dot{q}_+ / \lambda,$$

the equation of a heat generation along a cable line may be transformed into the form

$$\frac{d^2\theta}{dx^2} - k^2\theta = -w. \qquad (1)$$

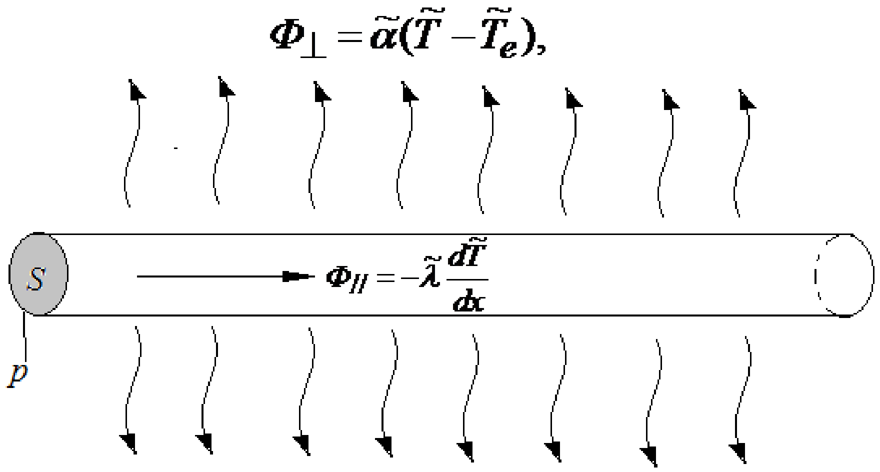


Figure 2. Computation model of the heat exchange in the equivalent cable line

The solution of the last equation will be obtained on the half-infinite line starting in ($x = 0$) the middle of the in-tube area of the line l. In addition, the equation (1) parameters step-like change occurs on the boundary ($x = l/2$) between the in-tube and in-ground cable areas.

$$k = k_1,\ w = w_1 \quad \text{at} \quad 0 \le x \le l/2;$$

$$k = k_2,\ w = w_2 \quad \text{at} \quad \infty \ge x > l/2.$$

Accordingly it appears to be rational to write down the equation (1) solution in form of the two functions – $\theta_1(x)$ и $\theta_2(x)$ for the in-tube and the in-ground areas consequently. In that case the terms of temperature and the longwise heat flow in the boundary ($x = l/2$) of the indicated segments are fulfilled which means

$$\theta_1(l/2) = \theta_2(l/2);$$

$$S_1\tilde{\lambda}_1 \left.\frac{d\theta_1}{dx}\right|_{x=l/2} = S_2\tilde{\lambda}_2 \left.\frac{d\theta_2}{dx}\right|_{x=l/2} \tag{2}$$

Besides, due to the symmetry of the temperature distribution along the line with respect to the in-tube segment middle point (x=0) another boundary condition can be received.

$$\left.\frac{d\theta_1}{dx}\right|_{x=0} = 0\,. \tag{3}$$

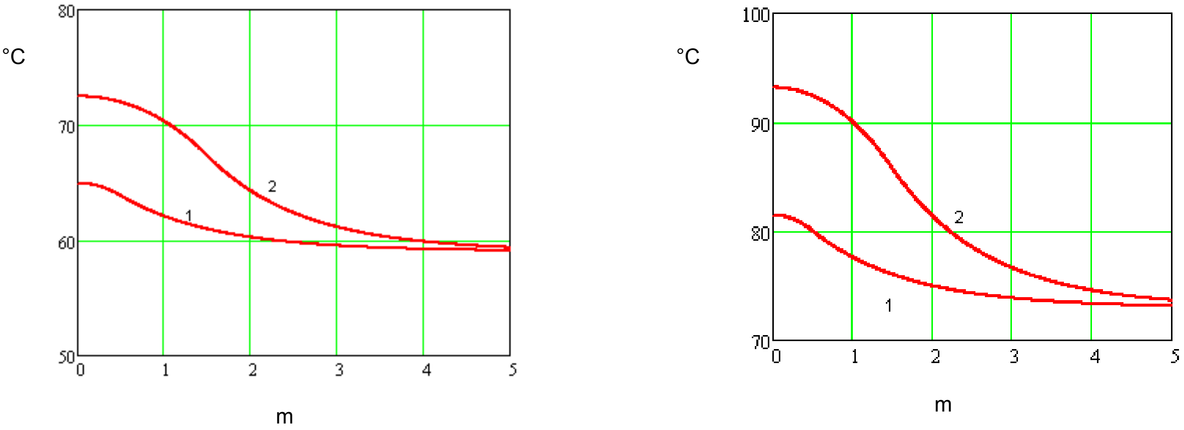
Equation (1) solution with regard to the boundary conditions (2)–(3) formulates the equations for the temperature distribution along the line given below

