SHORT-CIRCUIT CURRENTS IN 6-500 kV ELECTRICAL NETWORKS CONTAINING CABLE LINES

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Active and inductive impedances of overhead and cable lines are important for calculating various normal and emergency operating modes. In particular, they are important for the correct determination of short-circuit currents of the network, on which the choice of the cross-section of wires and cables, as well as the choice of switches, depends.

The use of correct parameters of cable lines, taking into account all the main influencing factors, shows that in the high-voltage cable networks, the real currents of three-phase and single-phase short-circuit can be up to 30% higher than those values possessed by the specialized organizations.

Keywords: short-circuit current, overhead line, cable line, single-core cable, cross-linked polyethylene (XLPE), longitudinal impedance of the line, positive-sequence, zero-sequence, screen grounding.

1. Introduction

Power transmission lines of 6-500 kV classes play a key role in the transmission and distribution of electric energy. The parameters of the lines have an impact on a wide range of characteristics of the electrical network:

- losses of active and reactive power;
- voltage levels in network nodes (busbars);
- short-circuit currents.

To calculate the normal and emergency modes of the network, it is important to use the correct values of positive-sequence and zero-sequence line parameters:

- longitudinal active impedance (R_1, R_0);
- longitudinal inductive impedance (X_1, X_0);
- transverse capacity (C_1, C_0).

Below in the article we will evaluate the consequences that an incorrect setting of line parameters may have when calculating short-circuit currents. It is worth recalling that short-circuit currents play a key role in the design of electrical networks. For example, they have a direct impact:

- to choose the cross-section of overhead line (shield) wires as well as to choose the cross-section of cores and screens of underground cables (issues of thermal resistance);
- on the choice of fastening of current-carrying parts (issues of dynamic stability);
- on the choice of switches (issues of breaking capacity);
- to set up relay protection and automation;
- on the potentials of grounding devices and the safety of personnel;
- on electromagnetic compatibility (magnetic field issues).

Further, talking about short-circuit currents, we will not consider the capacity of the line C_1, C_0, but we will focus only on the longitudinal parameters R_1, R_0 and X_1, X_0. This assumption is due to the fact that the capacitance of the line C_1, C_0, as a rule, does not affect the value of the short-circuit current (here we do not take into account the fault-to-ground in the network with an isolated neutral).

Ways of determining the longitudinal parameters differ depending on the sequence in question. If the impedances R_1 and X_1 are usually found by calculations using known formulas, then the impedances R_0 and X_0, on the contrary, are calculated only indirectly – by multiplying the already found R_1 and X_1 by the standard ratios R_0/R_1 and X_0/X_1 given in regulatory documents:

$$R_0 = R_1 \cdot R_0/R_1$$

$$X_0 = X_1 \cdot X_0/X_1$$

In the article, we will assess the consequences of the fact that in cable networks around the world are used:

- incorrect formulas for calculating R_1 and X_1;
- incorrect relations R_0/R_1 and X_0/X_1.

In particular, we will show that the use of incorrect longitudinal CL parameters can lead to an underestimation of short-circuit currents, and the real values of these short-circuit currents in cable networks can be up to 20-30% higher.

It should be noted that the calculation of short-circuit currents is done by many organizations (designing, scientific, dispatching), but all of them use specialized computer programs for these purposes, which are overly trusted (since it is assumed that a computer "cannot be mistaken"). In fact, these programs are based on misconceptions about the CL parameters of the positive and zero-sequence, since, for example, their users are not even required to specify such important information as the cross-section of the screens and their grounding/bonding scheme.

2. CL parameters from cable catalogs

Catalogues of cable factories and some industry standards contain the same simple formulas for calculating the CL longitudinal parameters of the positive-sequence. For reasons that we will explain later, we will denote such catalog parameters as R_{11} and X_{11}:

$$R_{11} = R_{11}{}^{*} \cdot l_{CL}$$

$$X_{11} = \omega L_{11}{}^{*} \cdot l_{CL}$$

where $R_{11}{}^{*}$ and $L_{11}{}^{*}$ – linear values of active impedance and inductance;
$\omega = 2\pi f$ – circular frequency ($f = 50$ Hz);
l_{CL} – CL length.

