LONGITUDINAL IMPEDANCE CALCULATION METHOD FOR CABLE LINES WITH SINGLE-CORE HIGH VOLTAGE CABLES

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The article offers simple formulas that allow calculating the longitudinal active and inductive impedances of cable lines depending on the screen bonding/grounding schemes (one-side or both-sides grounding, screens cross-bonding) and depending on the sequence (positive or zero).

Keywords: cable line, single-core cable, cross-linked polyethylene, longitudinal impedance of the line, positive sequence, zero sequence, screen bonding, screen grounding

I. INTRODUCTION

For more than 20 years, cable lines (CL) made of single-core cables with cross-linked polyethylene (XLPE) insulation have been massively used in the world for all classes of rated voltage from 6 kV and above. Unfortunately, in the catalogs of numerous cable factories, there were no calculation methods that would allow us to find the CL active and inductive impedances of positive and zero sequences, depending on the cable screen bonding/grounding schemes.

It is obvious that the longitudinal active and inductive impedances for positive sequence (R_1 и X_1) and zero sequence (R_0 и X_0) depend on the following factors:

– cross-sections of the core (F_C) and screen (F_S);
– resistivity of the materials of core (ρ_C) and screen (ρ_S), which are usually Cu or Al;
– the average distance s_{CL} between the axes of the three single-core cables of CL;
– screen bonding/grounding scheme (one-side grounding, both-sides grounding, cross-bonding).

Most of cable catalogs offer only the following elementary formulas for positive sequence impedances $R_1{}^*$ и $X_1{}^*$ (per unit length):

$$R_1{}^* = \frac{\rho_C}{F_C}$$

$$X_1{}^* = \omega L_1{}^* = \omega \cdot \left[0.05 + 0.2 \cdot ln\left(\frac{s_{CL}}{r_1}\right)\right]$$

The first disadvantage of these formulas R_1 и X_1 is that they are not suitable for the case of screens both-sides grounding. With both-sides grounding of screens, induced currents I_S, arise in them, which, as is known, depend on the properties of the screen F_S и ρ_S. For example, the greater the F_S, the greater the induced current I_S, which means:

– will grow the power losses in CL and therefore the resistance $R_1{}^*$;
– will weaken the magnetic field of the CL and therefore the inductance $X_1{}^*$.

Obviously, the formulas given in the catalogs for R_1 и X_1, which do not take into account F_S и ρ_S, cannot be used for the case of screen both-sides grounding, but are suitable only for the case of the absence of currents I_S, i.e. for the following bonding/grounding screen schemes:

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

The second disadvantage of these formulas R_1 и X_1 is the fact that they cannot be used to calculate the zero sequence. The processes in the CL cores and screens are more complicated for the zero sequence than for the positive one. This is due to the fact that if a positive sequence is characterized by some mutual compensation of the magnetic fields of the three cables A, B, C, then for the zero sequence it is completely absent, leading to a significant increase in currents in the screens. Thus, the mentioned formulas for R_1 и X_1 given in the catalogs do not allow estimating the impedances R_0 и X_0 of the zero sequence. In particular, it would be a significant mistake to assume that $R_0 = R_1$ и $X_0 = X_1$ are valid for single-core cables.

Let's propose a simple way to estimate the values of R_1, X_1, R_0, X_0, which would allow us to correct errors inherent in a number of cable catalogs and put in order with calculations:

– power losses in the CL;
– voltage losses in CL;
– short-circuit currents of the grid.

II. CL DESIGN

The considered design of a single-core cable is schematically shown in Fig.1. The cable consists of a core, insulation, metallic screen, outer sheath. Usually, the core and the screen consist of separate round wires, but in Fig.1, the core and the screen are conventionally shown as solid (without any gaps between the wires). Fig.2 shows two main variants of the mutual arrangement of single-core cables forming a three-phase CL.

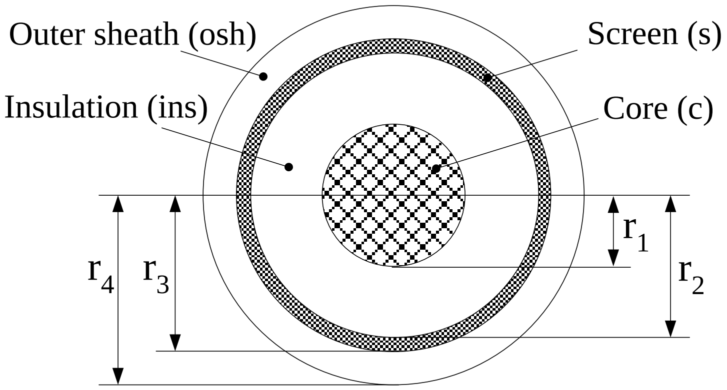

Fig.1. Single-core cable design.

