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O. Tkachenko, U. Pyrohova, V. Grinchenko

Highly accurate approximation for sheath currents in high-voltage three-phase cable line

Introduction. *This study focuses on sheath currents in high-voltage single-core XLPE-insulated power cables with solid bonding. The analysis covers flat and trefoil three-phase cable lines. Sheath current calculation is essential for evaluating thermal conditions, losses, and overall cable performance.* ***Problem.*** *The regulatory documents of the Ministry of Energy of Ukraine provide formulas for sheath currents. We examine them by comparing with verified analytical solutions and find significant discrepancies in a wide range of typical parameters of high-voltage three-phase cable line. So the formulas in the current regulatory document have a narrow range of applicability, and the engineering calculations based on them may lead to significant inaccuracies and incorrect decisions.* ***Goal.*** *The paper aims to develop novel formulas for the RMS values of sheath currents in high-voltage three-phase cable lines with flat and trefoil arrangements of power cables, ensuring the accuracy required for engineering calculations across a wide range of cable line parameters.* ***Methodology.*** *This study is grounded on the previously developed and experimentally verified analytical model and corresponding formulas for calculating sheath currents and cable line magnetic field. These verified formulas for sheath currents are too cumbersome, so an approximation technique is used to find compact ones.* ***Results.*** *A novel approximation for sheath current in the flat cable line is developed. The discrepancy between the approximation and the verified formulas is within 5 %. Additionally, a new form of the formula for sheath current in the trefoil cable line is proposed.* ***Scientific novelty****. To perform the approximation, an original quality index is proposed. It is derived from the heat output of metal sheaths of cables.* ***Practical value.*** *The developed approximation for sheath current can be directly applied to the design of high-voltage cable lines, the analysis of the operating modes, and the control of the compliance of existing cable lines with actual operating conditions.* References 20, table 1, figures 4.

Keywords: **metal sheath, cable line, single-core cable, solid bonding, regulatory document.**

Вступ. *В роботі розглянуто струми в екранах одножильних силових кабелів високої напруги, з ізоляцією зі зшитого поліетилену (XLPE), при заземленні з обох кінців. Аналіз охоплює кабельні лінії змінного струму з розташуванням кабелів за схемами «у площині» та «у трикутник». Розрахунок струму в екранах є важливим при оцінці теплового стану, втрат та режиму роботи кабельної лінії.* ***Проблема.*** *Нормативні документи Міністерства енергетики України містять співвідношення для розрахунку струмів в екранах. Аналіз цих співвідношень шляхом порівняння з верифікованими аналітичними формулами показав значну розбіжність у широкому діапазоні типових параметрів трифазної кабельної лінії високої напруги. Відповідно, співвідношення в чинних нормативних документах мають вузький діапазон застосовності, а їх використання для інженерних розрахунків може призвести до значних неточностей та хибних висновків.* ***Метою*** *роботи є розробка нових наближених співвідношень для розрахунку діючих значень струмів у екранах кабелів трифазних кабельних ліній високої напруги, прокладених за схемами «у площині» та «у трикутник», задля забезпечення необхідної точності у широкому діапазоні параметрів кабельної лінії.* ***Методологія.*** *Дослідження ґрунтується на раніше розробленій авторами та експериментально верифікованій аналітичній моделі та відповідних співвідношеннях для розрахунку струмів в екранах, та магнітного поля трифазної кабельної лінії. Оскільки зазначені співвідношення для струмів є занадто громіздкими, тому для знаходження компактного співвідношення використовується апроксимація.* ***Результати.*** *Розроблено нове наближене співвідношення для розрахунку струму в екранах кабельної лінії з розташуванням кабелів «у площині». Розбіжність між наближенням та верифікованими формулами становить до 5 %. Крім того, запропоновано нову форму співвідношення для розрахунку струму в екранах кабельної лінії з розташуванням кабелів «у трикутник».* ***Наукова новизна.*** *Для виконання апроксимації запропоновано оригінальний показник якості, який визначається величинами теплової дії струмів в екранах кабелів.* ***Практична значимість.*** *Розроблене наближене співвідношення для розрахунку струму в екранах може бути безпосередньо застосоване при проєктуванні трифазних кабельних ліній високої напруги, аналізі режимів їхньої роботи та контролі відповідності існуючих кабельних ліній фактичним умовам експлуатації.* Бібл. 20, табл. 1, рис. 4.