Active impedance

$$R_{11}{}^{*} = K_{SE} \cdot \frac{\rho_C}{F_C}$$

where F_C is the cross-section of the core;
ρ_C is the resistivity of the core material (depends on the temperature at which it is necessary to determine the CL parameters);

K_{SE} is the coefficient of the surface (skin) effect depending on the core cross-section F_C (for copper core $K_{SE} = 1 \div 1.15$, for aluminum core $K_{SE} = 1 \div 1.06$).

In the case of two-sides grounding of the CL screens, according to [1,2], alternating currents I_S are induced in them and losses of active power P_S occur. Currents I_S and losses P_S increase as they grow:

- the distance between cables of the cable line s_{CL};
- screen cross-sections F_S.

The active impedance of the positive-sequence ${R_1}^*$ must necessarily take into account the main sources of active power losses of the CL – losses in the cores P_C and losses in the screens P_S. Therefore, in the case of two-sides grounding of the CL screens, the formula for ${R_1}^*$ must contain not only the cross-section F_C, on which the losses P_C depend, but also the values s_{CL} and F_S, on which the losses P_S depend.

If you look at the above formula for active impedance, then there are no s_{CL} and F_S in it, which means that such a formula takes into account only losses P_C in cores and does not take into account losses P_S in screens. Thus, this formula is applicable only for CL with the following schemes that do not have currents and losses in the screens [1,2]:

- one-side grounding;
- screens cross-bonding.

So, the CL positive-sequence active impedance, which is given by the formula from the catalogs, is better denoted not ${R_1}^*$, but otherwise – let ${R_{11}}^*$.

Inductance

$${L_{11}}^* = {L_{INT}}^* + \frac{\mu_0}{2\pi} ln\left(\frac{s_{CL}}{r_1}\right)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant;
s_{CL} – the average distance between the cable axes along the CL route;
r_1 – the radius of the core;
${L_{INT}}^* = 0.05 \cdot 10^{-6}$ H/m is the internal inductance of the core.

After converting all values from the dimension of H/m to the dimension of mH/km:

$${L_{11}}^* = 0.05 + 0.2 \cdot ln\left(\frac{s_{CL}}{r_1}\right)$$

With two-sides grounding of the CL screens, induced currents I_S pass through them, which are the greater the greater the distance between the phases s_{CL} and the cross-section of the screen F_S. These screen currents with their magnetic field weaken the magnetic field of the currents I_C of the cores, and therefore the CL inductance of the positive-sequence ${L_1}^*$ decreases.

If you look at the above formula for inductance, then there is no cross-section F_S in it, which means that the formula does not take into account induced screen currents I_S. Thus, the formula is applicable only for CL with the following schemes that do not have currents and losses in the screens [1,2]:

- one-side grounding;
- screens cross-bonding.

So, the CL positive-sequence inductance, which is given by the formula from the catalogs, is better denote not $L_1{}^*$, but otherwise – let $L_{11}{}^*$.

Once again, note that for any CL with two-sides screen grounding, the CL positive-sequence longitudinal inductance $L_1{}^*$ will always be less than the value $L_{11}{}^*$ from the catalogs. In particular, this means that in cable networks where there are a lot of cable lines with two-sides grounding of screens (usually all 6-35 kV networks), the real currents of the three-phase short-circuit will be greater than the values calculated using catalogs.

Conclusion on parameters from catalogs

Formulas for the CL positive-sequence longitudinal parameters, which are given in the catalogs of cable factories, can be used exclusively for CL with one-side grounding of screens or their cross-bonding, and they are not suitable for two-sides grounding of screens. Since catalogs do not provide explanations about it, engineers have the erroneous impression that catalog formulas are universal and applicable to any CL.

It should be noted that often in catalogs the formulas $R_{11}{}^*$ and $L_{11}{}^*$ are indicated without the indexes "1", simply as R^* and L^*. This leads to the fact that engineers perceive them not as parameters of a positive-sequence, but as universal CL parameters that are valid for both positive and zero-sequences, which will be incorrect. In fact, the parameters of the CL in the zero-sequence may differ at times from the positive-sequence parameters – we will consider this question further.

3. CL parameters from the standards

As a rule, the standards contain the same formulas for positive-sequence parameters that are given in cable catalogs. These formulas are correct not for any of well-known screen grounding/bonding schemes. However, regardless of the screen grounding/bonding scheme, it is impossible to calculate the parameters of the zero-sequence using such formulas.