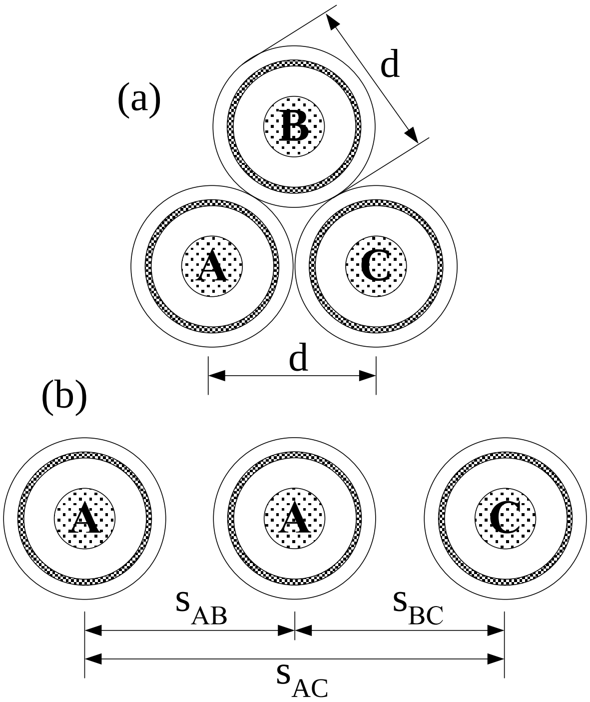

Fig.2. Single-core cable mutual arrangement for three-phase CL:
(a) – a closed triangle; (b) – in a row at a distance from each other.

The following designations are introduced in Fig.1-2: r_1 – the core radius, r_2 – the inner radius of the screen, r_3 – the outer radius of the screen, r_4 – the cable radius, $d = 2r_4$ – the cable diameter, s_{AB}, s_{BC}, s_{AC} – the distances between the axes of adjacent cables.

In the future, we will not focus on the position of the three cables relative to each other, but introduce the value s_{CL}, which characterizes the average distance between the cable axes:

$$s_{CL} = \sqrt[3]{s_{AB} \cdot s_{BC} \cdot s_{AC}} = 1.26 \cdot s_{AB}$$

$$s_{CL} = s_{AB} = s_{BC} = s_{AC} = d$$

In some cases, the distance s_{CL} between the cable axes can take different values for different sections of the CL route, then decreasing, then increasing. In such situations, the calculations should include the average value of s_{CL} along the CL route.

III. SINGLE-CORE CABLE GEOMETRY CALCULATION

The exact values of the radii r_1, r_2, r_3, r_4 can be obtained from the manufacturer of a specific brand of cable, however, such data is not available in full in the manufacturers' catalogs (with rare exceptions). Therefore, the evaluation of these radii has to be performed independently based on the known cross-sections of the core F_C (mm^2) and the screen F_S (mm^2):

$$F_C = \psi_C \cdot \pi \cdot {r_1}^2$$

$$F_S = \psi_S \cdot \pi \cdot ({r_3}^2 - {r_2}^2)$$

where ψ_C and ψ_S – are the so-called fill coefficients of the core and the screen, depending on the compression degree of the gaps between the individual wires (p.u.).

Given the above, the formulas for r_1, r_2, r_3, r_4 (mm) will be as follows:

$$r_1 = \sqrt{\frac{F_C/\psi_C}{\pi}}$$

$$r_2 = r_1 + \Delta_{INS}$$

$$r_3 = \sqrt{{r_2}^2 + \frac{F_S/\psi_S}{\pi}}$$

$$r_4 = r_3 + \Delta_{OSH}$$

where Δ_{INS} and Δ_{OSH} – are the thickness of the cable insulation and the cable outer sheath (mm).

In the absence of reliable information about the values of ψ_C, ψ_S, Δ_{INS}, Δ_{SH}, it is allowed for modern cables with XLPE-insulation to accept:

$$\psi_C = 0.9\ ,$$

$$\psi_S = 0.5$$

$$\Delta_{INS} = 1.4 \cdot \sqrt{U_{CL}}$$

$$\Delta_{OSH} = 0.01 \cdot U_{CL} + 4$$

where U_{CL} – is the rated voltage CL (kV).

For example, for a CL 110 kV, you can estimate:

$$\Delta_{INS} = 1.4 \cdot \sqrt{U_{CL}} = 1.4 \cdot \sqrt{110} = 14.6 \text{ mm}$$

$$\Delta_{OSH} = 0.01 \cdot U_{CL} + 4 = 0.01 \cdot 110 + 4 = 5.1 \text{ mm}$$

Further, before calculating the CL longitudinal impedances, the radii r_1, r_2, r_3, r_4 and the cross-sections F_C, F_S must be converted to the international system of units (meters and meters^2).

