SELECTION AND IMPLEMENTATION OF BONDING/GROUNDING SCHEMES FOR SINGLE-CORE CABLE SCREENS

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Currently, the country's energy sector already has an idea of the problems that the mass use of single-core 6-500 kV cables with cross-linked polyethylene insulation has brought. For a number of such problems, industry experts have found simple and convenient technical solutions. Let's consider one of the important issues of creating cable lines with single-core cables – the selection and mounting of screen bonding/grounding schemes.

The method proposed in the article for calculating and selecting the screen bonding/ grounding schemes is scientifically proved and at the same time very simple and convenient. This contributes to its wide application both in the country and abroad. The bonding and grounding link-boxes recommended in the article should also be recognized as attractive.

1. Basic cable screen bonding/grounding schemes

Figure 1 shows basic schemes for screens bonding and grounding of three-phase cable lines (CL) with single-core cables. Schemes differ from each other by the currents and voltages induced in the screens, as well as active power losses in the screens. The choice of the optimal bonding/grounding scheme is possible only after calculating all these values, for example, according to the method [1,2].

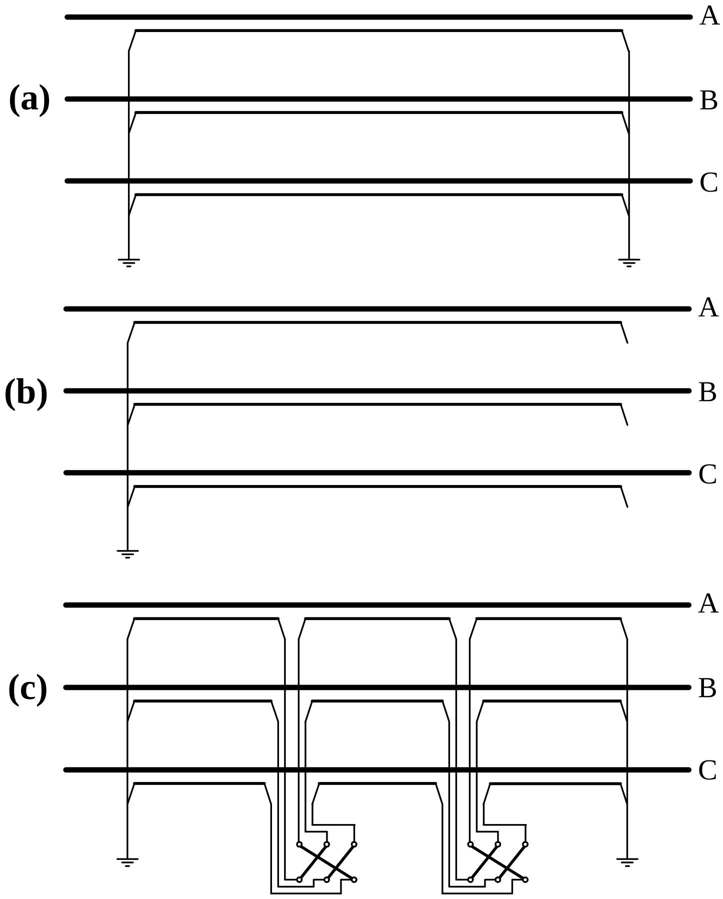

Fig.1. Basic screens bonding/grounding schemes for single-core cables:
(a) – two-side grounding; (b) – one-side grounding; (c) – screens cross-bonding.

The induced currents in the screens and the parasitic losses of active power caused by them are subject to calculation for scheme Fig.1,a. On the contrary, for schemes Fig.1,b and Fig.1,c there are no currents and active power losses in the screens, but it is necessary to check the induced voltage on the screen relative to the ground.

2. Calculation of screen currents and power losses

When calculating screen currents I_S and losses P_S, not only their specific magnitude plays an important role, but also how much they are noticeable against the background of core currents I_C and losses P_C.

The ratio I_S/I_C calculated by [1] is shown on Fig.2 which is valid only for the case of screens two-side grounding (scheme Fig.1,a). According to [1] this ratio depends on screen cross-section F_S (from 35 to 350 mm^2) and the ratio s/d_S, where s – is the average distance between the axes of the three phases (A,B,C), d_S – is cable screen outer diameter:

$$s = \sqrt[3]{d_{AB} \cdot d_{BC} \cdot d_{AC}} \qquad\qquad d_S = d - 2\Delta_{OSH}$$

where d is the diameter of the cable according to the cable catalog, Δ_{OSH} is the thickness of the cable outer sheath according to the cable catalog (almost always 5-6 mm).

