SINGLE-CORE AND THREE-CORE 6-35 kV CABLES. DIFFERENCES IN THE SELECTION OF SCREENS CROSS-SECTION AND SCREENS GROUNDING SCHEME

M. Dmitriev, PhD
info@voltplace.com

In 110-500 kV networks, all power cables laid in recent years are single-core with cross-linked polyethylene insulation. For 6-35 kV networks, on the contrary, the range of cable products is quite wide, and therefore it is not always easy to justify the choice. We will give a number of considerations in this regard.

Keywords: single-core cable, three-core cable, cross-linked polyethylene (XLPE), screen cross-section, screen grounding, screen cross-bonding, short-circuit, neutral grounding.

1. INTRODUCTION

Currently, 6-35 kV networks can be built using three main three cable types:

- single-core cables with cross-linked polyethylene (XLPE) insulation;
- three-core cables with XLPE insulation;
- three-core cables with paper-oil insulation (POI);

As a rule, POI cables are cheaper than XLPE. Also, unlike XLPE, they can be serviced by high-voltage laboratories already available in networks (using standard DC test voltage and "burn-through" methods of cable damage detection). At the same time, for a number of reasons, the technical policy of large grid companies is aimed at using exclusively XLPE. Let's consider the features of such XLPE insulation cables depending on their design, which can be either single-core or three-core.

The advantages of single-core 6-35 kV XLPE cables over three-core are known:

- no restrictions on the core cross-section (for three-core it is no more than 3x240 mm^2 and only by special order – up to 3x300 mm^2 or, maybe, up to 3x400 mm^2);
- longer construction length and better flexibility;
- simple design, which means high reliability;
- convenient installation and repair work.

Disadvantages of single-core 6-35 kV XLPE cables are mentioned much less often:

- the need to select the screen cross-section for large short-circuit currents;
- the need to abandon simple and convenient two-side grounding of cable screens due to the presence of parasitic currents and active power losses in them (schemes without screen parasitic power losses are one-side grounding or cross-bonding [1]).
- the difficulty of detecting a damaged feeder with single-phase-to-ground fault in 6-35 kV networks with isolated (compensated) neutral, which is traditional for our country;
- efficiency of use is not for all 6-35 kV networks, but mainly for networks with resistive neutral grounding, where a single-phase-to-ground fault F(1) is quickly and selectively switched off by the action of relay protections.

Let's explain these disadvantages of single-core cables.

2. SINGLE-CORE CABLES

A feature of a single-core cable having a grounded copper screen is the absence of an electric field outside it, but the presence of a magnetic one. Magnetic fields of three single-core cables included in the same cable line, in normal mode, induce voltage to the contours formed by three screens of single-core cables.

With screens two-side grounding, these contours are closed, and the induced voltage causes the appearance of longitudinal currents of industrial frequency in the cable screens, leading to screens heating simultaneously along the entire length of the line, increasing the XLPE insulation temperature and reducing the permissible cable line current (cable current capacity). To minimize currents and losses in screens according to [1], it is necessary to:

- lay cables in a closed triangle (the area of contours decreases, and therefore the induced voltage decreases too, as well as induced currents and power losses), Fig.1,b;
- use cables with a small screen cross-section F_S (the impedance of the contours increases, which causes a decrease in their induced current and losses).

