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B1 Insulated cables
PS2 Recent experience with AC and DC cables, both land and submarine

Improving the efficiency of renewable energy cable networks

Mikhail Dmitriev
Cabelte
Portugal
info@voltplace.com

César Ferreira
Cabelte
Portugal
cesar.ferreira@cabelte.pt

Patricia Rebelo
Cabelte
Portugal
patricia.rebelo@cabelte.pt

SUMMARY

The present and future of energy is impossible without the mass use of medium-voltage power cables (6-35 kV). Despite the high quality of modern cables, owners of electrical networks suffer significant economic damage as a result of incorrect selection of type and cross-section of cables, as well as not optimal choice of the mutual arrangement of three phases. Such damage is especially noticeable for long cables, that is, for example, in cases where cables are used to connect wind generators to the electrical network. The article is related to some of these issues.

KEYWORDS

Single-core cable, XLPE insulation, screen bonding, solid bonding, trefoil formation, flat formation, induced current, power losses, cable ampacity, cable temperature.

1. Introduction

In AC 50 Hz medium-voltage networks of 6-35 kV classes, the most commonly used are cables with solid insulation (XLPE or EPR), of three-core or single-core design (Fig.1).

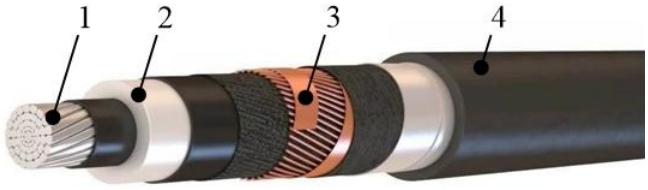


***Figure 1** – The principal design of single-core medium voltage cable:*
1 – core, 2 – solid insulation, 3 – screen, 4 – outer sheath

Single-core cables have a lot of advantages and are the most widespread. One of the few disadvantages of single-core cables is the presence of AC 50 Hz induced currents in screens (also known as "circulating currents") and losses of active power caused by them. Currents and losses heat the screens along the entire length of the cable line. Therefore, they lead:

- to the need to pay for these losses;
- to the heating of the insulation and, therefore, to reduction of the ampacity of the line.

Currents and losses in the screens occur when screens are bonded/grounded on both sides of the line. To eliminate currents and losses in screens, it is required using other types of screen bonding/grounding [1-6]:

- single-point bonding/grounding of the screens;
- cross-bonding of the screens.

The problem of currents/losses in screens of single-core cables is related to AC 50 Hz magnetic fields of core currents, and it does not depend on the voltage class of the cable line. Therefore, the selection of screen bonding/grounding type is almost equally important for both medium-voltage (6-35 kV) and high-voltage (110-500 kV). Despite this, owners and operating companies are ready to optimize screen bonding/grounding primarily only in high-voltage lines. As for 6-35 kV lines, they prefer to have screens bonded/grounded from both sides which is the easiest and cheapest screen connection type (in terms of design and operation).

In many countries, the practice is that in medium voltage networks, most of single-core cables, without proper calculations of currents/losses, receive screen bonding/grounding from both sides. Unfortunately, this "obvious" type of bonding could be not only not optimal but even dangerous. The situation is worst in those cases in which single-core cables of phases A, B, C are arranged not in a trefoil, but in a flat formation at a distance from each other.

This situation is also caused by the fact that, in catalogues and regulatory documents on medium-voltage cables, issues of optimizing screen bonding/grounding types are often omitted, creating the false impression that the problems of currents/losses in screens do not exist here.

2. Inspection of the line

The presence of currents in cable screens, the magnitude of these currents, heating of cables and terminations (caused by these currents) can be determined in several ways.

2.1. Thermal inspection

Fig.2a shows the terminations of a cable line made with 4 cables per phase at once. During the thermal inspection, increased heating of the exit points of the screens from the terminations to the outside was revealed (Fig.2b). The fact is that the cable itself is usually heated by the heat coming from the cable core and the screen. However, in termination, there are not two heating sources, but three: a core, a screen inside the termination, and a screen outside the termination (the screen touches the external surface of the termination). Thus, the presence of noticeable currents in the screens is often seen by the hot area on the surface of the termination.