Ключові слова: **екран, кабельна лінія, одножильний кабель, заземлення з обох кінців, нормативний документ.**

Introduction. The most advanced means of electrical energy transmission in urban areas are underground high-voltage three-phase cable line. A typical cable line consists of three single-core XLPE-insulated power cables. The main structural elements of these cables are an aluminum or copper conductor, XLPE insulation, and a copper sheath (Fig. 1). The metal sheath provides a uniform electric field in the insulation layer.

The Ukrainian industry uses the regulatory document [1]. According to them, the metal sheaths of cables require earthing. For this, sheaths are bonded and earthed at one or several points. Typically, there are three types of bonding: single-point bonding, cross-bonding, and solid bonding. Other types of bonding are discussed in [2], but they are not commonly used.

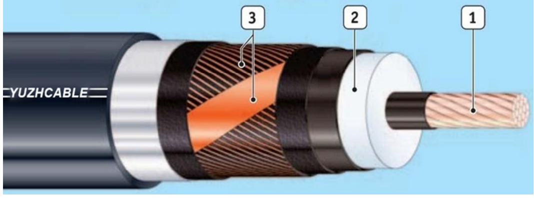


Fig. 1. Single-core XLPE-insulated power cable: 1 – aluminum or copper conductor, 2 – XLPE insulation, 3 – copper sheath

Single-point bonding is the simplest way. In this case, the metal sheaths of cables are solidly bonded together and earthed at only one point along an elementary section of cable line. The single-point bonding provides no circulating sheath currents and consequently no heating in sheaths. But sheaths are earthed only once. Thus, the cables have zero electric potential only at the earthing point. And additional protective devices are required for installation at each elementary section.

To implement the cross-bonding, the cable line length is divided into three approximately equal sections, and the metal sheaths in consecutive sections are cross-connected. As a result, there are no longitudinal sheath currents. However, this type of bonding is not widespread because of its relative complexity and high cost.

Solid bonding of high-voltage power cables is the most common one. All metal sheaths are electrically bonded together and earthed at two points: at the beginning and at the end of the cable line. Solid bonding ensures the absence of impulse overvoltage and does not require additional protective devices. Moreover, the cable metal sheaths form closed loops with induced longitudinal currents [3–6]. Thus, the magnetic field of induced currents decreases the total magnetic field of the cable line. This effect contributes to the solution of magnetic ecology problems [7–11]. But currents in the sheaths can disrupt the thermal regime of the cable line and reduce its capacity.

The transmission capacity is determined by the temperature of the cable conductor. This temperature can be determined by numerical simulation of the cable line thermal field [12–14] or by using the standard IEC 60287 [15]. IEC 60287 is applicable in most cases, and numerical simulation has almost no constraints when a specific case is under study. However, to simulate the cable line thermal field, the RMS values of sheath currents are required.

The analytical formulas for calculating sheath currents provided in the regulatory document [1] are compact. However, the analysis below demonstrates that they have a narrow range of applicability, and calculations based on them may lead to significant inaccuracies.

Solid bonding is studied in [16], and a compact formula for sheath current is proposed. It is derived via algebraic manipulation of the known formulas for metal sheath losses in the standard IEC 60287 [15]. While mathematically valid, it obscures the physical interpretation and lacks experimental or numerical verification. In contrast, this paper presents an alternative approach that gives a novel verified approximation for a flat cable line.

The paper aims to develop novel formulas for the RMS values of sheath currents in high-voltage three-phase cable lines with flat and trefoil arrangements of power cables, ensuring the accuracy required for engineering calculations across a wide range of cable line parameters.

Verified formulas for sheath currents. The reduction of cable line magnetic field in the case of solid bonding is studied in [17]. As a result, the analytical model of the cable line magnetic field and the corresponding formulas for sheath currents are developed and experimentally verified. The following natural assumptions are used in [17]: the distribution of the induced current is uniform within each metal sheath, and the sheath thickness is much smaller than the cable radius. The discrepancy between calculations carried out according to [17] and experimental results from [18] is within 5 %.