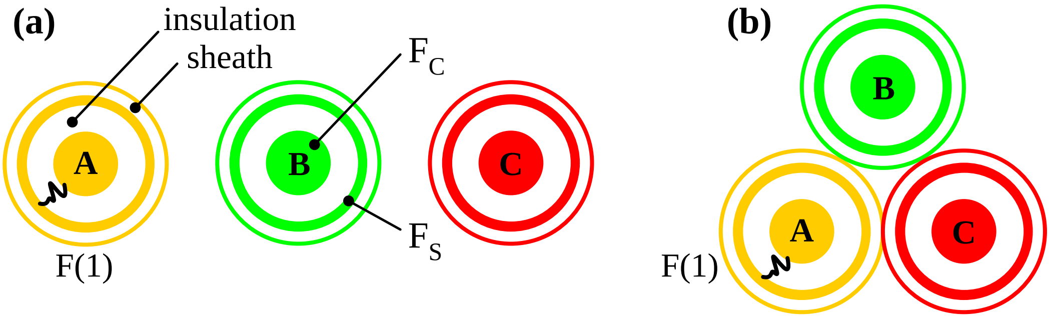

Fig.1. Cable line with single-core cables:
(a) – cables laying in a row; (b) – cables laying in a closed triangle.

As you can see, the choice of the screen cross-section is fundamental in matters of active power losses in the cable in normal mode, which means that it directly determines the efficiency of single-core cables in electrical networks. Unfortunately, it rarely turns out to use cables with a small F_S, and the reason for this is the need to avoid overheating of the screen with a short-circuit current, which, in case of cable main insulation fault, enters the screen and passes through it to the grounding points (Fig.2). Thus, the choice of the cross-section F_S is not an easy task, since:

- in normal operating mode, it is desirable to have a small F_S;
- for short-circuits, it is desirable to have a large F_S.

Single-phase-to-ground fault F(1) is the most common in networks, and therefore we will focus on it. In case of insulation single-phase fault, the current from the cable core of the emergency phase enters its screen and goes further along the screen into its grounding devices. If the relay protection promptly (no more than a few seconds) disconnects the cable line from the grid, then, according to operating experience, almost regardless of the specific value of the current F(1), the damage does not have time to have any significant thermal effect on two adjacent phases. This observation applies not only to the cases of laying three single-core cables at a distance from each other (Fig.1,a), but even to laying three cables in a closed triangle (Fig.1,b).

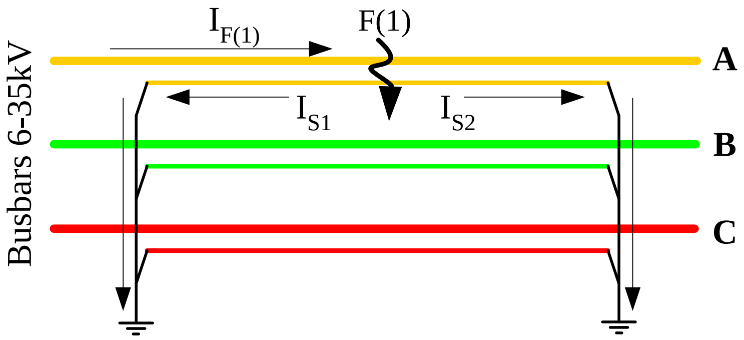

Fig.2. F(1) currents in single-core cables with screens grounded at both ends.

One of the significant advantages of single-core cables is that their installation and repair can be carried out in phases. It would also be an advantage if damage to one of the phases would never harm the other two, located nearby. Therefore, it can be argued that it will be possible to effectively use single-core cables mainly in those networks where single-phase fault F(1) is automatically disconnected with minimal time delays and for this reason does not allow for the development of an accident to neighboring phases and circuits.

In 6-35 kV networks, the issues of F(1) quick disconnection fundamentally depend on the method of neutral grounding used. Some of them are shown in Fig.3. Let's consider an insulation fault of a single-core cable in a 6-35 kV network:

- with isolated (compensated) neutral (Fig.3,a);
- with a neutral grounded through a resistor (Fig.3,b).