To estimate the CL parameters of the zero-sequence, the standard [3] is used, where information is given on both the overhead line and the CL. For example, according to clause 4.2.5, the overhead line is characterized by $X_0/X_1 = 2.0 \div 5.5$, and the specific values depend on the properties of the shield wire and the number of line circuits (Table 1). It can be seen that the better the shield wires conduct current, the smaller the value X_0/X_1 will be. For example, if overhead line shield wires, like screens of XLPE-cables, could be made not of steel (or aluminum alloys), but of pure copper, with a large cross-section, then it is likely that even $X_0/X_1 < 1$ would be obtained for overhead lines.

Table 1. The ratio X_0/X_1 for overhead lines, depending on shield wires and circuits.

Overhead line features	X_0/X_1	
	1 circuit	2 circuits
no grounded shield wires	3.5	5.5
with grounded shield wires made of steel	3.0	4.7
with grounded shield wires made of low impedance metals	2.0	3.0

For CL according to clause 4.2.6, "The CL impedance of the zero-sequence depends on the design of their laying, the presence or absence of a conductive metallic sheath, the grounding impedance of the conductive sheath (if any) and other factors. With approximate calculations, it is acceptable to take":

$$X_0/X_1 = 3.5 \div 4.5$$
$$R_0/R_1 = 10$$

It can be seen that, in general, the ratio X_0/X_1 for overhead lines and CL according to the standard [3] is approximately the same. However, it is worth noting here that [3] was published in 1998, when paper-insulated cables without copper wire screens were dominant. The appearance of such screens in CL (in clause 4.2.6 they are called a "conductive sheath"), of course, will significantly change the typical X_0/X_1 ratios for CL.

Modern power cables with insulation made of cross-linked polyethylene (XLPE) are necessarily equipped with well-conducting copper screens, which means that for such cables, a decrease in X_0/X_1 should be expected, and up to $X_0/X_1 < 1$. It turns out that the values given in [3] $X_0/X_1 = 3.5 \div 4.5$ currently, most likely, can no longer be applied.

If we refer to Table 1 for overhead lines, it clearly states that the influence of the properties of shield wires on X_0/X_1 occurs exclusively under the condition of grounding of shield wires, that is, when currents can pass through them. A similar situation will be for CL – the appearance of well-conducting copper screens can reduce X_0/X_1, but only if currents can pass through them.

If the CL screens are one-side grounded, then currents cannot pass there (even if the screens are made of copper), which means that the ratio $X_0/X_1 = 3.5 \div 4.5$ of the standard [3], apparently, has not lost relevance here. As for the two-sides grounding of the CL screens or their cross-bonding, the zero-sequence currents are easily passed on such screens, which means that the ratio X_0/X_1 will be less than in [3], up to $X_0/X_1 < 1$.

So, in the modern cable network, not $X_0/X_1 = 3.5 \div 4.5$ is true for CL, as it was supposed earlier, but smaller ratios, up to $X_0/X_1 < 1$. This means that in cable networks, single-phase short-circuit currents may actually be significantly higher than the values that were calculated earlier using the parameters from [3].

4. Correct CL parameters

In [1,2], formulas are proposed for calculating the longitudinal parameters of modern CL with shielded cables. These formulas take into account the main influencing factors, including:

- the grounding/bonding scheme of the screens;
- cross-section and material of screens;
- distance between cables;
- sequence (positive, zero).

The range of changes in the CL parameters calculated according to [1,2] was given in the article [4] and duplicated in Table 2 (the above formulas from cable catalogs are correct for calculating the impedances R_{11} and X_{11}). From Table 2, the following conclusions can be drawn:

- the CL positive-sequence parameters for the case of two-sides screen grounding may differ markedly from the catalog's R_{11} and X_{11}, which are valid exclusively for one-side grounding of screens or their cross-bonding;
- the CL zero-sequence parameters differ markedly from the standard [3], and it is especially necessary to pay attention to the possibility of the situation $X_0/X_1 < 1$.

Table 2. Parameters of CL with XLPE-insulation cables (according to the article [4]).