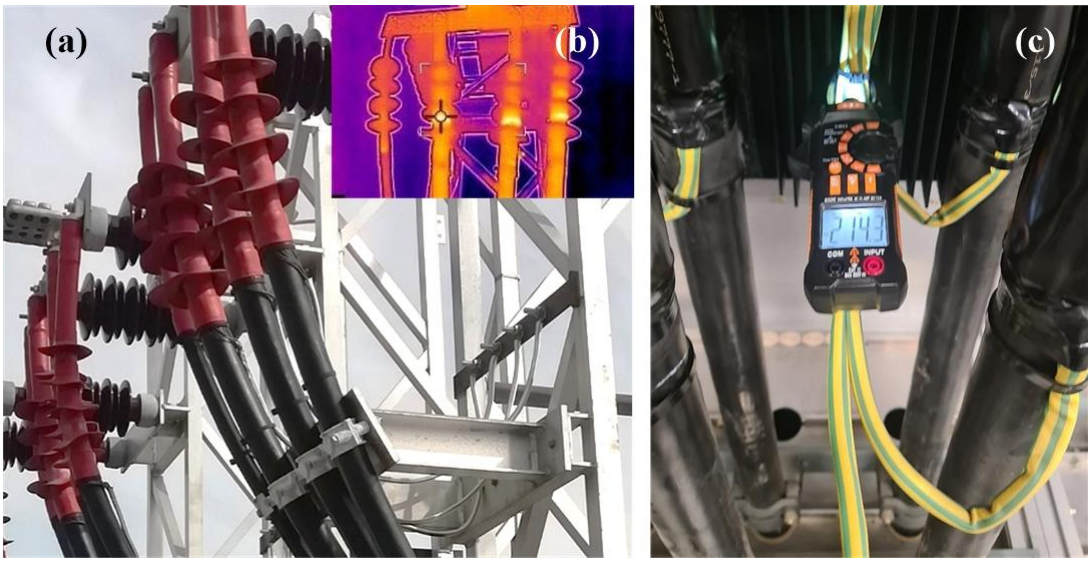


Figure 2 – Example of monitoring of circulating currents:
(a) – group of cables of the same phase; (b) – thermographic analysis;
(c) – measurements of the currents of all screens of the same phase using a clamp meter

2.2. Measurement of currents in screens

Fig.2c shows another way to check for cable screen currents – they can be measured with a conventional low voltage clamp meter (although the cable line is not of low voltage, its screens are grounded, and their electric potential is near zero). The photo shows that the total current of the four screens of the same phase was 214 A (approximately 53.5 A in each of four screens). It is important to note that not only the magnitude of current in the screen I_s is of interest at the time of measurement, but also the magnitude of current in the cable core I_c (conductor), because using these two currents, as will be shown below, it is possible to find the ratio I_s/I_c and assess the degree of influence of the screen on the losses in the line.

2.3. Visual inspection of the terminations

Fig.3a shows the result of a visual inspection of the termination (this case is known from another line, not the same as Fig.2). It can be seen that the outer sheath of the termination is overheated and cracked, thereby violating the tightness of the termination. A circle is shown around the very place where the termination is exposed to three sources of heating – the core, the screen from the inside, the screen from the outside. This overheated place is similar to what was seen as hot point on the thermal inspection of the previous line (Fig.2b).

Interestingly, for single-core cables, circulating currents occur not only in the screens, but also in the armor. The armor of single-core cables, if any, is usually made of wires of aluminum or its alloy, and, therefore, it is highly conductive. Since the armor wires tightly cover the surface of the cable, the total cross-section of the armor can be several times larger than the cross-section of the screen. Therefore, the currents in the armor can be several times greater than the currents in the screens, creating additional problems for cables and their terminations.

Fig.3b shows a case where a visual inspection revealed overheating of the termination and even melting of some of its elements and materials (to get this photo, the line was disconnected, and the termination was disassembled).