$$\theta_1(x) = \frac{(Q_2 - Q_1)}{ch\left(\frac{k_1 l}{2}\right) + \frac{k_1\tilde{\lambda}_1 S_1}{k_2\tilde{\lambda}_2 S_2}\, sh\left(\frac{k_1 l}{2}\right)}\, ch(k_1 x) + Q_1; \tag{4}$$

$$\theta_2(x) = \frac{(Q_2 - Q_1)\left(\frac{k_1\lambda_1 S_1}{k_2\lambda_2 S_2}\right) sh\left(\frac{k_1 l}{2}\right)}{ch\left(\frac{k_1 l}{2}\right) + \frac{k_1\lambda_1 S_1}{k_2\lambda_2 S_2}\, sh\left(\frac{k_1 l}{2}\right)} \exp\left[k_2\left(\frac{l}{2} - x\right)\right] + Q_2\,, \tag{5}$$

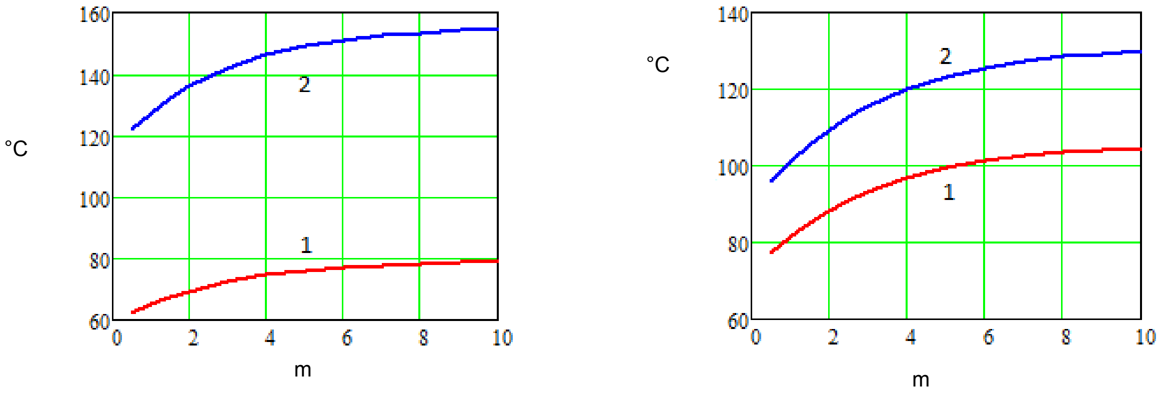
where

$$Q_1 = w_1/k_1^2, \quad Q_2 = w_2/k_2^2.$$



a) b)

Figure 3. Functional correlation betwen the average line temperature excess with respect to the ground and the distance from the in-tube segment middle point at the tube length 1 m (curve 1) and 3 m (curve 2). Cable laid in big (a) and small (b) tubes



a) b)

Figure 4. Functional correlation between the average (1) and the maximum (2) line temperature in the in-tube segment middle point and the in-tube segment length. The cable is laying in big (a) and small (b) tubes.

Figure 3 shows averaged temperature distribution examples along the line with the zero point in the middle of the in-tube segment calculated by (4) and (5).

Figure 3 and 4 show that the in-tube segment extension leads to the significant increase in temperature in its middle point. It is essential to know the maximum temperature, i.e. the cable core temperature to estimate carrying capacity. Averaged and maximum temperatures ratio is determined in context of a plain problem solution (fig.1). For the cases assumed the averaged and the maximum temperatures are interrelated by the linear ratios $T_{\max} \cong 1.96\tilde{T}$ for a big tube and $T_{\max} \cong 1.2\tilde{T}$ for a small one.