Analytical formulas for the phasors of sheath currents are represented in [17]. To obtain the formulas for the RMS values of the sheath currents, we compute the modulus of the current phasors and divide by $\sqrt{2}$. Furthermore, the currents can be conveniently described with only two dimensionless parameters of the cable line:

$$Q=\frac{\mu_0\omega}{2\pi R},\quad \varDelta=\frac{s}{d}, \tag{1}$$

where ω=2π·50 rad/s is the angular frequency of current; R is the DC resistance of a cable sheath unit length, Ω/m; s is the distance between axes of adjacent cables, m; d is the metal sheath diameter, m; μ_0 is the vacuum permeability.

Parameters Q and $\varDelta$ vary within specific ranges related to the high-voltage cable line. Namely, the parameter $\varDelta$ varies from 1 to 10, and Q varies from 0.1 to 0.5. The minimum of $\varDelta$ occurs for closely laid cables, and the junction zone of cables exhibits maxima of $\varDelta$. The parameter Q is inversely proportional to DC resistance R. Table 1 shows the Q values for typical high-voltage power cables from [19].

Table 1

Parameter Q for a typical high-voltage single-core XLPE-insulated power cables

No.	Metal sheath cross-section S, mm^2	Metal sheath DC resistance R 10^{-3}, Ω/m	Q
1	35	0.524	0.12
2	50	0.387	0.16
3	70	0.268	0.23
4	95	0.193	0.33
5	120	0.153	0.41
6	150	0.124	0.51

We consider two types of arrangements of solidly bonded high-voltage power cables. In the case of the trefoil arrangement, the RMS values of sheath currents are equal and have the following form:

$$I_{sh}=I\cdot\sqrt{\frac{Q^2\ln^2 2\varDelta}{1+Q^2\ln^2 2\varDelta}}\,. \tag{2}$$

In case of the flat arrangement, when currents in conductors form a positive sequence set, we get the following formulas for the RMS values of sheath currents:

$$I_{sh1}=I\cdot\sqrt{\frac{\left(Q\cdot\ln 4\varDelta\cdot\ln 4\varDelta^3+\sqrt{3}\cdot\ln 2\right)^2+\ln^2 32\varDelta^3}{\left(Q\cdot\ln 4\varDelta\cdot\ln 4\varDelta^3-\dfrac{3}{Q}\right)^2+4\cdot\ln^2 16\varDelta^3}};$$

$$I_{sh2}=I\cdot\sqrt{\frac{Q^2\cdot\ln^2 4\varDelta^3}{9+Q^2\cdot\ln^2 4\varDelta^3}}; \tag{3}$$

$$I_{sh3}=I\cdot\sqrt{\frac{\left(Q\cdot\ln 4\varDelta\cdot\ln 4\varDelta^3-\sqrt{3}\cdot\ln 2\right)^2+\ln^2 32\varDelta^3}{\left(Q\cdot\ln 4\varDelta\cdot\ln 4\varDelta^3-\dfrac{3}{Q}\right)^2+4\cdot\ln^2 16\varDelta^3}},$$

where I is the RMS value of current in the conductors of the cables.

If the flat cable line has negative-sequence current, then the right sides of the first and the third formulas in (3) are swapped.

Note that the difference between formulas (2), (3) and their original forms from [17] is due to the difference in the definition of the dimensionless parameter $\varDelta$. Here we use the metal sheath diameter in the denominator. At the same time, the sheath radius is used as the denominator in [17].

Thus, we get verified formulas (2) and (3) for sheath currents within the accepted assumptions. Formula (2) is sufficiently compact for a trefoil cable line. But we treat formulas (3) as too cumbersome for a flat cable line.

Sheath current in trefoil cable line. The regulatory document [1] provides the following formula for sheath current in a trefoil cable line when its power cables are solidly bonded:

$$I_{sh}^{reg}=I\cdot\sqrt{\frac{0.0019}{R_{70}^2+0.0019}}\,, \tag{4}$$

where R_{70} is a DC resistance of the metal sheath per one kilometer length at a temperature of 70 °C, Ω/km.