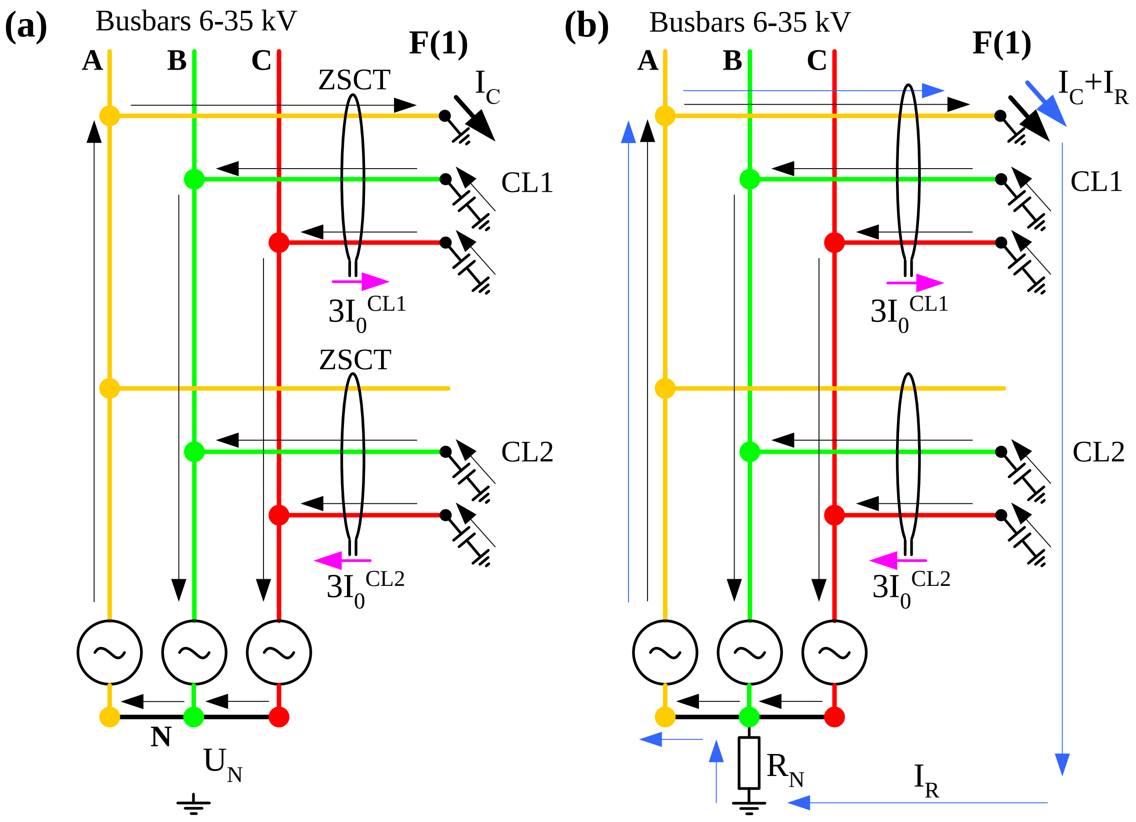

Fig.3. Single-phase-to-ground fault F(1) in a 6-35 kV network:
(a) – isolated neutral; (b) – neutral, grounded through a resistor.

The neutral is isolated

Fig.3,a shows the busbars of the 6-35 kV network with an isolated neutral and, as an example, two outgoing cable lines CL1 and CL2. With a single-phase-to-ground fault F(1) of phase "A" on CL1, the single-phase fault current I_C passes from the core into the screen (into the ground) but cannot pass through the neutral of the network (since it is isolated) and is forced to pass through capacitances of undamaged phases "B" and "C" of lines CL1 and CL2. Therefore, I_C is capacitive in nature, its value is determined by the rated voltage of the network U_r and its summary phase-to-ground capacity C_{SUM}:

$$I_C = \sqrt{3} \cdot U_r \cdot C_{SUM}$$

Capacitive currents (units-tens of Amperes) are superimposed on the operating load currents of cable lines (tens-hundreds of Amperes). It is also important that both these and other currents are at the same time in the damaged CL1 and in undamaged CL2 (CL3, CL4, CL5....). As a consequence, relay protections built on measuring the phase currents of cables are not able to selectively determine exactly where in the network a ground fault occurred.