IV. SELF AND MUTUAL IMPEDANCES OF CL

Formulas [1] are known for calculating the longitudinal impedances of the CL, which take into account the mutual influence of single-core cables on each other, as well as the frequency dependences of the parameters. However, these formulas are quite complex and inconvenient to use without special computer programs for their calculation.

We obtain alternative expressions for the CL parameters based on well-known formulas for the longitudinal active-inductive impedances of an overhead line (OHL), which is a multi-wire system "wires and ground" located above the ground at a height of h. When calculating the OHL parameters, the influence of the ground is taken into account by replacing it with some "return wires" located at a depth of D_G, which is hundreds of meters (for alternating currents of frequency 50 Hz). Thus, the distance from OHL wires located above the ground to the "return wires" located in the ground will be $D_G + h$.

Since $D_G \gg h$ is usually true, then the distance from the wires to the "return wire" can be valued not as $D_G + h$, but D_G. At the same time, it becomes completely unimportant whether the wires were located above ground ($h > 0$, which is typical for OHL) or underground ($h < 0$, which is typical for CL). Thus, the use of concept of D_G allows us to apply to the calculation of the CL parameters almost the same approaches that are traditionally used to calculate the OHL parameters.

Fig.3 shows the CL and the ground, which is replaced by a "return wire" removed from the CL at a distance D_G. At the same time, the location of the CL does not matter – it could be laid both above the ground and in the ground. Using the concept of D_G allows us to find the following simple and convenient formulas for the CL longitudinal impedances.

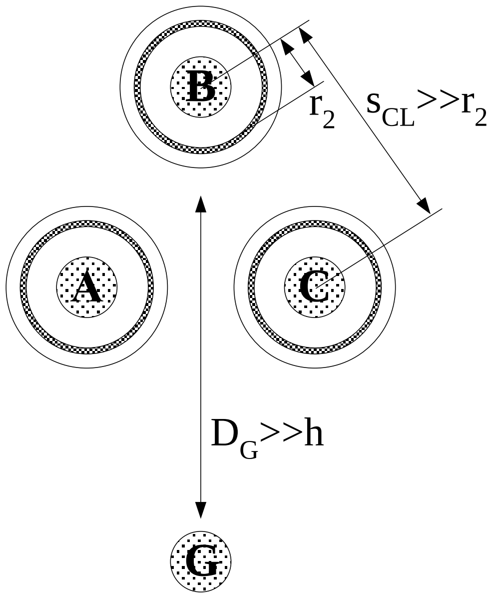

Fig.3. Arrangement of single-core cables and ground "return wire".

Similarly, as it is always done for multi-wire OHL, we introduce a system of self and mutual longitudinal active-inductive impedances (consider the values per CL unit length):

$\dot{Z}_C{}^* = R_G{}^* + R_C{}^* + j\omega L_C{}^*$ – the self-impedance of the core,

$\dot{Z}_S{}^* = R_G{}^* + R_S{}^* + j\omega L_S{}^*$ – the self-impedance of the screen,

$\dot{Z}_{CS}{}^* = R_G{}^* + j\omega M_{CS}{}^*$ – the mutual impedance between the core and the screen,

$\dot{Z}_{CL}{}^* = R_G{}^* + j\omega M_{CL}{}^*$ – the mutual impedance between adjacent cables,

where f – frequency (Hz), $\omega = 2\pi f$ – circular frequency (rad/s), $j = \sqrt{-1}$ – imaginary unit.

To obtain the full (non per unit length) CL impedances, it is necessary to calculate:

$$\dot{Z}_C = \dot{Z}_C^{\ *} \cdot l_{CL}$$
$$\dot{Z}_S = \dot{Z}_S^{\ *} \cdot l_{CL}$$
$$Z_{CS} = \dot{Z}_{CS}^{\ *} \cdot l_{CL}$$
$$\dot{Z}_{CL} = \dot{Z}_{CL}^{\ *} \cdot l_{CL}$$

where l_{CL} is the total length of the CL.

Next, we propose expressions for the calculation of the parameters $\dot{Z}_C^{\ *}$, $\dot{Z}_S^{\ *}$, $\dot{Z}_{CS}^{\ *}$, $\dot{Z}_{CL}^{\ *}$. When determining these values at an industrial frequency $f = 50$ Hz, we assume:

– the mutual arrangement of single-core cables is such that $s_{CL} >> r_2$;
– the cable screen is quite thin compared to its radius $r_3 >> (r_3 - r_2)$; this allows you to neglect the final thickness of the screen and use only its inner radius r_2 in calculations.