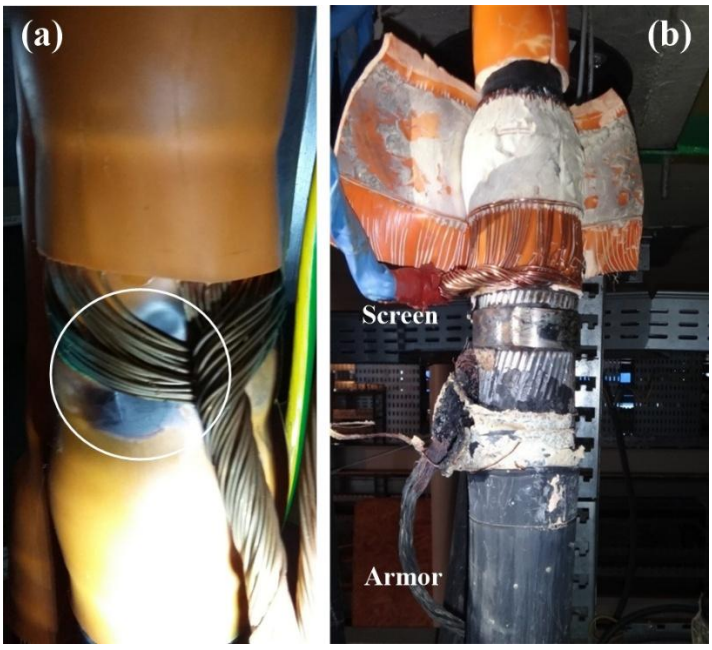


Figure 3 – Consequences of screen currents in medium-voltage cable lines:
(a) – overheating of the termination; (b) – overheating of the termination of the armored cable

In any of the cases shown in Fig.3, it is not practical to replace such a termination with a new one, since exactly the same thing will happen again, and it means that it is necessary to review the entire project. To solve the problem, sometimes it is possible to change the screen bonding/grounding from solid bonding to a lossless option (for example, single-point bonding). However sometimes it is not possible, and serious expensive changes may be required:

- bring the three phases A, B, C together (decrease the distance between phases);
- replace old cables with new cables of a smaller screen cross-section.

3. The distance between phases

The main options for the mutual arrangement of three single-core cables of phases A, B, C (each has an outer diameter of d) are shown in Fig.4 and differ from each other by the average (geometric mean) distance S between the centers of phases A, B, C:

$$S = \sqrt[3]{S_{AB} \cdot S_{BC} \cdot S_{AC}}\,. \qquad (1)$$

Using (1), for Fig.4a, 4b and 4c, we can calculate average distances $S = d$, $S = 1.26 \cdot d$ and $S = 1.26 \cdot S_{AB}$ respectively.

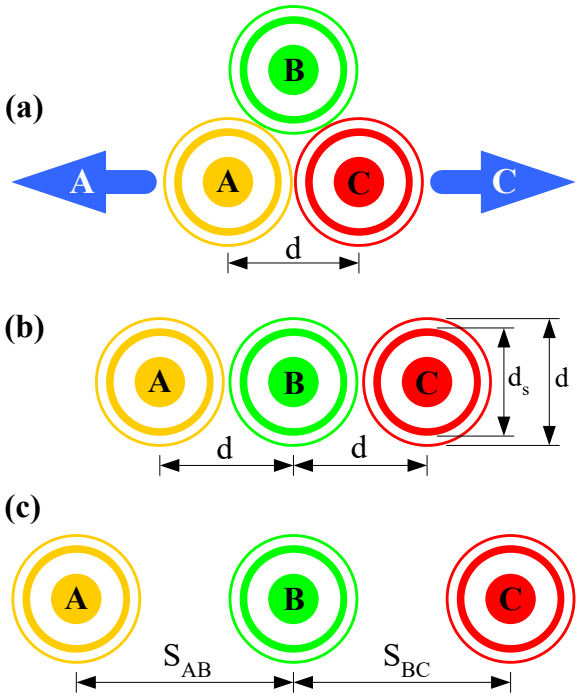


Figure 4 – Typical arrangements of three single-core cables:
(a) – trefoil; (b) – "deformed trefoil"; (c) – flat formation

It can be shown that even a slight increase in the distance S can cause a significant increase in losses P_s in cable screens. For example, there are 6-35 kV lines with solidly bonded screens, where the ratio of losses in screens and cores reached $P_s/P_c = 2 \div 3$, i.e. the power losses in the screens were up to 2-3 times greater than the power losses in the cores. This means that:

- the main source of heating of the cable insulation is not the core, which is usually the main focus of designers, but the screen, which performs an auxiliary function;
- the cost of losses in the screens, depending on the length of the line and other parameters, can amount to dozens of thousands of euros annually, which cannot be ignored.