Using Fig.2, it is not difficult to find the relative power losses:

$$\frac{P_S}{P_C} = \frac{{I_S}^2 \cdot ({R_S}^* \cdot l_{CL})}{{I_C}^2 \cdot ({R_C}^* \cdot l_{CL})} = \left(\frac{I_S}{I_C}\right)^2 \cdot \frac{\rho_S}{\rho_C} \cdot \frac{F_C}{F_S} \qquad (1)$$

where ${R_C}^*$ and ${R_S}^*$ are linear resistances of the core and screen;

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

where F_C and F_S are the cross-sections of the core and the screen, ρ_C and ρ_S are resistivities of the core and screen materials (for copper $2 \cdot 10^{-8}$ Ω·m, for aluminum $3.2 \cdot 10^{-8}$ Ω·m), l_{CL} – cable line length (m).

Losses in a single-core cable heat its insulation, the temperature of which should not exceed the long-term permissible value. Therefore, it is obvious that in the case of absence of screen losses P_S, the CL rated current will be greater than in the case of such losses. The coefficient characterizing the degree of reducing CL rated current according to [1]:

$$K_P = \frac{1}{\sqrt{1 + P_S/P_C}} \qquad (2)$$

The ratio P_S/P_C of parasitic losses in the screen and unavoidable losses in the core is an important criterion for choosing the screens bonding/grounding scheme. This ratio does not depend on the CL length, and therefore it turns out that with a given type of single-core cables and the method of laying them, special measures to combat screen currents I_S are equally necessary for both short and long CL. At the same time, it is clear that the costs of implementing measures to combat screen losses can be felt compared to the cost of a short CL, but are negligible against the background of the price of a long CL. Therefore, it seems appropriate to introduce an additional criterion for choosing the screens bonding/grounding scheme that would take into account economic aspects. Let this be the cost of power loss.

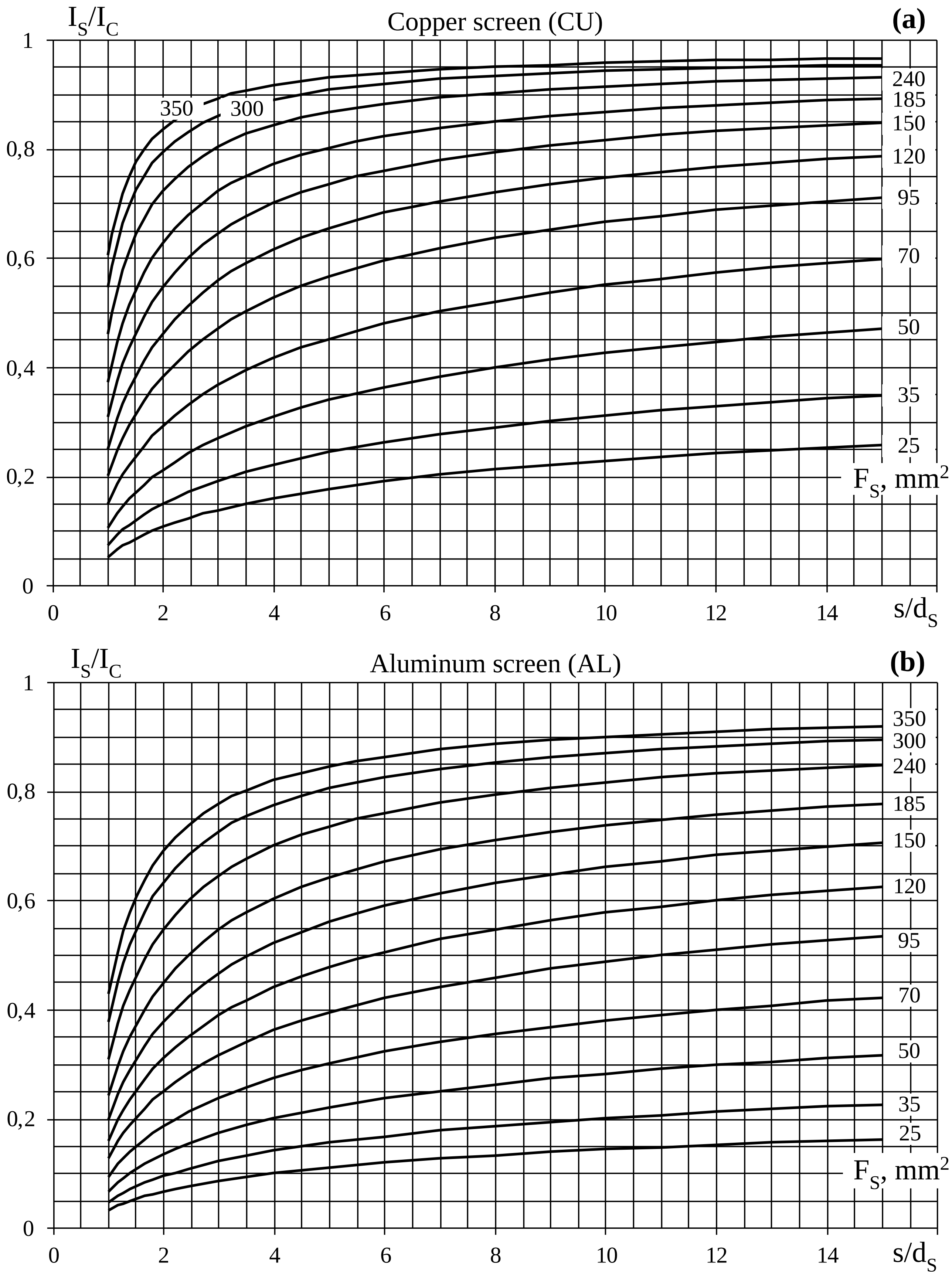

Fig.2. Relative currents in two-side grounded screens for CL with single-core cables depending on the screen cross-section $F_Э$ (mm^2) and the phases relative position $s/d_Э$: (a) – copper screen; (b) – aluminum screen.