Additionally, we neglect:

– the surface effect in the cores and screens of CL;
– the effect of proximity between neighboring cables;
– the capacity and active conductivity of the CL insulation;
– the screen grounding resistances at the CL ends;
– the mutual influence of neighboring CL circuits.

Active impedances

We introduce the following per unit length (Ω/m) active impedances of the core and screen:

$$R_C^{\ *} = \frac{\rho_C}{F_C}$$
$$R_S^{\ *} = \frac{\rho_S}{F_S}$$

where the resistivity of the core ρ_C and the screen ρ_S depends on the temperature:

$$\rho_C \ = \rho_{C20} \ \cdot [1 + \alpha_C \cdot (T_C - 20)]\,,$$
$$\rho_S \ = \rho_{S20} \ \cdot [1 + \alpha_S \cdot (T_S - 20)]\,,$$

where T_C и T_S – are the actual temperature of the core and screen (°C);
ρ_{C20} и ρ_{S20} – are resistivities (Ω·m) of the core and screen materials at a 20°C temperature;
α_C и α_S – are the temperature coefficients of resistance of the core and screen material (Cu, Al).

For calculations, you can take the following reference values ρ_{C20} and ρ_{S20}:
$\rho_{20} = 1.72 \cdot 10^{-8}$ Ω·m – for core or screen made of copper (Cu);
$\rho_{20} = 2.8 \cdot 10^{-8}$ Ω·m – for core or screen made of aluminum (Al).
$\alpha = 0.0039$ – suitable for both copper and aluminum.

In normal operation mode, the temperature of the cable screen is usually at $(5 \div 10)$°C less than core. Therefore, for XLPE-insulation cables designed to operate at insulation temperatures up to 90°C, it is possible to accept:

– $T_C = 90$°C and $T_S = 80$°C in full load mode
– $T_C = 65$°C and $T_S = 60$°C in the average load mode.

Self and mutual inductive impedances

We introduce the following per unit length (H/m) inductances:

$$L_C{}^* = \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{r_1}\right)$$

$$L_S{}^* = \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{r_2}\right)$$

$$M_{CS}{}^* = \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{r_2}\right)$$

$$M_{CL}{}^* = \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{s_{CL}}\right)$$

where $L_C{}^*$ – the self-inductance of the core,
$L_S{}^*$ – the self-inductance of the screen,
$M_{CS}{}^*$ – the mutual inductance between the core and the screen,
$M_{CL}{}^*$ – the mutual inductance between adjacent cables,
D_G – the distance to the ground "return wire",
$\mu_0 = 4\pi \cdot 10^{-7}$ – is the absolute magnetic permeability of the vacuum (H/m).

Parameters of the ground

The active ground resistance R_G and the distance D_G can be determined simplistically, for example, by the formulas of Rüdenberg [2]:

$$R_G{}^* = \frac{\pi}{4}\mu_0 f$$

$$D_G = 2.24\sqrt{\frac{\rho_G}{\omega \cdot \mu_0}}$$

where ρ_G – is the soil resistivity (Ω·m).

V. THE SYSTEM OF CL EQUATIONS

In steady-state operation, voltage drops along the cores $\Delta\dot{U}_C$ and the screens $\Delta\dot{U}_S$ of the three cables A, B, C are related to the currents $\dot{I}_C$ and $\dot{I}_S$ in them by the following system of equations:

$$\Delta\dot{U}_{CA} = \dot{Z}_C\dot{I}_{CA} + \dot{Z}_{CS}\dot{I}_{SA} + \dot{Z}_{CL}(\dot{I}_{CB} + \dot{I}_{SB}) + \dot{Z}_{CL}(\dot{I}_{CC} + \dot{I}_{SC})$$
$$\Delta\dot{U}_{CB} = \dot{Z}_C\dot{I}_{CB} + \dot{Z}_{CS}\dot{I}_{SB} + \dot{Z}_{CL}(\dot{I}_{CA} + \dot{I}_{SA}) + \dot{Z}_{CL}(\dot{I}_{CC} + \dot{I}_{SC})$$
$$\Delta\dot{U}_{CC} = \dot{Z}_C\dot{I}_{CC} + \dot{Z}_{CS}\dot{I}_{SC} + \dot{Z}_{CL}(\dot{I}_{CA} + \dot{I}_{SA}) + \dot{Z}_{CL}(\dot{I}_{CB} + \dot{I}_{SB})$$
$$\Delta\dot{U}_{SA} = \dot{Z}_S\dot{I}_{SA} + \dot{Z}_{CS}\dot{I}_{CA} + \dot{Z}_{CL}(\dot{I}_{CB} + \dot{I}_{SB}) + \dot{Z}_{CL}(\dot{I}_{CC} + \dot{I}_{SC})$$
$$\Delta\dot{U}_{SB} = \dot{Z}_S\dot{I}_{SB} + \dot{Z}_{CS}\dot{I}_{CB} + \dot{Z}_{CL}(\dot{I}_{CA} + \dot{I}_{SA}) + \dot{Z}_{CL}(\dot{I}_{CC} + \dot{I}_{SC})$$
$$\Delta\dot{U}_{SC} = \dot{Z}_S\dot{I}_{SC} + \dot{Z}_{CS}\dot{I}_{CC} + \dot{Z}_{CL}(\dot{I}_{CA} + \dot{I}_{SA}) + \dot{Z}_{CL}(\dot{I}_{CB} + \dot{I}_{SB})$$