Figure 4 shows dependences indicating that in the in-tube segment length exceeding 3 m the lengthwise heat transfer along the line is not able to promote a temperature reduction in the middle point. At the same time in the in-tube segment length no more than 1 m temperature is going down by 30 % in comparison with long in-tube segments. The temperature mode of long in-tube cable segments may be improved by filling the tube with higher thermal conductivity than the ground one after cable laying.

The increase in temperature in the in-tube cable segment in comparison with regular laying area leads to the maximum load-carrying capacity limitation. In the considered case the presence of the in-tube segment leads to the necessity of reducing load current from 850 A to 650 A in case of small tube laying and to 600 A in case of big tube laying for the maximum permissible temperature of 96 °C. It corresponds to the decrease of load-carrying capacity by 24 % and 29 % respectively.

Typical elements of engineering network infrastructure are heating mains. Heating mains placed in the proximity of a cable line, especially in case of their thermal insulation faults, may complicate heat exchange of the cable line with the ground. This circumstance is also the reason for the reduction of cable line load-carrying capacity. Below we consider two extreme cases of the heating main and the cable line heat fields superposition – the rapprochement (parallel heating main and cable line axes orientation) and the intersection (a cable line and the heating main axes are placed perpendicularly).

It is convenient to examine the cable line load-carrying capacity limitation caused by the proximity of a heating main for the case of rapprochement of a cable line with parallel directed heating main. In this case a well-approved plain-parallel electromagnetic and heating field model and suitable finite-element software can be applied. Figure 5 shows the example of this calculation.