Power losses P_S in the screen of one phase are conveniently found through P_C:

$$P_C = {I_C}^2 \cdot ({R_C}^* \cdot l_{CL})$$
$$P_S = P_C \cdot \frac{P_S}{P_C} \tag{3}$$

where P_C is the power losses in the core of one phase (W),
I_C is the average annual current in the core (A),
P_S/P_C is the relative losses in the screen by (1).

The cost C_1 of screen parasitic power losses for 1 year of CL operation:

$$W_1 = \frac{3P_S}{1000} \cdot 8760$$
$$C_1 = W_1 \cdot C_W \tag{4}$$

where W_1 is the annual energy losses for all three phases of entire CL, (kWh)/year,
P_S is the power losses in the screen of one phase (W),
3 is number of phases (number of single-core cables of entire CL),
8760 is the number of hours in 1 year,
C_W is the price of power losses, rub/kWh.

For all single-core cables, regardless of their rated voltage class, it follows from (1)-(4) that an effective reduction of screen parasitic losses and their cost can be achieved:

- using cables with a small screen cross-section F_S (with a large ${R_S}^*$);
- laying the CL phases in a closed triangle, since in this case the ratio s/d_S is minimized.

If laying the CL phases in a closed triangle does not allow to reduce screen currents and power losses to an acceptable level, then you should abandon the two-side grounding scheme and use alternative schemes like:

- one-side grounding (Fig.1,b);
- screens cross-bonding (Fig.1,c).

3. Calculation of the voltage on the screen relative to the ground

In [1] it was shown that the voltage on the screen is directly proportional to the core current I_C and the CL length l_{CL}. In addition, the voltage on the screen depends on:

- the distance between the phases s, the screen diameter d_S, the ratio s/d_S;
- the equivalent depth of current flow in the ground D_G, which is calculated as

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

where ρ_G is the resistivity of the soil (Ω·m),
$\mu_0 = 4\pi \cdot 10^{-7}$ – absolute magnetic permeability of vacuum (H/m),
$\omega = 2\pi f$ is the circular frequency of voltages and currents (rad/s).

Fig.3 and Fig.4 show the results of calculations of the voltage on the screen according to the formulas from [1]. The voltage U_S on the screen relative to the ground is determined for the core current $I_C = 1000$ A and the cable length $l_{CL} = 1000$ m.