There are 6 equations in the system with respect to 6 voltages and 6 currents. Therefore, to solve it we need to find an additional equations and boundary conditions.

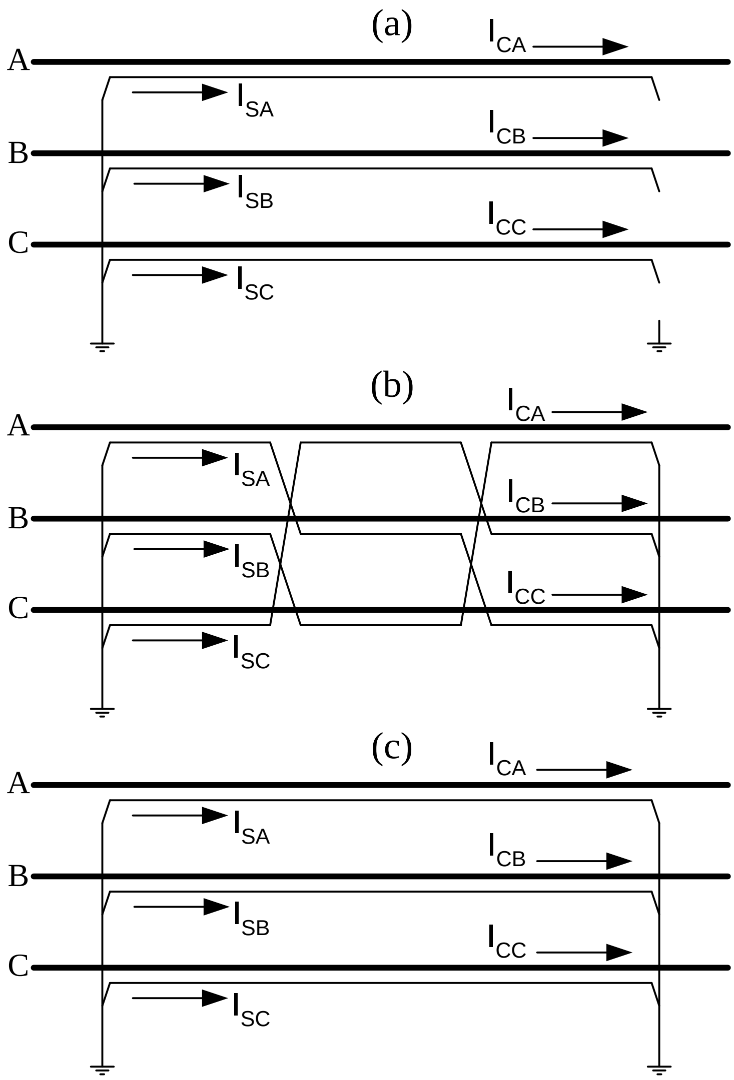

Fig.4. CL screen bonding/grounding schemes:
(a) – one-side grounding, (b) – screens cross-bonding, (c) – both-sides grounding.

Boundary conditions

For screen one-side grounding (Fig.4,a):

$$\dot{I}_{SA} = 0$$
$$\dot{I}_{SB} = 0$$
$$\dot{I}_{SC} = 0$$

For screen cross-bonding (Fig.4,b) or screen both-sides grounding (Fig.4,c):

$$\Delta\dot{U}_{SA} = 0$$
$$\Delta\dot{U}_{SB} = 0$$
$$\Delta\dot{U}_{SC} = 0$$

It should be noted that in the case of screen cross-bonding, the equations $\Delta\dot{U}_{SA}$, $\Delta\dot{U}_{SB}$, $\Delta\dot{U}_{SC}$ must be written several times – according to the number of sections between the cross-bonding nodes (for example, for Fig.4,b there will be 3 sections, and the system must be written three times). Then, in accordance with the screen connection scheme at the cross-bonding nodes, it is taken into account that the screen currents at the end of one section are equal to the corresponding screen currents at the beginning of the next section.