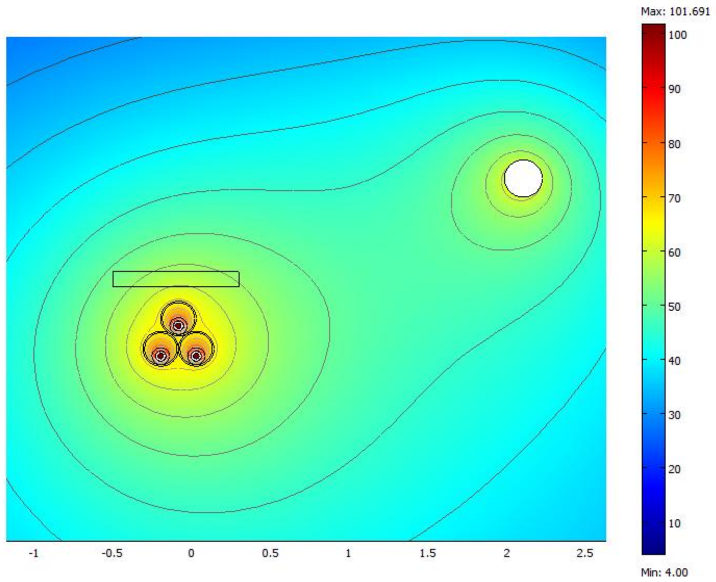


Figure 5. Temperature field fragment of a cable line near the heating main

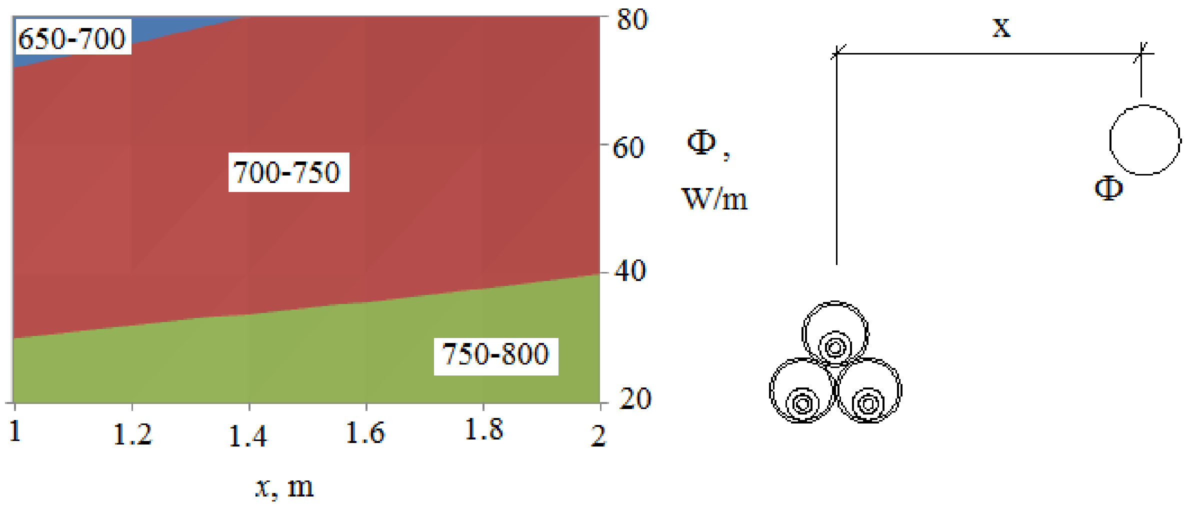


Figure 6. Limiting continuous phase current (A) according to rapprochement distance of a cable line with a heating main with linear heat flux Φ

Figure 6 shows the functional correlation between the maximum phase load current in terms of thermal stability and the rapprochement *x* of a cable line with a heating main which thermal insulation permits linear heat flux F.

Figure 6 indicates a negative combination of rapprochement of a cable line and a heating main in addition to its thermal insulation property deterioration (e.g. in case of local damage) may cause the reduction of cable line load-carrying capacity by 15–20 %.

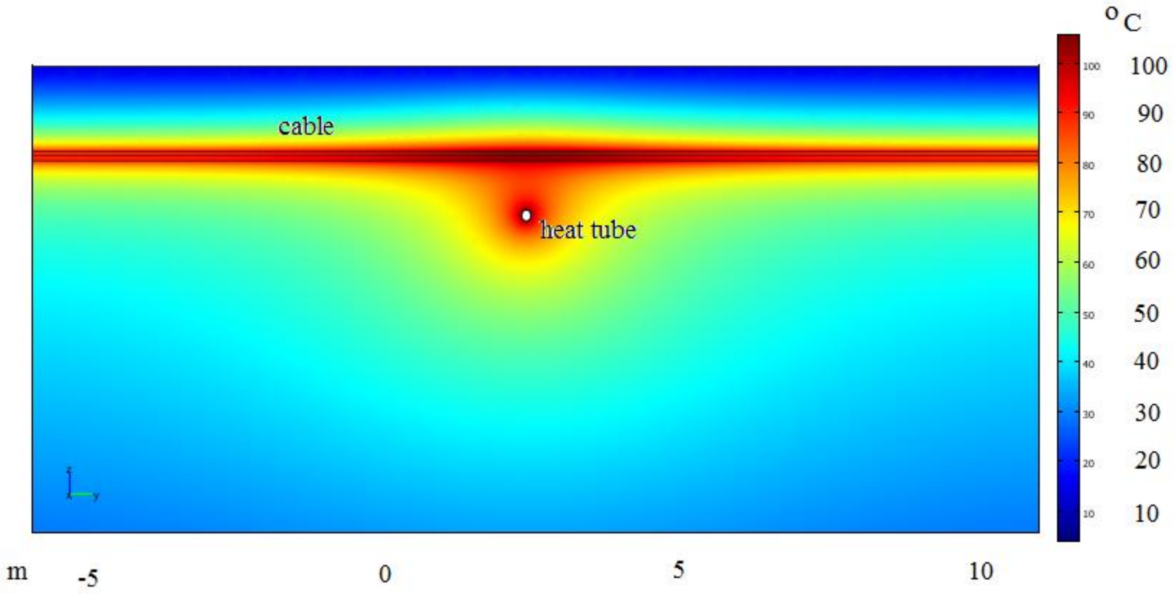


Figure 7. Temperature filed in the proximity of a cable line and a heating main intersection

Table 2. Cable line local temperature excess in the proximity of a heating main intersection

Linear heat flux to the ground, W/m	Distance from a cable line to a heating main	
	0.5 m	1 m
	Temperature excess, C	
50	24	14
100	47	29

The calculation results of the example for the second extreme case considered in this study are the following. A perpendicular intersection of a cable line and a heating main (Fig. 7.) indicates the local temperature increase in the area of heating main projection. At the same time, according to a heat flux intensity from the heating main surface and the distance from a heating main to a cable line the local temperature excess in the considered case may reach several tenths of degrees Celcius.