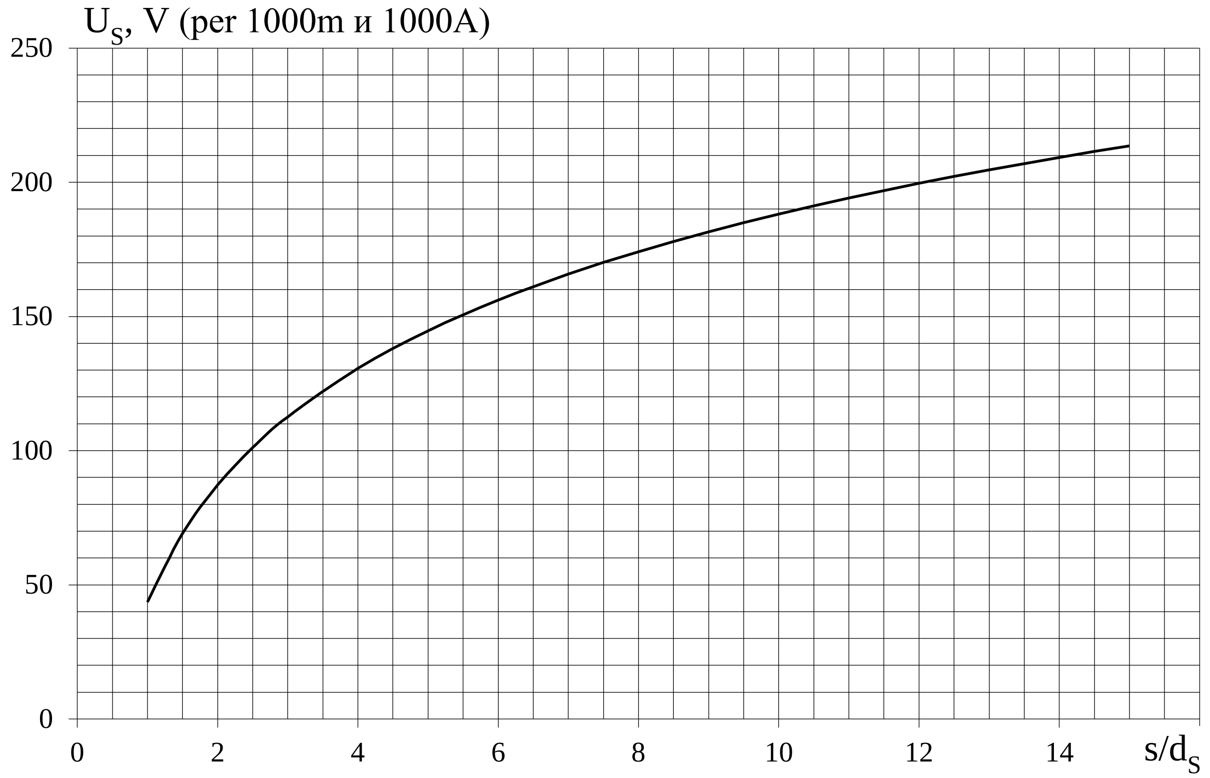

Fig.3. The voltage on the single-core cable screen relative to the ground for a 1000 m long CL with a core current of 1000 A, depending on the s/d_S ratio.

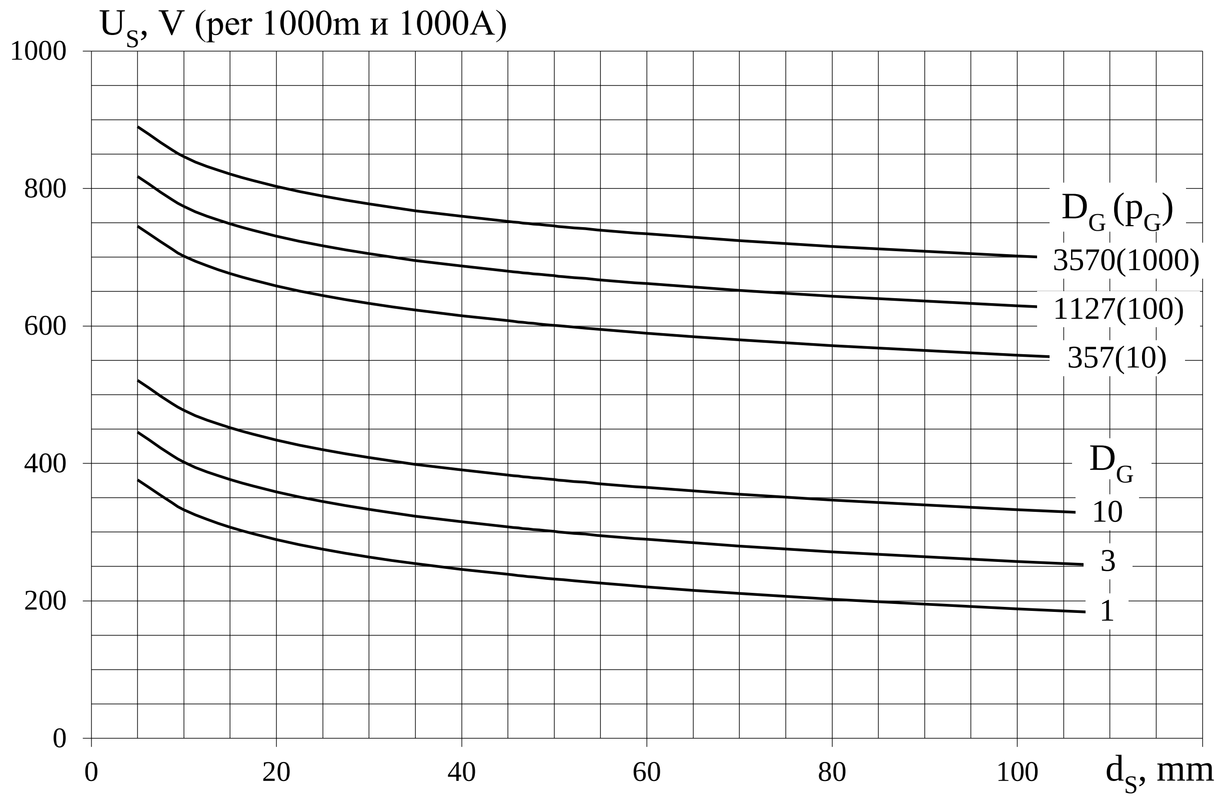

Fig.4. The voltage on the single-core cable screen relative to the ground for a 1000 m long CL with a core current of 1000 A, depending on the screen diameter d_S and depth D_G.

If the CL is laid in a territory of switchgear or manufacture, etc., then the depth D_G is small (1, 3, 10 m) and is determined by the presence in the ground a grounding system or various metal structures. In other cases, D_G depends on the ground resistance ρ_G (10, 100, 1000 Ω·m). Because of this, Fig.4 shows both values of D_G and ρ_G.