If for some reason the laying of single-core cables of phases A, B, C in a trefoil is not performed, then for such a line it is necessary to refrain from the use of solid bonding and, instead, use one of the alternative bonding types (single-point bonding or cross-bonding).

As a rule, in medium voltage cable networks, specialists do not want to get involved in selecting the optimal bonding/grounding type for screens of single-core cables and want to have the simplest option – that is solid bonding. This means that for such medium voltage cable lines, for sure, it is necessary to lay single-core cables in trefoil (Fig.4a).

4. Cross-section of the screen

The ratio P_s/P_c and the cost of losses in the screens depend not only on the distance S between phases A, B, C, but also on the cross-section of the cable screen F_s. Previously, it was said that the larger the screen cross-section, the greater the losses in the screens and their cost – but this statement, at first glance, seems erroneous, because it is known that an increase in the cross-section usually causes a decrease in its heating and its losses, rather than an increase. Let us explain that this is not a mistake, for which we will give very approximate estimates of the

effects achieved in the case of an increase in the cross-sections of the core F_c and the screen F_s. To do this in a simple manner, let us omit the inductive impedance of the cable screen.

Assume that we have increased the cross-section F_c of the core by a factor of 2. Then:

- the active impedance of the core $R_c \sim 1/F_c$ will decrease by 2 times;
- the current in the core I_c, determined by the load on the cable line, will not change;
- the power losses in the core $P_c = {I_c}^2 \cdot R_c \cdot l_{cl}$ will decrease by 2 times.

Assume that we have increased the cross-section of the F_s screen by 2 times. Then:

- the active impedance of the screen $R_s \sim 1/F_s$ will decrease by 2 times;
- the AC 50 Hz voltage U_s, induced on the screens and determined by the core current I_c, will not change;
- the induced current in the screen $I_s \sim U_s/R_s$ will increase by 2 times;
- the power losses in the screen $P_s = {I_s}^2 \cdot R_s \cdot l_{cl}$ will increase by 2 times (although R_s decreased by 2 times, the current in the screen I_s increased by 2 times, and it is squared).

So, for single-core cables, in order to reduce the overall losses $P_{sum} = P_c + P_s$ existing in the cores and screens in normal operation, it is recommended to:

- increase the core cross-section F_c;
- reduce the screen cross-section F_s (if the values of the short-circuit current allow it).

5. Calculation method

The methods for calculating currents and losses in screens are known and described in CIGRE technical brochures [1-3] and standards [4-6]. Since all these documents are focused on performing the most accurate calculations, they require numerous inputs and contain complex mathematical expressions not convenient for everyday use. Therefore, to make calculations of currents and losses easier, we will use the methodology of books [7-8]. Formulae [7-8] provide results easier, and they differ from the results obtained with the help of the electro-magnetic process simulation software [9] by no more than 5 %, which is acceptable in engineering.

5.1. Input data

Core/screen cross-sections and materials:

F_c – the core cross-section (mm^2);

F_s – the screen cross-section (mm^2);

ρ_c – the specific active impedance of the core material at operating temperature (say, 65°C);

ρ_s – the specific active impedance of the screen material at operating temperature (say, 60°C).

Values of ρ_c and ρ_s can be taken as $2 \cdot 10^{-8}$ Ω · m (for Cu) or $3.2 \cdot 10^{-8}$ Ω · m (for Al).

Main dimensions required for calculations:

S – the geometric mean distance between phase cables A, B, C (mm);

d – the outer diameter of the cable (mm);

d_s – the outer diameter of the screen (mm);

Δ_{osh} – the thickness of the outer sheath (for 6-35 kV, it is about 2.5-4 mm, according to [10]).

The screen diameter d_s (in mm) can be found as:

$$d_s \approx d - 2\Delta_{osh} \,. \qquad (2)$$

5.2. Active and inductive impedances

Active impedances of the core/screen, and mutual inductive impedance between them:

$$R_c = \rho_c \cdot \frac{1}{(F_c \cdot 10^{-6})}\,, \qquad R_s = \rho_s \cdot \frac{1}{(F_s \cdot 10^{-6})}\,, \tag{3}$$

$$X \approx \omega \frac{\mu_0}{2\pi} ln\left(\frac{2S}{d_s}\right), \tag{4}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ – the magnetic constant (H/m);
$\omega = 2\pi f$ – the angular frequency of network voltages and currents (rad/s), $f = 50$ Hz.