Screen bonding/ grounding scheme	Positive-sequence		Zero-sequence	
	R_1	X_1	R_0/R_1	X_0/X_1
One-side grounding	R_{11}	X_{11}	$3 \div 15$	$4 \div 25$
Two-sides grounding			$2 \div 30$	$0.25 \div 2$
Cross-bonding	$(1.01 \div 5) \cdot R_{11}$	$(0.45 \div 0.99) \cdot X_{11}$	$1 \div 20$	$0.5 \div 2$

5. An example of evaluation the three-phase short circuit current

Consider a simple radial cable network shown in Figure 1. In this scheme, we evaluate the current I_K of the three-phase short-circuit at the end of the CL. The specified current I_K may be needed, for example, to select the cross-section of cores and screens of cables connected in series with the circuit in question (such cables are conventionally designated as "consumers" in the diagram).

For certainty, we assume that we are talking about a 110 kV class grid with an internal inductive impedance $X_G = 2\ \Omega$ and the highest operating voltage $U_{MAX} = 127$ kV. Suppose a 110 kV CL has a length of $l_{CL} = 5$ km and is made by single-core cables with copper cores $F_C = 1000$ mm^2 and screens $F_S = 240$ mm^2. Let the three single-core cables be laid in three polymer pipes with a diameter of $D = 225$ mm each (the pipes are located close to each other in a bundle, that is, in a closed triangle).

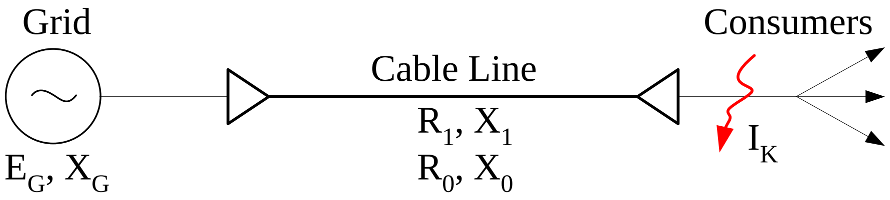

Figure 1. Radial cable network.

CL parameters by catalogs

With a cross-section $F_C = 1000$ mm^2 for copper, according to [2], it is possible to take $K_{SE} = 1.151$ and $\rho_C = 2 \cdot 10^{-8}$ $\Omega \cdot$m. Then, using the formula from the catalog, we will find:

$$R_{11}{}^{*} = 23 \text{ m}\Omega/\text{km}$$
$$R_{11} = 23 \cdot 5 = 115 \text{ m}\Omega$$

For a single-core 110 kV cable with $F_C = 1000$ mm^2, the core radius $r_1 = 18.8$ mm, cable outer diameter $d = 80$ mm. When laying the cables in a closed triangle, the distance between the cable axes would be $s_{CL} = d = 80$ mm, but when the cables are placed in pipes, the distance $s_{CL} = D = 225$ mm should be taken. Then, using the formula from the catalog, we will find:

$$L_{11}{}^{*} = 0.546 \text{ mH/km}$$
$$X_{11} = (2\pi \cdot 50) \cdot 0.546 \cdot 5 = 858 \text{ m}\Omega$$

Correct CL parameters by [1,2]

If the CL has a one-side screen grounding or their cross-bonding, then the catalog formulas are correct, and we get:

$$R_1 = R_{11} = 0.115\ \Omega$$
$$X_1 = X_{11} = 0.858\ \Omega$$

If the CL has two-side screen grounding, then the catalog formulas do not apply to such a case. For a copper screen $F_S = 240$ mm^2, we define (Tables 1a and 1b from [4]):

$$R_1 = 3.85 \cdot R_{11} = 3.85 \cdot 0.115 = 0.443\ \Omega$$
$$X_1 = 0.472 \cdot X_{11} = 0.472 \cdot 0.858 = 0.405\ \Omega$$

Evaluation of the three-phase short circuit current

Three-phase short-circuit current at the end of the CL:

$$I_{K(3)} = \frac{E_G}{\sqrt{(R_1)^2 + (X_G + X_1)^2}}$$

where $X_G = 2\ \Omega$ is the internal inductive impedance of the grid;
$E_G = U_{MAX}/\sqrt{3} = 127/\sqrt{3} = 73$ kV.

If we put into the formula the parameters $R_1 = 0.115\ \Omega$ and $X_1 = 0.858\ \Omega$ according to the catalog (they are used in specialized programs for calculating short-circuit currents), then the short-circuit current at the end of the CL will be $I_{K(3)} = 25.5$ kA.