With screen one-side grounding for arbitrary cable core current I_C and CL length l_{CL}, the voltage at the ungrounded end of the screen can be found as:

$$U_S = {U_S}^{FIG} \cdot \frac{I_C}{1000} \cdot \frac{l_{CL}}{1000} \quad (5)$$

where in normal operation mode or with an external (not in CL) three-phase short-circuit of the network, the data of Fig.3 should be used, and with an external (not in CL) single-phase short-circuit of the network, the data of Fig.4.

With a CL screens cross-bonding having N complete cycles, the voltage at the node of cross-bonding can be found as

$$U_S = \frac{{U_S}^{FIG}}{3N} \cdot \frac{I_C}{1000} \cdot \frac{l_{CL}}{1000} \quad (6)$$

where it is always necessary to use the data of Fig.3, since for the screens cross-bonding, a single-phase short-circuit of the network is not a calculated case [1].

The calculated voltage U_S on the screen should not exceed the values acceptable for the cable outer sheath, which are according to [1,2]:

– 100 V in normal operation mode;
– 5000 V in case of a short-circuit in the network.

4. Example of selection and mounting of screens one-side grounding scheme

Choosing a scheme

A 110 kV CL with a length of $l_{CL} = 600$ m with a copper core $F_C = 800$ mm^2 and a copper screen $F_S = 240$ mm^2 is laid in a closed triangle. The current of the normal operation mode is $I_C = 1000$ A, the current of the three-phase short-circuit is 38 kA, the current of the single-phase short-circuit is 42 kA. Let's choose the optimal screens bonding/ grounding scheme.

For 110 kV 800/240 cable according to the cable catalog the diameter is $d = 80$ mm. With a typical outer sheath thickness $\Delta_{OSH} = 5$ mm, we find the screen diameter:

$$d_S = d - 2\Delta_{OSH} = 70 \text{ mm}$$

When laying CL cables in a closed triangle, we have $d_{AB} = d_{BC} = d_{AC} = d$, then the average distance between the axes of the phases:

$$s = \sqrt[3]{d_{AB} \cdot d_{BC} \cdot d_{AC}} = d = 80 \text{ mm}$$

The necessary ratio is $s/d_S = 80/70 = 1.14$. According to Fig.2, with $s/d_S = 1.14$ and $F_S = 240$ mm^2, we have:

$$\frac{I_S}{I_C} = 0.5 \text{ pu}$$

By (1), (2) we find the relative losses P_S/P_C and losses coefficient K_P:

$$\frac{P_S}{P_C} = \left(\frac{I_S}{I_C}\right)^2 \cdot \frac{\rho_S}{\rho_C} \cdot \frac{F_C}{F_S} = 0.5^2 \cdot \frac{2 \cdot 10^{-8}}{2 \cdot 10^{-8}} \cdot \frac{800}{240} = 0.83 \text{ pu}$$

$$K_P = \frac{1}{\sqrt{1 + P_S/P_C}} = \frac{1}{\sqrt{1 + 0.83}} = 0.74 \text{ pu}(74\%)$$

By (3), (4) we find screen power losses P_S and their annular cost C_1:

$$P_C = I_C{}^2 \cdot (R_C{}^* \cdot L_{CL}) = 1000^2 \cdot \left(\frac{2 \cdot 10^{-8}}{800 \cdot 10^{-6}} \cdot 600\right) = 15 \cdot 10^3 \text{ W}$$

$$P_S = P_C \cdot (P_S/P_C) = (15 \cdot 10^3) \cdot 0.83 = 12.5 \cdot 10^3 \text{ W}$$

$$W_1 = \frac{3P_S}{1000} \cdot 8760 = \frac{3 \cdot (12.5 \cdot 10^3)}{1000} \cdot 8760 = 330 \cdot 10^3 \text{ (kWh)/year}$$

$$C_1 = W_1 \cdot C_W = (330 \cdot 10^3) \cdot 1 = 330 \cdot 10^3 \text{ Rub/year}$$

where the loss price is assumed to be equal to $C_W = 1$ Rub/kWh.

It follows from the calculations that when we have screens two-sides grounding, the CL cable current capacity can be used only by 74% of its maximum value, and the cost of power losses in the screens is 330 thousand rubles per year (about 5 thousand euro per year). Obviously, such a screens scheme is unprofitable and unacceptable.

Consider screens one-side grounding. Comparing Fig.3 and Fig.4, it can be seen that the induced voltage with a single-phase short-circuit is greater than with a three-phase one. According to Fig.4, with a typical soil resistivity $\rho_G = 100$ Ω m and a screen outer diameter $d_S = 70$ mm, the voltage induced on the screen is $U_S{}^{FIG} = 650$ V per 1000 A and 1000 m.

According to (5) with a single-phase short-current of 42 kA, we find the voltage on the screen:

$$U_S = U_S{}^{FIG} \cdot \frac{I_C}{1000} \cdot \frac{l_{CL}}{1000} = 650 \cdot \frac{42000}{1000} \cdot \frac{600}{1000} = 16380 \text{ V}$$

which turned out to be significantly more than the permissible value of 5000 V.