5.3. Currents

In normal operating mode, the formula linking the core current and the induced current in the screen of the single-core cable:

$$\frac{I_s}{I_c} = \frac{1}{\sqrt{1 + (R_s/X)^2}}\,, \tag{5}$$

where I_c – the cable core current, known as "load current";
I_s – the cable screen current, known as "circulating current".

The induced current (in Amperes) in cable screen can be found as:

$$I_s = \frac{I_s}{I_c} \cdot I_c\,. \tag{6}$$

5.4. Power losses

In normal operating mode, losses in the screen relative losses in the core:

$$\frac{P_s}{P_c} = \frac{R_s/R_c}{1 + (R_s/X)^2}\,. \tag{7}$$

Total power losses in the single-core cable, relative to the ideal case without losses in the screen (when the ampacity is determined only by losses in the core):

$$\frac{P_{sum}}{P_c} = \frac{P_c + P_s}{P_c} = 1 + \frac{P_s}{P_c}. \tag{8}$$

A coefficient showing the ratio of the ampacity of the cable line to the ideal case without losses in the screens (when the ampacity is determined only by losses in the core):

$$K_{use} = \frac{1}{\sqrt{1 + P_s/P_c}}\,. \tag{9}$$

5.5. Cost of losses

Power losses in the core and the screen of the single-core cable of a length l_{cl}:

$$P_c = {I_c}^2 \cdot R_c \cdot l_{cl}\,, \qquad P_s = \frac{P_s}{P_c} \cdot P_c\,. \tag{10}$$

Energy losses (kWh) in three cores and three screens, per year of operation:

$$W_{c.1y} = \frac{3P_c}{1000} \cdot 8760\,, \qquad W_{s.1y} = \frac{3P_s}{1000} \cdot 8760\,, \tag{11}$$

where $3P_c$ – power losses in cores of three single-core cables (three phases A, B, C);
$3P_s$ – power losses in screens of three single-core cables (three phases A, B, C);
1000 – conversion of power from W to kW;
8760 – the number of hours in a year.

Cost (in euro) of energy losses in the core and the screen, per 1 year of operation:

$$C_{c.1y} = W_{c.1y} \cdot C_{kWh}\,, \qquad C_{s.1y} = W_{s.1y} \cdot C_{kWh}\,. \tag{12}$$

Cost (in euro) of energy losses, per 30 years of operation (without inflation):

$$C_{c.30y} = 30 \cdot C_{c.1y}\,, \qquad C_{s.30y} = 30 \cdot C_{s.1y}\,, \tag{13}$$

where $C_{kWh} = 0.2$ euro/kWh – the cost of electric energy losses.

Next, we will perform current/loss calculations, in relative and absolute units.

6. Calculations per unit

Let us have "per unit" calculations to show the consequences of laying phases A, B, C with solidly bonded screens not in trefoil, but in a flat formation. For example, consider a 10 kV line:

- core cross-section $F_c = 500$ mm^2 made of aluminum;
- screen cross-section $F_s = 35$ mm^2 made of copper;
- outer diameter of the single-core cable $d = 44.1$ mm;
- thickness of the cable outer sheath $\Delta_{osh} = 2.8$ mm;
- laying methods: trefoil ($S_{AB} = 44.1$ mm) or flat formation ($S_{AB} = 100$ mm).

The length of the line does not affect the calculations in relative units and is therefore not given here. The calculation results are presented in Table 1. In addition to the options for laying the entire route in a trefoil and in a flat formation, another option is considered – when both methods meet on the line at once, and each of them is used for half the length of the route (that is "50/50"). In this case, the average distance between the phases required for calculations can be found using the following formula (which can be justified by decomposing into the Taylor series the natural logarithm included in the formula for inductive impedance X):

$$S = \frac{S_1 \cdot l_1 + S_2 \cdot l_2}{l_{cl}}, \tag{14}$$

where S_1 and S_2 – the average geometric distances between the phases in sections 1 and 2;
l_1 and l_2 – the lengths of sections 1 and 2; $l_{cl} = l_1 + l_2$ – the length of the line.