Additional conditions

In the positive-sequence mode:

$$\dot{I}_{CA} + \dot{I}_{CB} + \dot{I}_{CC} = 0$$
$$\dot{I}_{SA} + \dot{I}_{SB} + \dot{I}_{SC} = 0$$

In the zero-sequence mode:

$$\dot{I}_{CA} = \dot{I}_{CB} = \dot{I}_{CC}$$
$$\dot{I}_{SA} = \dot{I}_{SB} = \dot{I}_{SC}$$

VI. LONGITUDINAL PARAMETERS OF CL

The transformation of the system of equations for voltage drops along the CL, performed taking into account boundary and additional conditions, will allow us to find an expression for the ratio $\Delta\dot{U}_{CA}/\dot{I}_{CA}$, which will be the desired CL longitudinal impedance:

– the ratio equals to $\dot{Z}_1$, if the boundary conditions of the positive sequence were used;
– the ratio equals to $\dot{Z}_0$, if the boundary conditions of the zero sequence were used.

The expressions found for the CL longitudinal active-inductive impedances $\dot{Z}_1$ and $\dot{Z}_0$ are presented in Table 1 in the form of their per unit length values $\dot{Z}_1{}^*$ and $\dot{Z}_0{}^*$:

$$\dot{Z}_1 = \dot{Z}_1{}^* \cdot l_{CL}$$
$$\dot{Z}_0 = \dot{Z}_0{}^* \cdot l_{CL}$$

The formulas presented in Table 1 coincide with what was proposed in [3]. Our numerous calculations show that the CL impedances found using the formulas from Table 1 are close to the exact parameters [1], as well as to the results of CL modeling in the world well-known Canadian-American EMTP program [4].

It can be seen from Table 1 that the CL longitudinal impedances significantly depend on the desired screen bonding/grounding scheme and on the sequence (positive or zero). In the catalogs of a number of factories producing cables, this fact is completely ignored.

Table 1. CL longitudinal parameters depending on the screens grounding scheme.

Scheme fig.4	Positive sequence impedance	Zero sequence impedance
(a)	$\dot{Z}_1{}^* = \dot{Z}_C{}^* - \dot{Z}_{CL}{}^*$	$\dot{Z}_0{}^* = \dot{Z}_C{}^* + 2\dot{Z}_{CL}{}^*$
(b)	$\dot{Z}_1{}^* = \dot{Z}_C{}^* - \dot{Z}_{CL}{}^*$	$\dot{Z}_0{}^* = \left(\dot{Z}_C{}^* + 2\dot{Z}_{CL}{}^*\right) - \frac{\left(\dot{Z}_{CS}{}^* + 2\dot{Z}_{CL}{}^*\right)^2}{\dot{Z}_S{}^* + 2\dot{Z}_{CL}{}^*}$
(c)	$\dot{Z}_1{}^* = \left(\dot{Z}_C{}^* - \dot{Z}_{CL}{}^*\right) - \frac{\left(\dot{Z}_{CS}{}^* - \dot{Z}_{CL}{}^*\right)^2}{\dot{Z}_S{}^* - \dot{Z}_{CL}{}^*}$	$\dot{Z}_0{}^* = \left(\dot{Z}_C{}^* + 2\dot{Z}_{CL}{}^*\right) - \frac{\left(\dot{Z}_{CS}{}^* + 2\dot{Z}_{CL}{}^*\right)^2}{\dot{Z}_S{}^* + 2\dot{Z}_{CL}{}^*}$

VII. ABOUT LONGITUDINAL INDUCTANCE OF CL

Cable factories, as a rule, offer the following universal formula for calculating the per unit length CL inductance (mH/km):

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

At the same time, no explanation is given about which scheme of screen bonding/grounding in question and which sequence (positive or zero). Let's consider it in more detail.

According to Table 1, the CL positive sequence impedance for the schemes of Fig.4,a,b:

$$\dot{Z}_1{}^* = \dot{Z}_C{}^* - \dot{Z}_{CL}{}^* = (R_G{}^* + R_C{}^* + j\omega L_C{}^*) - (R_G{}^* + j\omega M_{CL}{}^*)$$

After conversion of this expression, taking into account $\dot{Z}_1{}^* = R_1{}^* + j\omega L_1{}^*$, we get:

$$R_1{}^* = R_C{}^*$$

$$L_1{}^* = L_C{}^* - M_{CL}{}^* = \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{r_1}\right) - \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{s_{CL}}\right) = \frac{\mu_0}{2\pi} ln\left(\frac{s_{CL}}{r_1}\right)$$

Substituting μ_0 and moving from the dimension of H/m to the dimension of mH/km, we get:

$$L_1{}^* = 0.2 \cdot ln\left(\frac{s_{CL}}{r_1}\right)$$

The specified $L_1{}^*$ expression differs from what is given in the catalogs by the absence of a constant value of 0.05 mH/km – it represents the internal inductance of the core $L_{INT}{}^*$. In Table 1 the absence of $L_{INT}{}^*$ in the formulas for $L_1{}^*$ is due to the fact that these formulas were obtained from the theory of multi-wire OHL, where usually $s >> r_1$ and therefore the inductance $L_{INT}{}^*$ turns out to be too small compared to $L_1{}^*$.