If, with screens one-side grounding in a 110-500 kV network with a grounded neutral, as a result of calculations according to (5), the screen-ground voltage turns out to be greater than the permissible value of 5 kV, then it is possible to provide for laying along the CL of a special copper bus grounded at the ends. It is shown in [3] that the effect of its use is based on a decrease in the value D_G included in the calculations, which, according to Fig.4, will lead to a decrease in the induced voltage.

For example, according to Fig.4, at a depth of $D_G = 1$ m and a screen diameter of $d_S = 70$ mm, the induced voltage is only $U_S{}^{FIG} = 200$ V per 1000 A and 1000 m.

According to (5) with a single-phase short-circuit current of 42 kA, we find the voltage on the screen:

$$U_S = U_S^{FIG} \cdot \frac{I_C}{1000} \cdot \frac{l_{CL}}{1000} = 200 \cdot \frac{42000}{1000} \cdot \frac{600}{1000} = 5040\ \mathrm{V}$$

which is already acceptable.

So, for the 110 kV 800mm^2/240mm^2 CL in question, we accept screens one-side grounding. A copper conductive bus, grounded at both CL ends, must be laid along the CL route at a distance of no more than 1 m from cables.

At the ungrounded end of the screen, to protect the cable outer sheath from impulse overvoltages (lightning and switching), a metal oxide surge arrester (MOA) of voltage class 6 kV should be installed in each phase between the screen and the ground, as shown in [1,4].

Link-box mounting

At the CL end where cable screens are grounded, a special three-phase end link-box is provided for the placement of the screens MOA (lets name it like ELB/MOA). For the convenience of CL installation and maintenance at its opposite end (where the screens have a direct grounding without MOA), an end box is also installed that does not have any MOA inside and is called an end grounding link-box (ELB).

At each end of the CL, three screens are taken from the three cable terminations using a connecting wire (CW) with polyethylene insulation and then go into the ELB/MOA box, where they are connected to three MOAs, or into the ELB box, where they are connected to a bus mounted on insulators and grounded by a separate (already fourth) CW wire.

The connection wire has the same insulation strength as the main single-core cables outer sheath (insulation class about 6 kV), and its core cross-section is assumed to be equal to the cross-section of the screen of the main single-core cable (in this example, 240 mm^2).

As an example, consider the mounting of ELB without MOA (see photos 1-6):

1. Remove the lid from the box and install the box at the place of operation.
2. On the bottom panel, use a knife to cut the silicone seal to a diameter that corresponds to the diameter of the connection wire CW.
3. Cut the CW according to the size of the tips included with the box.
4. Put a heat shrinkable tube on CW, then compress the tip on the cut end of the CW wire.
5. Put the tip on the pin of the MOA and fix it with a nut, then heat-shrink the tube with a gas burner.
6. Perform 2-5 for the remaining CWs and then close the box with a lid.

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5. Example of selection and mounting of screens cross-bonding scheme

Choosing a scheme

A 10 kV CL with a length of $l_{CL} = 6000$ m with a copper core $F_C = 630$ mm^2 and a copper screen $F_S = 95$ mm^2 is laid in a closed triangle. The current of the normal operation mode is $I_C = 700$ A, the current of the three-phase short-circuit is 20 kA, the current of the single-phase-to-ground fault is not important, since it does not affect the calculations for 6-35 kV cable networks with ungrounded neutral (isolated, compensated). Let's choose the optimal screens bonding/ grounding scheme.

For 10 kV 630/95 cable according to the cable catalog the diameter is $d = 50$ mm. With a typical outer sheath thickness $\Delta_{OSH} = 5$ mm, we find the screen diameter:

$$d_S = d - 2\Delta_{OSH} = 40 \text{ mm}$$

When laying CL cables in a closed triangle, we have $d_{AB} = d_{BC} = d_{AC} = d$, then the average distance between the axes of the phases:

$$s = \sqrt[3]{d_{AB} \cdot d_{BC} \cdot d_{AC}} = d = 50 \text{ mm}$$

The necessary ratio $s/d_S = 50/40 = 1.25$. According to Fig.2, with $s/d_S = 1.25$ and $F_Э = 95$ mm^2, we have:

$$\frac{I_S}{I_C} = 0.25 \text{ pu}$$

By (1), (2) we find the relative losses P_S/P_C and losses coefficient K_P:

$$\frac{P_S}{P_C} = \left(\frac{I_S}{I_C}\right)^2 \cdot \frac{\rho_S}{\rho_C} \cdot \frac{F_C}{F_S} = 0.25^2 \cdot \frac{2 \cdot 10^{-8}}{2 \cdot 10^{-8}} \cdot \frac{630}{95} = 0.41 \text{ pu}$$

$$K_P = \frac{1}{\sqrt{1 + P_S/P_C}} = \frac{1}{\sqrt{1 + 0.41}} = 0.84 \text{ pu } (84\%)$$