It can be seen from Table 1 that screen currents I_s/I_c and losses P_s/P_c increase:

- as the distance S between the phases increases;
- as the screen cross-section F_s increases.

Table 1 – Relative (per unit) currents and power losses for 10 kV cable line

Value	Screen, mm²	Mutual arrangement of phases		
		Trefoil	"50/50"	Flat
Screen currents I_s/I_c	35	0.091	0.161	0.202
	95	0.240	0.405	0.489
Screen losses P_s/P_c	35	0.074	0.232	0.365
	95	**0.190**	0.541	**0.787**
Sum power losses P_{sum}/P_c	35	1.074	1.232	1.365
	95	**1.190**	1.541	**1.787**
Coefficient of usage of ampacity K_{use}	35	0.965	0.901	0.856
	95	0.917	0.806	0.748

For example, for screens with a cross-section of 95 mm², increasing the distance S can:

- significantly increase the relative losses in the screens (instead of 0.190, they became 0.787, i.e. increased by about 4 times);
- increase the total losses in the cable line by tens of percent (for example, instead of 1.190 they became 1.787, i.e. increased 1.5 times or by 50 %).

Using Table 1, we can pay attention to another problem – the problem of calculating ampacity of the cable line which has solidly bonded screens. Let us consider that it is required to calculate ampacity for "50/50" option shown in the middle column of Table 1 or in Fig.5.

Usually, cable software performs a thermal calculation based on the known mutual arrangement of the three phases A, B, C. For example, for a screen cross-section of 95 mm²:

- the ampacity for section No.1 (phases are in a trefoil) will be determined based on the value of losses in the screens equal to 0.190;
- the ampacity for section No.2 (phases are in a flat formation) will be determined based on the value of losses in the screens equal to 0.787.

However, these ampacities have nothing to do with reality, because in fact, the losses in the screens along the entire line are the same, and amount to 0.541 (not 0.190 and not 0.787). Thus, software for thermal calculation should use in calculations not a local value of losses in screens, but the average value, determined using the average distance $S = f(S_1, S_2)$ between phases A, B, C along the entire line route (can be found by (14)). Not every software can do this, and hence there are mistakes in ampacity calculations and cable selection, which can cost a lot.

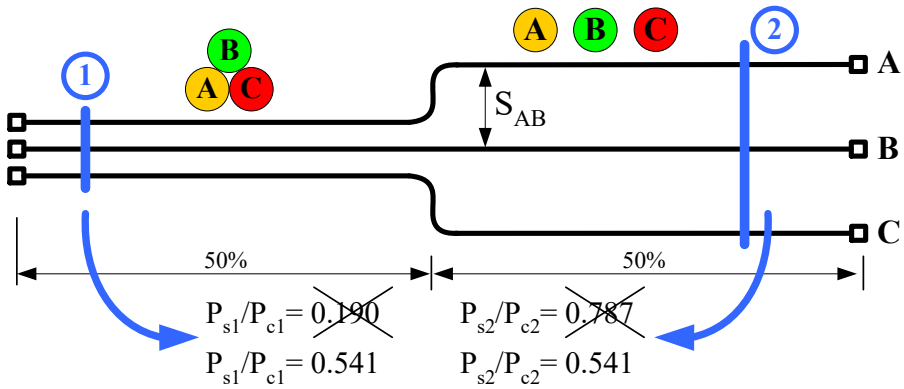


Figure 5 – Example of the line with two different types of phase arrangement

7. Calculations in absolute units

Let us show again the consequences of laying A, B, C not in a trefoil, but in a flat formation. We will perform calculations for the same 10 kV line as before, but this time in absolute units. This will require the cable length (say, $l_{cl} = 10$ km) and core current (say, $I_c = 250$ A).

For the cores, regardless of the screens, the following values can be obtained:
$3P_c = 120$ kW – power losses in three cores;
$W_{c.1y} = 1050$ kWh/year – energy losses in three cores per 1 year of operation;
$C_{c.30y} = 6.31$ million euros – cost of losses in three cores per 30 years of operation (for the cost of electricity in the amount of 0.2 euros per 1 kWh).

For the screens, the values I_s, $3P_s$, $W_{s.1y}$, $C_{s.30y}$ are given in Table 2. As before, it can be seen that the currents and losses in the screens increase:

- as the distance S between the phases increases;
- as the screen cross-section F_s increases.