A number of companies propose to build the process of automating the search for damage not on phase currents, but on zero-sequence currents, for measuring which each CL should be equipped with a zero-sequence current transformer (ZSCT). Such a transformer gives an information of the sum of the phase current vectors $3\dot{I}_0 = \dot{I}_A + \dot{I}_B + \dot{I}_C$. According to Fig.3,a the currents $3\dot{I}_0{}^{CL1}$ and $3\dot{I}_0{}^{CL2}$ have opposite signs, and it is not difficult to show: in undamaged lines (CL2, CL3, CL4....) the zero sequence current is always directed from lines to busbars, and only in a damaged line – this current goes from busbars to the line.

Comparing the signs of the zero sequence currents really allows you to identify a section of the network with F(1), however, under one condition – the damage is not arc, but is stable. Since many damages occur through an arc, the zero-sequence currents cease to be sinusoidal currents of industrial frequency, and comparison of their signs is difficult. For this reason, in networks with isolated (compensated) neutral, despite the considerable efforts of many scientists, the automation of the F(1) search process has not yet been achieved.

When fault to the ground, the voltage of the damages phase decreases to almost zero, and the voltage on the other two phases increases from normal value to linear. The increased voltage of phases "B" and "C" occurs immediately throughout the network and can cause a breakdown of insulation in some weakened place on some other part of the network (say, in an old cable line with POI insulation). An example of such a development of an accident is shown in Fig.4,a, where after some time of having F(1) in phase "A" of CL1 was added F(1) in phase "B" of CL2, and the damage from a simple single-phase fault F(1) turned into two single-phase faults, i.e. it became a double-ground fault F(1,1).

It is possible that the accident scenario will be the same as in Fig.4,b. It is more likely for those 6-35 kV networks where single-core cables are laid in a closed triangle. When F(1) occurs in phase "A" of CL1, due to the proximity of phases "B" and "C", the insulation, for example, of phase "B", overheats due to the thermal effect of the arc, after which the damage from a simple single-phase fault F(1) turns into an inter-phase short circuit (F2). However, even if phases are laid in a closed triangle, there are always places where they diverge – for example, these are areas near cable terminations or joints. Therefore, the option shown on Fig.4,a cannot be excluded in any way.

It can be seen that in 6-35 kV network with an isolated (compensated) neutral, scenarios for phase-to-ground fault propagation may be very different, but the principle of choosing cross-section F_S is unchanged: the screen must withstand the current F(1,1) taking into account the time of its flow.