By (3), (4) we find screen power losses P_S and their annular cost C_1:

$$P_C = {I_C}^2 \cdot ({R_C}^* \cdot l_{CL}) = 700^2 \cdot \left(\frac{2 \cdot 10^{-8}}{630 \cdot 10^{-6}} \cdot 6000\right) = 93 \cdot 10^3 \text{ W}$$

$$P_S = P_C \cdot (P_S/P_C) = (93 \cdot 10^3) \cdot 0.41 = 38 \cdot 10^3 \text{ W}$$

$$W_1 = \frac{3P_S}{1000} \cdot 8760 = \frac{3 \cdot (38 \cdot 10^3)}{1000} \cdot 8760 = 990 \cdot 10^3 \text{ (kWh)/year}$$

$$C_1 = W_1 \cdot C_W = (990 \cdot 10^3) \cdot 1 = 990 \cdot 10^3 \text{ Rub/year}$$

where the loss price is assumed to be equal to $C_W = 1$ Rub/kWh.

It follows from the calculations that when we have screens two-sides grounding, the CL cable current capacity can be used only by 74% of its maximum value, and the cost of power losses in the screens is 990 thousand rubles per year (15 thousand euro per year). Obviously, such a screens scheme is unprofitable and unacceptable.

It is clear in advance that for CL with a length of 6000 m, screens one-side grounding will not be acceptable. Therefore, let's consider one complete cycle of screens cross-bonding (number of full transposition cycles is $N = 1$).

For 6-35 kV networks with an ungrounded neutral, when determining the voltage on the screen, a three-phase short-circuit is calculated. According to Fig.3, at $s/d_S = 1.25$, the induced voltage is $U_S{}^{FIG} = 50$ V per 1000 A and 1000 m.

According to (5) with a three-phase short-circuit current of 20 kA, we find the voltage on the screen:

$$U_S = \frac{U_S{}^{FIG}}{3N} \cdot \frac{I_C}{1000} \cdot \frac{l_{CL}}{1000} = \frac{50}{3 \cdot 1} \cdot \frac{20000}{1000} \cdot \frac{6000}{1000} = 2000 \text{ V}$$

which is less than the permissible value of 5000 V (if the voltage turned out to be higher than the permissible one, then it would be necessary to repeat the calculations already for increased number of full transposition cycles $N = 2,3\ldots$).

So, for the 10 kV 630mm^2/95mm^2 CL in question, we accept one complete cycle of screens cross-bonding ($N = 1$). If it is not possible to place the screen cross-bonding nodes at the point of 1/3 and 2/3 of the CL route, then it is necessary to carry out calculations using the technique [5] for those cross-bonding conditions that are feasible.

In the screens cross-bonding nodes, to protect the cable outer sheath from impulse overvoltages (lightning and switching) a metal oxide surge arrester (MOA) of voltage class 6 kV should be installed in each phase between the screen and the ground, as shown in [1,4].

Link-box mounting

To place three MOAs in each cross-bonding nodes, a special cross-bonding link-box (transposition link-box TLB/MOA) is provided, installed in the so-called transposition well (as a rule, this is a reinforced concrete well). At each screens cross-bonding node, six screens are taken from the three cable joints using a connecting wire (CW) with polyethylene insulation and then go into the TLB/MOA box, where they are connected to three MOAs.

The connection wire has the same insulation strength as the main single-core cable outer sheath (insulation class about 6 kV), and its core cross-section is assumed to be equal to the cross-section of the screen of the main single-core cable (in this example, 95 mm^2).

As an example, consider the mounting of TLB/MOA (see photos 1-8):

1. Prepare the link-box for installation (install it in the transposition well). There is no need to open lid of the box, because the box equipped with the system of bushings.
2. Cut the CW wire, removing the insulation from it to the required length, then put on the heat shrinkable tube.
3. Insert the CW prepared end into the bushing and tighten bushing screws using a hexagon socket wrench.
4. Wrap the CW with the help of TYCO "Tape 23" in two layers, starting from the bushing.
5. Push the heat shrinkable tube on the bushing to the end.
6. Perform heat shrinkage of the tube using a gas burner, starting from the bushing.
7. Complete the shrinkage.
8. Perform paragraphs 2-7 for the remaining CW and then close the transposition well lid.