For CL, the distance s_{CL} between the cable axes is only several times greater than the radius of the core r_1. Therefore, strictly speaking, for Table 1 when define self-inductances of the core $L_C{}^*$ and the screen $L_S{}^*$, it's necessary to take into account the internal inductance $L_{INT}{}^*$, the value of which depends on the design features of the core and the screen, but in the first approximation can be made, equal $L_{INT}{}^* = 0.05 \cdot 10^{-6}$ H/m (0.05 mH/km):

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

$$L_S{}^* = L_{INT}{}^* + \frac{\mu_0}{2\pi} ln\left(\frac{D_G}{r_2}\right)$$

In the future, in order to simplify formulas, we will refuse to take into account the internal inductance $L_{INT}{}^*$. The assumption $L_{INT}{}^* = 0$ is made in the following examples of calculations.

Regardless of the $L_{INT}{}^*$ question, we can conclude that the catalog formula for L^* coincides with the formula $L_1{}^*$ from Table 1 only when two conditions are fulfilled simultaneously:

– there is a positive-sequence mode;
– there are no induced currents in the screens (schemes Fig.4,a and Fig.4,b).

VIII. ABOUT RETURN WIRE PARAMETERS OF CL

The formulas of Table 1 for the CL impedance $\dot{Z}_1 = R_1 + j\omega L_1$ are written with $\dot{Z}_C$, $\dot{Z}_S$, $\dot{Z}_{CS}$, $\dot{Z}_{CL}$, which includes the distance D_G, taking into account the influence of the ground (ground surface effect). In fact, there are no currents in the ground in the positive-sequence mode, and $\dot{Z}_1$ does not depend on D_G in any way – this will become clear if we simplify the formulas for $\dot{Z}_1$ by substituting in them the known expressions for $\dot{Z}_C$, $\dot{Z}_S$, $\dot{Z}_{CS}$, $\dot{Z}_{CL}$. In particular, D_G is missing in the expression for inductance $L_1{}^*$ just considered.

So, the value of D_G does not affect the positive sequence processes, but should be taken into account only in the calculations of various asymmetric modes, including the zero-sequence mode. Speaking of D_G, it is impossible not to note two significant differences in the use of this value for calculating the parameters of the OHL and CL.

Firstly, OHL in most cases pass outside cities, i.e., where the distance D_G of the current in the ground is determined only by the properties of the soil. CL, on the contrary, are mainly used in cities and industrial enterprises, where there are many metal structures in the ground that reduce the value of D_G.

Secondly, when calculating D_G, we neglect the edge effects, i.e., we believe that the length of the line is several times greater than the distance (depth) D_G. For OHL, this assumption is quite true, since their length is many kilometers, while the depth D_G is several hundred meters. For CL, the length of which is often only a few hundred meters, it is impossible to neglect the edge effects. In other words, for CL the current is unlikely to be able to penetrate into the ground to the depth D_G, to which it would penetrate for long OHL.

Considering the above, in some cases, instead of calculating D_G based on data on the soil resistivity ρ_G, the depth of D_G should be taken equal to several meters, guided by expert opinion, taking into account the CL route characteristics. The minimum value of D_G could be considered $D_G = 1$ m.

IX. CALCULATION EXAMPLES

Here are 2 examples of calculating the impedances according to the formulas from Table 1:

– CL 10 kV with core $F_C = 240$ мм^2 and screen $F_S = 50$ мм^2, both made of copper;
– CL 110 kV with core $F_C = 1000$ мм^2 and screen $F_S = 185$ мм^2, both made of copper.

The results are given:

– in Tables 2,3 for CL 10 kV;
– in Tables 4,5 for CL 110 kV.

Calculations were performed under the following conditions: $T_C = 65$°C, $T_S = 60$°C, $\psi_C = 0.9$, $\psi_S = 0.5$, $f = 50$ Hz. The cases of laying cables in a closed triangle (Fig.2,a) and in a row with the distance between the axes $s_{AB} = s_{BC} = 0.2$ m (Fig.2,b) are considered.

The parameters of the positive sequence do not depend on D_G, but the parameters of the zero sequence do. Therefore, two values of D_G were considered in the zero sequence calculations:

– $D_G = 1130$ m (evaluated for soil resistivity $\rho_G = 100$ Ω·m);
– $D_G = 1$ м m (accepted by expert opinion, based on the assumption that there are some metal pipelines, rails, metal structures along the CL route).