We express (4) in terms of Q and obtain the following formula for the sheath current:

$$I_{sh}^{reg}=I\cdot\sqrt{\frac{4.75\cdot Q^2}{\pi^2+4.75\cdot Q^2}}\,. \tag{5}$$

To examine (4), (5) and to compare them with the verified analytical formula (2), we use the original quality index ε derived from the heat output of sheaths of power cables. It shows the discrepancy in the total heat output of sheaths when different formulas for sheath current are used. As the sheath heat output $W = I_{sh}^2 \cdot R$, then

$$\varepsilon = \left| 1 - \frac{3 \cdot \left(I_{sh}^{reg}\right)^2}{3 \cdot I_{sh}^2} \right| \cdot 100\% = \left| 1 - \frac{\left(I_{sh}^{reg}\right)^2}{I_{sh}^2} \right| \cdot 100\%, \quad (6)$$

where the numerator is calculated via (4) or (5), and the denominator is calculated via (2).

The factor 3 in the numerator and denominator of (6) indicates the number of cables.

Figure 2,*a* shows that the quality index ε weakly depends on parameter Q, and Fig. 2,*b* – significant dependence on parameter Δ. Particularly, ε rapidly rises from 0 to 60 % with the growth of Δ from 1 to 1.5. So the formula (4) has a narrow range of applicability when Δ is close to 1. But in general, it is not appropriate for engineering calculations. In contrast, the formula (2) is accurate and compact for engineering calculations of sheath current in a trefoil cable line.

Note that the value Δ=1.1 from Fig. 2,*a* refers to the cables laid in direct contact. The value Δ=2.2 refers to the cable spacing equal to one cable diameter. And according to the regulatory document [20], the value Δ=4.4 represents the maximum permissible cable spacing along the cable route.

Sheath current in flat cable line. Here, we calculate the sheath current in the flat cable line by analogy with our calculations for the trefoil one.

The regulatory document [1] provides the following formula for sheath current in a flat cable line when its power cables are solidly bonded:

$$I_{sh}^{reg} = I \cdot \sqrt{0.75 \cdot \frac{0.017}{R_{70}^2 + 0.017} + 0.25 \cdot \frac{0.01}{R_{70}^2 + 0.01}}. \quad (7)$$

We express (7) in terms of Q and get the following:

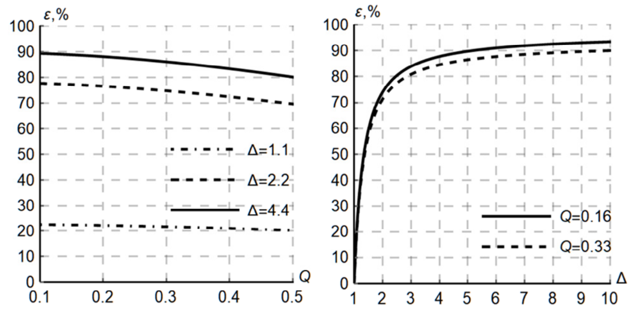
$$I_{sh}^{reg} = I \cdot \sqrt{0.75 \cdot \frac{42.5 \cdot Q^2}{\pi^2 + 42.5 \cdot Q^2} + 0.25 \cdot \frac{25 \cdot Q^2}{\pi^2 + 25 \cdot Q^2}}. \quad (8)$$

Then we examine (7), (8) by evaluating the discrepancy between the total heat output of the sheaths. The quality index ε is as follows for the flat cable line:

$$\varepsilon = \left| 1 - \frac{3 \cdot \left(I_{sh}^{reg}\right)^2}{I_{sh1}^2 + I_{sh2}^2 + I_{sh3}^2} \right| \cdot 100\%, \quad (9)$$

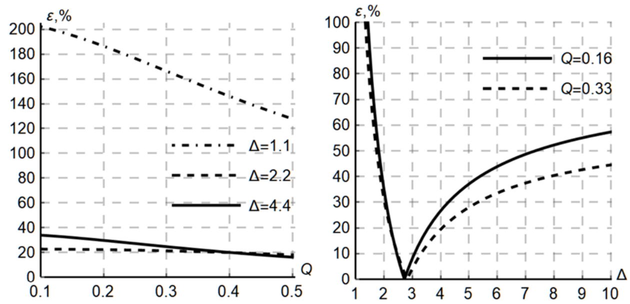
where the sheath current is calculated via (8) in the nominator and via (3) in the denominator.