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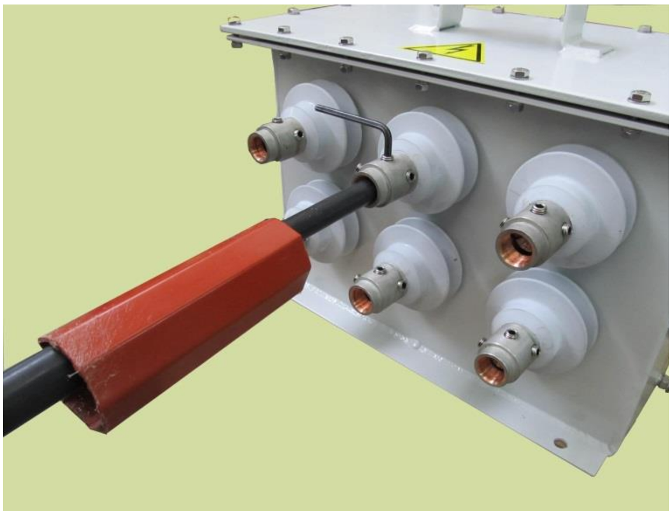

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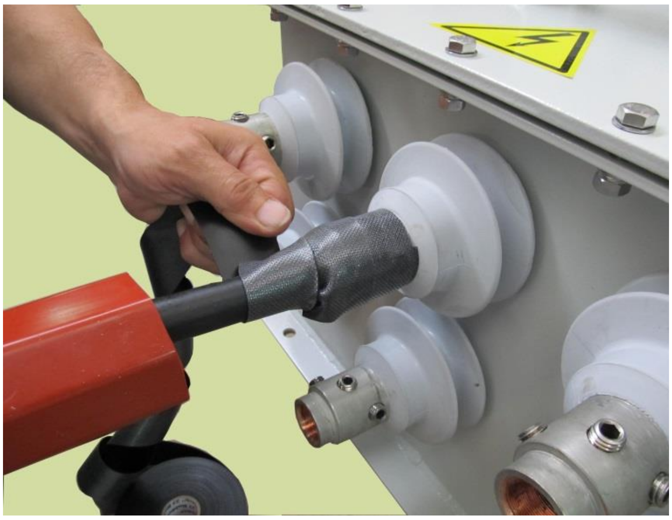

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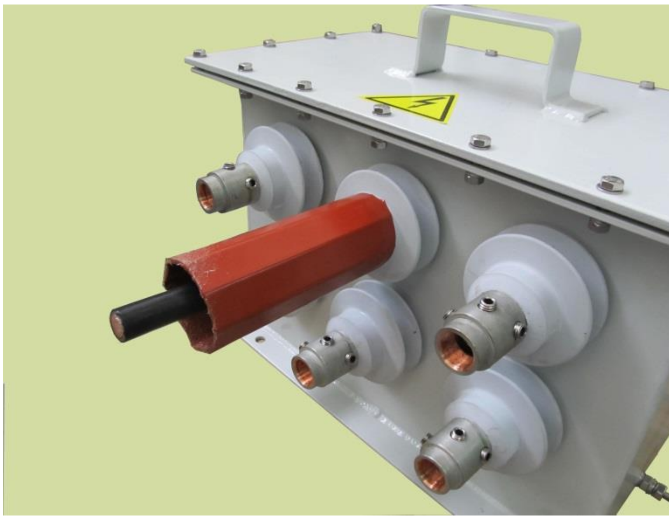

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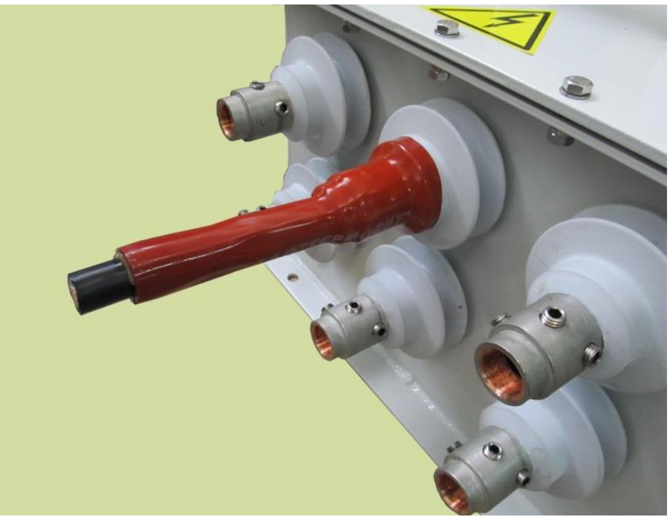

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6. Conclusions

In recent years, specialists have done a lot of work, which has made it possible to create everything for the reasonable choice of screens bonding/grounding schemes and their mounting on 6-500 kV cable lines with single-core cables.

1. The choice of the screens bonding/grounding scheme can be carried out using the method given in the article and proved in the book [1].
2. As it was shown in the article, screens cross-bonding is an effective way to combat screen power losses and it may be required even for 6-35 kV cable lines.
3. An MOA of class 6 kV should be installed at the ungrounded end of the screen or at the cross-bonding nodes to protect the cable outer sheath from overvoltages. Installation of MOA of classes 1,3,5 kV is unacceptable because of their frequent damages [1].
4. It is convenient to place MOA in special quick-mounted link-boxes.
5. It is convenient to connect MOAs with cable terminations and cable joints by using the connection wire of class 6(10) kV, the cross-section of the core of which is equal to the cross-section of the screen of the main single-core cable. Connection wires of voltage classes 0.4, 1.5, 3 kV are unacceptable because of their frequent damages [1].

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