Table 2 shows that the most difficult mode form corresponds to the reduction of cable line load-carrying capacity by 30 %.

Conclusions

In this study we have come to the conclusion that the examples of the power cable lines laying inside or in the proximity of the elements of engineering networks features show that they may lead to the remarkable local temperature excess of the cable line. The given circumstance causes the reduction of load-carrying capacity reduction by 30 %.

The underestimation of local temperature excess of the cable line laid near the municipal engineering networks may lead to emergency mode and cable line outage.

Typical analytic computation models of cable line heating mode developed for regular laying cases are not applicable for the terms considered in the given study. The most suitable approach for the described cases is the finite-element analysis and also the specially oriented calculation methods which are similar to the “breach” model proposed in this study.

References

1. Heinhold L. *Power Cables and Their Applications, third edition*. Berlin, Munchen: Siemens-Aktienges, 1990. Part 1. 464 p.
2. Larina E.T. *Silovyye kabeli i vysokovoltnyye kabelnyye linii* [Power cables and high-voltage cable line]. Moscow: Energoatomizdat, 1996. 464 p.
3. High voltage XLPE cable systems. Technical user guide. BRUGG KABEL AG. 2006.

4. Nevar G. Ob ekspluatatsii kabeley s izolyatsiyey iz sshitogo polietilena [On the operation of cables with XLPE insulation]. *Kabel-news*. 2011. No. 3. Pp. 40–46.
5. Shevelev V. Sovremennyye metody stroitelstva i montazha silovykh kabelnykh liniy napryazheniyem 110–220 kV [Modern methods of construction and installation of power cable lines 110-220 kV]. *Kabel-news*. 2011. No. 1. Pp. 44–52.
6. Novoposelenskikh N. Vysokovoltnyye kabelnyye seti. Nadezhnaya ekspluatatsiya v techeniye dlitelnogo sroka [HV cable networks. Reliable operation over the long term]. *Kabel-news*. 2012. No. 6. Pp. 44-52.
7. Diagnostika silovykh kabelnykh liniy [Diagnosis of power cable lines] Elektronpribor . 2012. Vol. 2. [Online resource]. URL: http://www.electronpribor.ru/resources/docs/journal_022012.pdf.
8. Kucherenko V., Kuryumov G., Zakharov M. Diagnostika kabelnykh liniy klassov napryazheniya 35-110 kV [Diagnostics cable lines classes of 35-110 kV]. *Kabel-news*. 2012. No. 6. Pp. 52–57.
9. Kaniskin V.A., Kostenko E.M., Tadzhibayev A.I. Nerazrushayushchiy metod opredeleniya resursa elektricheskikh kabeley s polimernoy izolyatsiyey v usloviyakh ekspluatatsii [Non-destructive method for determining the resource of electrical cables with polymeric insulation under operating conditions]. *Electricity*. 1995. No. 5. Pp. 19–13.
10. Nazarychev A., Andreyev D. Vybor metodiki opredeleniya srabotannogo resursa, sovremennykh kabelnykh liniy [The choice of methodology for determining the load resource, advanced cable lines]. *Kabel-news*. 2014. No.1. Pp. 40–45.
11. Anders G.J. *Rating of Electric Power Cables. Ampacity Computations for Transmission, Distribution and Industrial Applications*. New York: McGraw Hill, 1997. 494 p.
12. Nahmana J., Tanaskovich M. Evaluation of the loading capacity of a pair of three-phase high voltage cable systems using the finite-element method. *Electric Power Systems Research*. 2011. Vol. 81. Pp. 1550–1555.
13. Dudkin S.M., Tadjibaev A.I., Titkov V.V. Thermal conditions in three-phase cable lines of medium and high Voltages, featuring plastic insulation. *Proceedings of the 7-th Internaional Scientific Symposium Electrical Power Engeneering Elektroenergetika 2013*, September 18-20, 2013. Stara Lesna, Slovak Republic. Pp. 366–369.
14. Slim A., Hau X. Analytical method of calculating the transient and steady-state temperature rises for cable-bundle in tray and ladder. *IEEE Trans. PWRD 13*. 1998. Pp. 691–698.
15. Titkov V.V. K otsenke teplovogo rezhima trekhfaznoy linii iz SPE-kabelya [The estimation of the thermal regime of the three-phase line of XLPE cable]. *Kabel–news*. 2009. No. 10. Pp. 31–35.
16. Rachek M., Larbi S.N. Magnetic eddy-current and thermal coupled models forthe finite-element behavior analysis of underground power cables. *IEEE Trans. Magn.* 2008. Vol. 44(12). Pp. 4739–4746.
17. Electric cables – calculation of the current rating – part 3-2: Sections on operating conditions – economic optimization of power cable size, IEC Standard 60287.
18. Dudkin S.M., Titkov V.V. Kabelnyye linii 6-10 kV i vyshe. Vliyaniye sposobov prokladki na temperaturnyy rezhim [Cable lines 6-10 kV and above. Influence of ways of laying on the temperature regime]. *Electrical Engineering News*. 2012. No.3(75). Pp. 38–40.
19. Sukhichev M.I., Titkov V.V. K voprosu o teplovoy diagnostike kontaktnykh soyedineniy [On the issue of thermal diagnostics of contact connections]. *Elektro*. 2010. No.3. Pp. 42–44.
20. Carlos del-Pino-López J., Cruz-Romero P., Serrano-Iribarnegarayb L., Martínez-Román J. Magnetic field shielding optimization in underground power cableduct banks. *Electric Power Systems Research*. 2014. Vol. 114. Pp. 21–27.