Table 2 – Absolute currents, power losses and their cost for 10 kV cable line

Value	Screen, mm²	Mutual arrangement of phases		
		Trefoil	"50/50"	Flat
Induced current in each of three screens, $\boldsymbol{I_s}$ (A)	35	22.7	40.3	50.6
	95	60	101.3	122.3
Power losses in three screens, $\boldsymbol{3P_s}$ (kW)	35	8.23	27.9	43.9
	95	**22.8**	64.9	**94.4**
Energy losses in three screens per one year, $\boldsymbol{W_{s.1y}}$ (kWh/year)	35	77	244	384
	95	199	568	827
Cost of losses in three screens per 30 years, $\boldsymbol{C_{s.30y}}$ (million euros)*	35	0.46	1.46	2.31
	95	**1.20**	3.41	**4.96**

* – at the cost of electricity in the amount of 0.2 euros per 1 kWh.

For example, for screens with a cross-section of 95 mm², increasing the distance S can:

- significantly increase power losses in screens (instead of 22.8 kW, they became 94.4 kW, i.e. increased by about 4 times);
- increase the cost of losses in screens by tens of percent (for example, instead of 1.2 million euros, they became 4.96, i.e. increased by about 4 times or by 3.76 million).

Thus, if for a medium-voltage cable line with solidly bonded screens, the phases of the line are mostly arranged not in a trefoil, but in a flat formation, then the owner of the line will receive economic damage reaching several million euros (the value depends on the length of the cable line, on the cross-section of its screens, as well as depends on the average current in the core, since it determines the value of the current induced in the screens).

Total power losses in a single-core cable are the sum of losses in the core and losses in the screen, $P_{sum} = P_c + P_s$. If the cable line has solidly bonded cable screens, then as the distance between the phases S increases, the losses in the core P_c almost do not change, while the losses in the screen P_s increase significantly, thereby increasing the total losses of P_{sum}.

Thus, as the distance between the phases A, B, C increases (when replacing a trefoil with a flat formation), two processes occur simultaneously:

- increasing of total losses P_{sum} (by how much depends on the screen cross-section F_s);
- improving cooling conditions of the phases A, B, C of the cable line.

Both processes should be taken into account when carrying out the thermal calculation of the line, which allows to find the ampacity of the line. Without performing calculations, it is difficult to state in advance whether an increase in the distance S between the phases A, B, C will lead to an increase in the ampacity or not. However, the accumulated calculation experience shows that with screen cross-sections $F_s \geq 50$ mm^2, the ampacity is likely to decrease [11-12].

It can be concluded that for medium-voltage lines (they are characterized by solidly bonded screens), changing a trefoil of three phases A, B, C to a flat formation not only significantly increases losses in the screens and their cost, but also reduces the line ampacity, creating risks of overheating of the cable insulation and even cable damaging along the entire route.

8. Two types of trefoils

Suppose that a line has three single-core cables for each of the three phases A, B, C, as is sometimes found in medium voltage networks. The question arises as to which of the options (Fig.6a or 6b) is better to place single-core cables, provided that the screens are solidly bonded.

It was explained that the phases with different names (A, B, C) should be placed in a trefoil, and, therefore, only the option Fig.6a is preferable. Unfortunately, in practice, we can find an option Fig.6b, and Fig.7 presents the consequences of such a wrong technical solution.

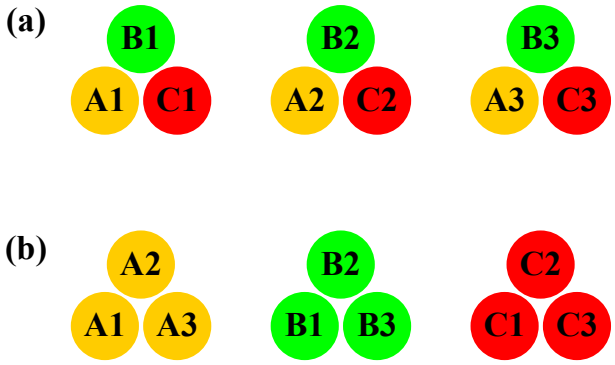


Figure 6 – Two main types of trefoil formation:
(a) – Trefoil of ABC type; (b) – Trefoil of AAA type

Fig.7 shows a 35 kV line made with three single-core cables per phase, and cable screens were solidly bonded. Each single-core cable had a copper core of $F_c = 400$ mm^2 and a copper screen of $F_s = 35$ mm^2. Since the cables were not correctly arranged (Fig.6b), and the processes in the screens were not taken into account at the design of the cable line, this line turned out to be overheated, and caught fire. The development of the fire was limited only by the fact that:

- the cables were coated from outside with a special compound;
- the pipes inside had a layer resistant to open flame;
- the personnel noticed the situation in time and turned off the entire line.