Figure 3 shows the dependences of the quality index ε on the parameters Δ and Q. Figure 3,*a* shows that ε is approximately 20 % and does not depend on Q when Δ=2.2 only. In contrast, ε changes significantly with Q at other values of Δ. Figure 3,*b* shows that the quality index ε rapidly falls from 100 % to 20 % as the parameter Δ increases from 1.5 to 2.2. The quality index ε takes appropriate values in the range 0–20 % only when Δ lies in the narrow range from 2.2 to 4. And ε is about zero when Δ is about 2.8.



a *b*

Fig. 2. Quality analysis of the regulatory formula for sheath current in the trefoil cable line



a *b*

Fig. 3. Quality analysis of the regulatory formula for sheath current in the flat cable line

So the formula in regulatory document [1] has a narrow range of applicability, and the engineering calculations based on it may lead to significant inaccuracies and incorrect decisions.

To develop an accurate approximation for sheath current in a flat cable line, we use the following form based on (2):

$$I_{sh}^{approx} = I \cdot F(Q, \Delta) \cdot \sqrt{\frac{Q^2 \ln^2(2.52 \cdot \Delta)}{1 + Q^2 \ln^2(2.52 \cdot \Delta)}}, \quad (10)$$

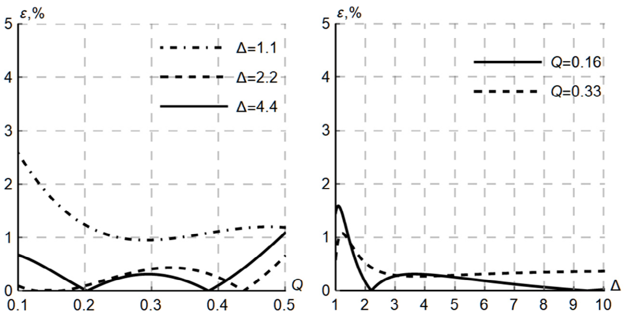
where $F(Q, \Delta)$ is a non-dimensional correcting coefficient, and $2.52 \cdot \Delta$ is a geometrical mean value of three pairwise distances between cables.

In definition (9), we substitute I_{sh}^{reg} with (10) and find the unknown function $F(Q, \Delta)$ by minimizing the quality index ε under the constraints that Q varies from 0.1 to 0.5 and Δ varies from 1 to 10. Thus, we obtain the following novel approximation:

$$I_{sh}^{approx} = I \cdot \sqrt{\frac{Q^2 \ln^2(2.52 \cdot \Delta)}{1 + Q^2 \ln^2(2.52 \cdot \Delta)}} \times \left(1 + \frac{0.05 - 0.3Q}{\Delta} + \frac{0.1 + 0.075Q}{\Delta^2}\right). \quad (11)$$

To find the discrepancy between the approximation (11) and the verified formulas (3), we substitute I_{sh}^{reg} with (10) in the definition (9) and analyze the quality index ε in Fig. 4. It shows that ε is less than 3 %. And it is less than the 5 % error of analytical model used to find formulas (2) and (3).

Thus, the proposed formulas (2) and (11) are directly applicable to the design of high-voltage cable lines, the analysis of operating modes, and the assessment of compliance with actual operating conditions.



a *b*

Fig. 4. Quality analysis of the novel approximation for sheath current in the flat cable line

Conclusions. This paper demonstrates that the formulas for calculating the RMS values of sheath currents in high-voltage three-phase cable line, as recommended by the regulatory documents of the Ministry of Energy of Ukraine when sheaths are solidly bonded, have narrow ranges of applicability. And the engineering calculations based on them may lead to significant inaccuracies and incorrect decisions.

A novel approximate formula for calculating the RMS values of sheath current in the flat cable line is developed. The approximation error is within 5 %. Additionally, the new form of the formula for the trefoil cable line is proposed. These formulas for calculating sheath currents cover the entire range of parameters of high-voltage cable lines.

The developed formulas are recommended for use in revising the regulatory documents of the Ministry of Energy of Ukraine that govern the calculation of sheath currents in cable lines with solidly bonded sheaths.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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O. Tkachenko[1]*, PhD, Senior Researcher,*
U. Pyrohova, Independent Researcher,
V. Grinchenko[2]*, PhD, Senior Researcher,*
[1] Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine,
2/10, Komunalnykiv Str., Kharkiv, 61046, Ukraine.
[2] General Energy Institute of National Academy of Sciences of Ukraine,
172, Antonovycha Str., Kyiv, 03150, Ukraine
e-mail: oleksandr.tk7@gmail.com (Corresponding Author)

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