Vasily V. Titkov, St. Petersburg, Russia
+78125554286; e-mail: titkovprof@yandex.ru

Sergey M. Dudkin, St. Petersburg, Russia
+78125554286; e-mail: dudkin@eef.spbstu.ru

Pavel D. Tukeev, St. Petersburg, Russia
+78125554286; e-mail: paultuk@yandex.ru

Anton V. Kosorukov, St. Petersburg, Russia
+78125554286; e-mail: kosorukov_anton@inbox.ru

doi: 10.5862/MCE.50.8

Ограничения нагрузочной способности кабельных линий электропередачи в структуре инженерных сетей промышленных и гражданских объектов

Д.т.н., заведующий кафедрой В.В. Титков
Санкт-Петербургский государственный политехнический университет,
Санкт-Петербург, Россия
Тел. раб.: +78125554286; e-mail: titkovprof@yandex.ru
к.т.н., доцент С.М. Дудкин
Санкт-Петербургский государственный политехнический университет,
Санкт-Петербург, Россия
Тел. раб.: +78125554286; e-mail: dudkin@eef.spbstu.ru
аспирант П.Д. Тукеев
Санкт-Петербургский государственный политехнический университет,
Санкт-Петербург, Россия
Тел. раб.: +78125554286; e-mail: paultuk@yandex.ru
технический директор А.В. Косоруков
ООО «ЭЛНАП», Санкт-Петербург, Россия
Тел. раб.: +78125554286; e-mail: kosorukov_anton@inbox.ru

Ключевые слова

подземные силовые кабельные линии высокого напряжения; нагрузочная способность; предельно допустимая темепратура

Аннотация

В работе анализируются тепловые режимы кабельных линий высокого напряжения, характерные для условий прокладки в области коммуникаций, разного рода препятствий и инженерных сетей, таких как, например, трассы горячего водоснабжения.

Хорошо известно, что нагрузочная способность современных высоковольтных кабельных линий с пластмассовой изоляцией ограничена предельной температурой нагрева порядка 90 °С. При прокладке даже относительно короткого участка подземной кабельной линии в условиях с затрудненным теплообменом это приводит к ограничению пропускной способности всей линии передачи. В работе рассмотрены три характерных случая влияния элементов инженерных сетей и коммуникаций на теплообмен силовой кабельной линии с окружающим грунтом: 1) тепловой режим линии в «проколе» – коротком участке, где в целях механической защиты кабеля применяется прокладка в трубе; 2) сближение силовой кабельной линии с теплотрассой – участок параллельного расположения кабеля и тепловой трубы; 3) пересечение кабеля и теплотрассы – области, в которой кабель, проходя над теплотрассой, пересекает ее направление под углом 90 градусов.