Table 2. CL 10 kV impedances (240/50 mm^2, Cu/Cu, a closed triangle)

<table>
<tr><th rowspan="2">Scheme fig.4</th><th colspan="4">Ω/km</th></tr>
<tr><th>R_1^*</th><th>X_1^*</th><th>R_0^*</th><th>X_0^*</th></tr>
<tr><td>(a)</td><td rowspan="2">0.0842</td><td rowspan="2">0.0886</td><td>0.232 (0.232)</td><td>2.03 (0.706)</td></tr>
<tr><td>(b)</td><td rowspan="2">0.462 (0.369)</td><td rowspan="2">0.098 (0.166)</td></tr>
<tr><td>(c)</td><td>0.0943</td><td>0.0869</td></tr>
</table>

Table 3. CL 10 kV impedances (240/50 mm^2, Cu/Cu, in a row $s_{AB} = s_{BC} = 0.2$ м).

<table>
<tr><th rowspan="2">Scheme fig.4</th><th colspan="4">Ω/km</th></tr>
<tr><th>R_1^*</th><th>X_1^*</th><th>R_0^*</th><th>X_0^*</th></tr>
<tr><td>(a)</td><td rowspan="2">0.0842</td><td rowspan="2">0.208</td><td>0.232 (0.232)</td><td>1.79 (0.468)</td></tr>
<tr><td>(b)</td><td rowspan="2">0.457 (0.307)</td><td rowspan="2">0.106 (0.167)</td></tr>
<tr><td>(c)</td><td>0.154</td><td>0.176</td></tr>
</table>

Table 4. CL 110 kV impedances (1000/185 mm^2, Cu/Cu, a closed triangle)

<table>
<tr><th rowspan="2">Scheme fig.4</th><th colspan="4">Ω/km</th></tr>
<tr><th>$R_1{}^*$</th><th>$X_1{}^*$</th><th>$R_0{}^*$</th><th>$X_0{}^*$</th></tr>
<tr><td>(a)</td><td rowspan="2">0.0202</td><td rowspan="2">0.0915</td><td>0.168 (0.168)</td><td>1.89 (0.566)</td></tr>
<tr><td>(b)</td><td rowspan="2">0.127 (0.119)</td><td rowspan="2">0.0424 (0.0539)</td></tr>
<tr><td>(c)</td><td>0.0427</td><td>0.0799</td></tr>
</table>

Table 5. CL 110 kV impedances (1000/185 mm^2, Cu/Cu, in a row $s_{AB} = s_{BC} = 0.2$ м).

<table>
<tr><th rowspan="2">Scheme fig.4</th><th colspan="4">Ω/km</th></tr>
<tr><th>$R_1{}^*$</th><th>$X_1{}^*$</th><th>$R_0{}^*$</th><th>$X_0{}^*$</th></tr>
<tr><td>(a)</td><td rowspan="2">0.0202</td><td rowspan="2">0.163</td><td>0.168 (0.168)</td><td>1.75 (0.423)</td></tr>
<tr><td>(b)</td><td rowspan="2">0.127 (0.114)</td><td rowspan="2">0.0429 (0.0571)</td></tr>
<tr><td>(c)</td><td>0.0828</td><td>0.0892</td></tr>
</table>

X. CONCLUSIONS

1. The article offers formulas for estimating the longitudinal active and inductive impedances of CL with single-core cables, taking into account:
   - sequences (positive or zero);
   - screen bonding/grounding schemes (fig.4).
2. Positive sequence impedances $R_1{}^*$ и $X_1{}^*$ significantly depend on the screen bonding/grounding scheme, and this is especially true of the resistance $R_1{}^*$.
3. Zero sequence impedances $R_0{}^*$ и $X_0{}^*$ can be more or less than positive sequence impedances $R_1{}^*$ и $X_1{}^*$, and the ratio $R_0{}^*/R_1{}^*$ и $X_0{}^*/X_1{}^*$ depend on the screen bonding/grounding scheme, on the core and screen cross-sections, on the distance between CL cables, on the value of D_G.
4. In the power grid regime calculations, including the calculations of grid short circuit currents, it is impossible:
   - to neglect the CL active impedances $R_1{}^*$ и $R_0{}^*$, assuming that they, like on overhead lines, significantly less than inductive impedances $X_1{}^*$ и $X_0{}^*$;
   - assume that the zero sequence impedances $R_0{}^*$ и $X_0{}^*$ will be the same as the positive sequence impedances $R_1{}^*$ и $X_1{}^*$.
5. It is important to understand that the formulas for the CL active and inductive impedances, given in the cable catalogs of companies, usually refer only to the case of a positive sequence, moreover, provided there is no currents in the screens (the screens cross-bonding or their one-side grounding is applied). In other cases, it is not recommended to use catalog formulas due to the occurrence of significant errors!

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