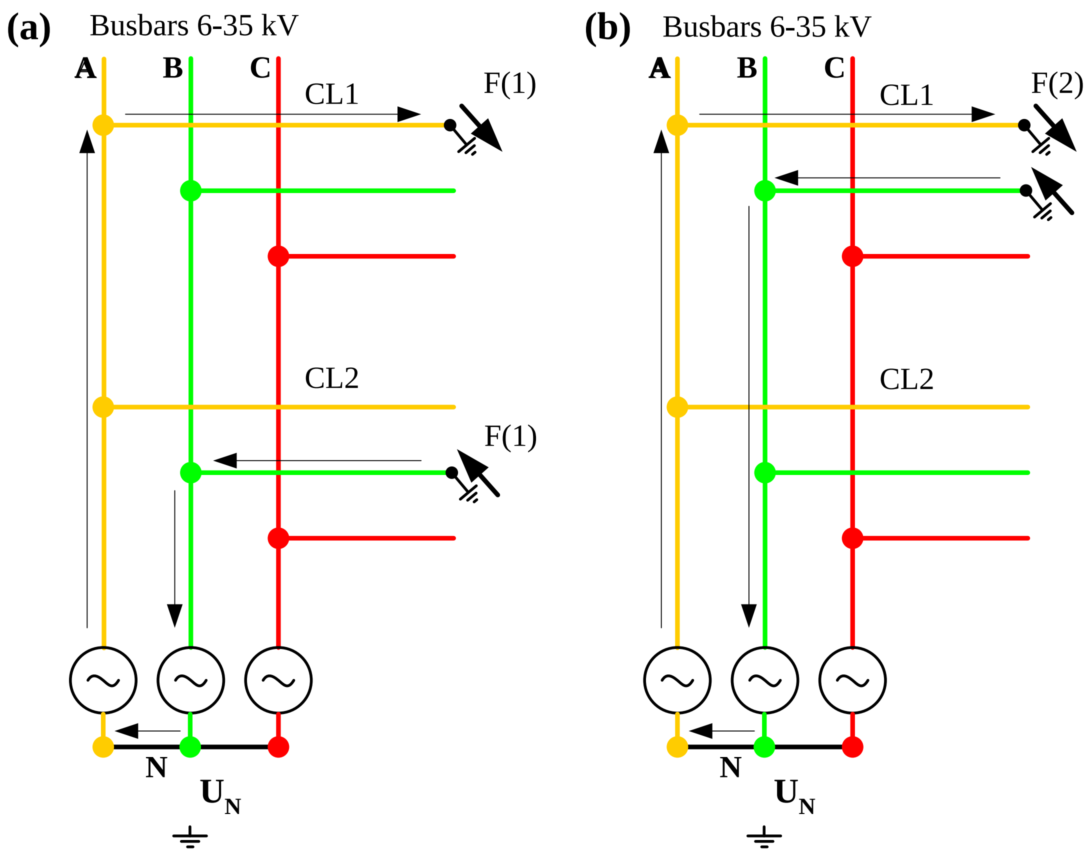

Fig.4. Development of a single-phase-to-ground fault in a 6-35 kV network with an isolated neutral: (a) – two faults on two different CLs; (b) – two faults on the same place of the same CL.

The neutral is grounded through a resistor

In the country, medium-voltage 6-35 kV networks have traditionally been performed with an isolated (compensated) neutral. Such a neutral provides low currents at F(1) and allows for a long time not to disconnect consumers – because consumers get electric power by phase-to-phase (linear) voltages. There are also a possibilities of self-elimination of such low-current F(1) accident. These network properties were very useful in conditions of weak development of electric networks, when consumers often had only one power source – and not a cable line at all, but an overhead distribution line, where the annual number of damages is much greater than in a cable one.

Currently, 6-35 kV networks are developed, especially in large cities, where all consumers receive power from double-circuit cable lines. Therefore, even in case of fault on one of the two circuits, it can be turned off immediately, and the consumer will remain powered. To continue the operation of the cable network with a ground fault F(1) not only makes no sense (the damage itself will not be eliminated), but even harmful (the voltage on the two undamaged phases of the network rises above the normal phase value up to phase-to-phase value and can cause new fault somewhere in a place with weakened insulation).

In order to increase the selectivity of the relay protection against single-phase fault F(1) in recent years, the possibility of transferring 6-35 kV networks to a different neutral grounding method – to a resistive one – has been actively discussed. This issue is especially relevant for cable network built with single-core XLPE cables, where a quick and error-free disconnection of any F(1) will eliminate the spread of an accident, which means reducing the amount of damage, simplifying and speeding up repair work.

The appearance of a resistor in the neutral gives an increase in the ZSCT current of the damaged CL by so much that relay protection has no doubt which of the CL is damaged. In other words, in networks with a resistor, protection is based not on comparing signs of ZSCT currents, but already on the values of these currents.

Fig.3,b shows that the presence of a resistor leads to the appearance in a fault current, in addition to "traditional" capacitive component I_C, another active I_R, which passes through a resistor in neutral. The magnitude of this current is determined by the phase EMF and the resistance of the resistor R:

$$I_R = E_A/R = \left(U_r/\sqrt{3}\right)/R$$

The peculiarity of the active component is that it passes only in the damaged line, and is absent in undamaged ones. Thus, a successful choice of R will provide a noticeable difference in the values of the zero sequence currents $\left|3\dot{I}_0{}^{CL1}\right| >> \left|3\dot{I}_0{}^{CL2}\right|$ and a confident operation of relay protections. The accumulated experience suggests that it is sufficient to use resistors R, providing $I_R = 500 \div 1000$ A.