Figure 7 – The result of laying cables in trefoil of AAA type

9. Ways to maintain trefoil

The above examples and photos show how important it is for medium voltage lines with solidly bonded screens to lay phases A, B, C of different names close to each other in a trefoil. However, unfortunately, this not always happens in practice, and one of the reasons is that the cables laid in the trench in a trefoil were not fastened together before backfilling the trench.

In Fig.4a the cables are laid in a trefoil, but when the trench is backfilled, it may happen that under the influence of the weight of the soil, the middle phase will fall between the two lower ones, and then the cables will be arranged in the form of a "deformed trefoil" (Fig.4b), i.e., in fact, they will be arranged in a flat formation, which should not be allowed. Therefore, single-core medium voltage cables, before backfilling, should be fastened together, as shown in Fig.8a.

If the fastening of single-core cables into a trefoil seems burdensome, then an alternative solution is known – the twisting of cables into a trefoil by manufacturer, for example, as shown in Fig.8b. Three single-core cables twisted together are known as Triplex, and are used only for those cables that have a core cross-section F_c, usually only up to 240-300 mm^2, since otherwise Triplex turns out to be massive, inconvenient for transportation and installation.

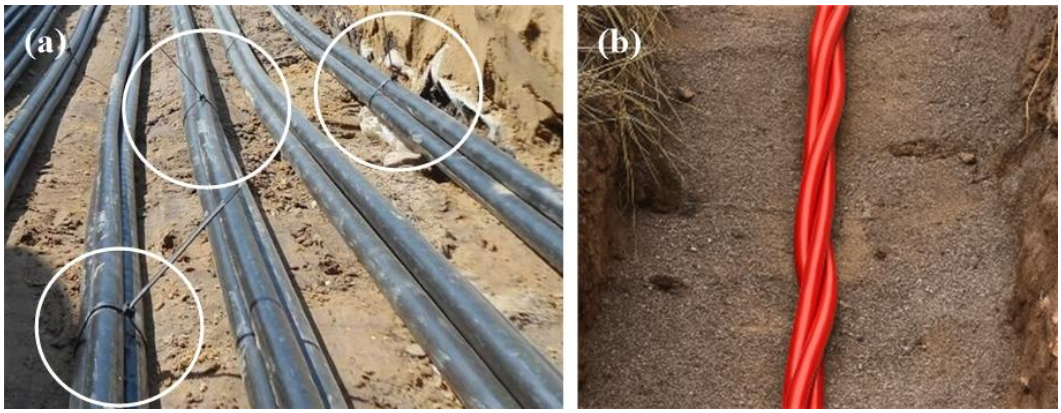


Figure 8 – ABC trefoil formation:
(a) – fixed by belts/straps; (b) – by twisting cables together (Triplex cable)

10. Conclusions

In medium-voltage networks, screens of single-core cables often have solid bonding, and other options (single-point bonding or cross-bonding) are almost not used. This circumstance leads to the fact that in practice it is necessary to lay single-core cables of phases A, B, C in a trefoil. Failure to arrange trefoil can cause following significant damage:

- increased power losses (they need to be paid);
- increased temperature of cables and terminations (they can be damaged);
- decreased ampacity of the line;
- fires (especially if there are pipe sections of the route).

The cost of damage is especially noticeable for long AC 50 Hz cable lines, that is for cable networks, which are used to connect remote wind generators to the grid.

In addition, attention should be paid to the following problems of the software used in the industry for the thermal calculation of cable lines with solidly bonded screens:

- for cable lines which have different types of mutual arrangement of phases A, B, C along the line route, it is important to calculate correctly the currents and losses in the screens;
- it is important to show the user the cost of screen losses, not just the ampacity of the line.

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