If we put into the formula the parameters $R_1 = 0.443\ \Omega$ and $X_1 = 0.405\ \Omega$, which are valid for two-sides grounding of screens and are not in the catalog, then the short-circuit current at the end of the CL will be $I_{K(3)} = 29.9$ kA, which is 17% more.

So, the real short-circuit current turned out to be 17% higher than the value that was found using catalog formulas that do not take into account all the variety of grounding/ bonding schemes used in practice. It can be seen that the catalog formulas can give noticeable errors in the calculation of the currents of the three-phase short-circuit of the cable network.

6. An example of evaluation the single-phase short-circuit current

In the conditions of the previous example, let's assume that a 110 kV CL has a screen cross-bonding (one-side grounding for a 5 km long CL is usually not applicable). Then the positive-sequence parameters are $R_1 = 0.115\ \Omega$ and $X_1 = 0.858\ \Omega$, but the parameters of the zero-sequence are also required.

CL parameters by the standard [3]

According to standard [3], we take $R_0/R_1 = 10$ and $X_0/X_1 = 3.5$. Then

$$R_0 = 0.115 \cdot 10 = 1.15\ \Omega.$$

$$X_0 = 0.858 \cdot 3.5 = 3.0\ \Omega.$$

Correct CL parameters by [1,2]

We define (Table.3a and 3b from [4]) that $R_0/R_1 = 5.2$ and $X_0/X_1 = 0.25$. Then

$$R_0 = 0.115 \cdot 5.2 = 0.6\ \Omega.$$

$$X_0 = 0.858 \cdot 0.25 = 0.215\ \Omega.$$

Evaluation of the single-phase short-circuit current

Single-phase short-circuit current at the end of the CL:

$$I_{K(1)} = \frac{3E_G}{\sqrt{(2R_1 + R_0)^2 + \big(2(X_G + X_1) + (X_G + X_0)\big)^2}}$$

If we put into the formula the parameters of the zero-sequence [3], which are valid for outdated CL with paper insulation, we get $I_{K(1)} = 20.3$ kA. If we put into the formula the correct parameters of modern CL with XLPE-insulation cables according to [1,2], we get $I_{K(1)} = 27.5$ kA, which is 35% more.

So, the real short-circuit current turned out to be 35% higher than the value that was found using the formulas of the standard, which does not take into account that modern CL have well-conducting screens. It can be seen that the ratios R_0/R_1 and X_0/X_1 from the standard [3] can give noticeable errors in the calculation of single-phase short-circuit currents of the cable network.

7. Conclusions

1. The CL parameters of the positive-sequence, which are widely used in the calculations of the short-circuit currents of the network, are correct only if there are no currents in the cable screens, which is characteristic exclusively for one-side grounding of the screens or their cross-bonding. With two-sides grounding of the screens, the parameters of the CL may differ significantly.
2. The CL parameters of the zero-sequence, which are widely used in the calculations of the short-circuit currents of the network, are correct only for old-type cables with paper insulation. For modern CL with XLPE-insulation, which are equipped with copper screens (often of large cross-section), the parameters of the CL may differ significantly.

3. In design organizations and in the dispatching services of the grid, specialized programs for calculating short-circuit currents are used, but it is usually difficult to obtain information about the formulas that the programs use. At the same time, we can propose a simple rule for checking programs for their applicability for calculating short-circuit currents of the cable network: it is not recommended to trust those programs that do not require the user to provide initial data:
   - about the grounding/bonding scheme of cable screens;
   - about the cross-section of the cable screens;
   - about the material of cable screens;
   - about the distance between the cables of the CL.
4. The article showed that the use of incorrect CL parameters in calculations can lead to unpleasant surprises. Thus, in cable networks, the actual short-circuit currents may be up to 20-30% higher than the calculated values. For example, the article considered cases when the refinement of the CL parameters led to an increase in current:
   - by 17% for a three-phase short-circuit;
   - by 35% for single-phase short-circuit.
5. It is recommended to make the necessary edits to cable catalogs, regulatory documents, and algorithms of computer programs for calculating short-circuit currents in order to change the current situation with incorrect calculation of the longitudinal parameters of modern CL.

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