Количественный анализ описанных выше случаев показал, что для них характерно локальное по длине кабеля повышение температуры до нескольких десятков градусов. Это приводит к снижению передаваемой электрической мощности на 20–30 % и ограничивает возможности кабельной линии при покрытии пиковых нагрузок, возникающих вследствие техногенных, природных или иных причин. Кроме того, выход участка кабельной линии за пределы допустимого температурного режима приводит к аварии, отключению элетроэнергии и последующим ремонтным работам. Предложенные в работе методики и результаты позволят избежать при проектировании и расчете режимов кабельных линий опасных температурных режимов, способных привести к описанным выше последствиям.

Литература

1. Heinhold L. Power Cables and Their Applications, third edition. Berlin, Munchen: Siemens-Aktienges, 1990. Part 1. 464 p.
2. Ларина Э.Т. Силовые кабели и высоковольтные кабельные линии. М.:Энергоатомиздат, 1996. 464 с.
3. High voltage XLPE cable systems. Technical user guide. BRUGG KABEL AG. 2006.
4. Невар Г. Об эксплуатации кабелей с изоляцией из сшитого полиэтилена // Кабель-news. 2011. №3. С. 40–46.

5. Шевелев В. Современные методы строительства и монтажа силовых кабельных линий напряжением 110-220 кВ // Кабель-news. 2011. №1. С. 44–52.
6. Новопоселенских Н. Высоковольтные кабельные сети. Надежная эксплуатация в течение длительного срока // Кабель-news. 2012. №6. С. 44–52.
7. Диагностика силовых кабельных линий // Электронприбор. 2012. Вып. 2 [Электронный ресурс]. URL: http://www.electronpribor.ru/resources/docs/journal_022012.pdf.
8. Кучеренко В., Курюмов Г., Захаров М. Диагностика кабельных линий классов напряжения 35-110 кВ // Кабель-news. 2012. № 6. С. 52–57.
9. Канискин В.А., Костенко Э.М., Таджибаев А.И. Неразрушающий метод определения ресурса электрических кабелей с полимерной изоляцией в условиях эксплуатации // Электричество. 1995. №5. С. 19–13.
10. Назарычев А., Андреев Д. Выбор методики определения сработанного ресурса, современных кабельных линий // Кабель-news. 2014. №1. С. 40–45.
11. Anders G.J. Rating of Electric Power Cables. Ampacity Computations for Transmission, Distribution and Industrial Applications. New York: McGraw Hill, 1997. 494 p.
12. Nahmana J., Tanaskovich M. Evaluation of the loading capacity of a pair of three-phase high voltage cable systems using the finite-element method // Electric Power Systems Research. 2011. Vol. 81. Pp. 1550–1555.
13. Dudkin S.M., Tadjibaev A.I., Titkov V.V. Thermal conditions in three-phase cable lines of medium and high Voltages, featuring plastic insulation // Proceedings of the 7-th Internaional Scientific Symposium Electrical Power Engeneering Elektroenergetika 2013, September 18-20, 2013. Stara Lesna, Slovak Republic. Pp. 366–369.
14. Slim A., Hau X. Analytical method of calculating the transient and steady-state temperature rises for cable-bundle in tray and ladder // IEEE Trans. PWRD 13. 1998. Pp. 691–698.
15. Титков В.В. К оценке теплового режима трехфазной линии из СПЭ-кабеля // Кабель-news. 2009. №10. С. 31–35.
16. Rachek M., Larbi S.N. Magnetic eddy-current and thermal coupled models forthe finite-element behavior analysis of underground power cables // IEEE Trans. Magn. 2008. Vol. 44(12). Pp. 4739–4746.
17. Electric cables – calculation of the current rating – part 3-2: Sections on operating conditions – economic optimization of power cable size, IEC Standard 60287.
18. Дудкин С.М., Титков В.В. Кабельные линии 6-10 кВ и выше. Влияние способов прокладки на температурный режим // Новости электротехники. 2012. №3(75). С. 38–40.
19. Сухичев М.И., Титков В.В. К вопросу о тепловой диагностике контактных соединений // Электро. 2010. №3. С. 42–44.
20. Carlos del-Pino-López J., Cruz-Romero P., Serrano-Iribarnegarayb L., Martínez-Román J. Magnetic field shielding optimization in underground power cableduct banks // Electric Power Systems Research. 2014. Vol. 114. Pp. 21–27.

Полный текст статьи на английском языке: с. 75–83