In 6-35 kV networks with a resistor, the screen cross-section F_S of single-core cables must be selected for the current $\sqrt{I_C{}^2 + I_R{}^2}$ passing during the relay protection operation, and for these purposes, a minimum F_S is sufficient (small values of 16, 25, 35 mm^2).

Rational use of single-core cables is possible only in those 6-35 kV networks where automatic selective disconnection of any single-phase-to-ground fault F(1) is established, i.e. in networks with a resistor in neutral. Not using the resistor entails:

- risks of developing single-phase-to-ground fault F(1) in larger-scale accidents F(1,1) etc;
- the need to use cables with a large F_S capable of withstanding multiphase fault currents like F(1,1) which are already a short-circuit currents;
- the need to deal with currents and losses in screens in normal operation mode [1], since these currents/losses characteristic for cables with a large F_S.

3. THREE-CORE CABLES

There are different designs of three-core cables, but currently cables with screened cores are more common (Fig.5). They may also have an additional common screen or armor with a big cross-section of F_A.

The compact design of three-core cables is such that when a single-phase fault F(1) occurs, it quickly develops into two other phases in the same place of the cable line, and the fault turns from F(1) to F(2), then to F(3). Consequently, the cable line will be disconnected from the network by the simple maximum current relay protection.

As you can see, in a 6-35 kV network built with three-core cables, there is no problem of finding a ground fault, which was for single-core cables and caused the need of changing from an isolated network neutral to a resistor. It's obvious that a network with three-core cables can be successfully operated with any method of neutral grounding.

Some issues of using three-core cables, however, depend on the neutral, and the main one is the choice of the screen cross-section F_S.

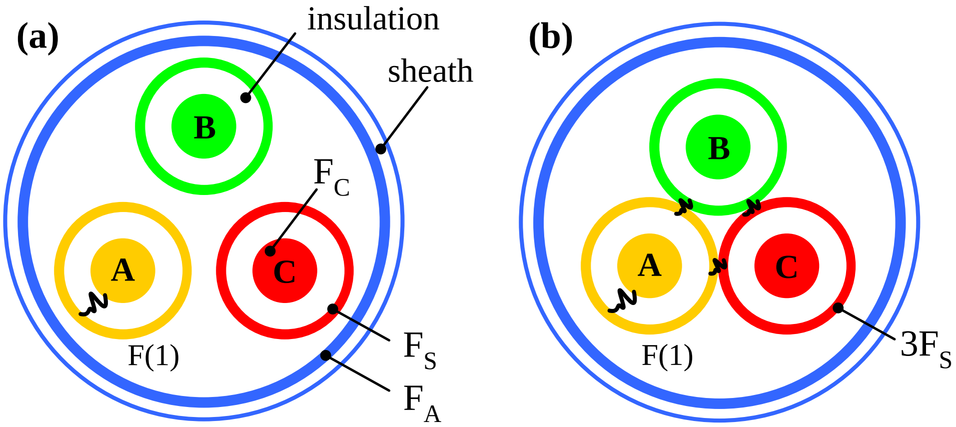

Fig.5. Three-core 6-35 kV cable with screened cores:
(a) – screens do not touch each other; (b) – screens touch each other.

The neutral is isolated

If the first fault F(1) occurred in a three-core cable, then most likely the development of the accident would be in the same place of the network (Fig.4,b), and the cable line would be automatically disconnected. Let us now assume that the fault F(1) did not occur in the three-core cable CL1 in question, but somewhere else in the network (for example, in phase "B" of CL2, made by single-core cables, Fig.4,a) – due to this fact voltages of phases "A" and "C" in the entire network would increase from normal phase values to linear values, and in some place with defective insulation, a second F(1) may occur – let it be phase "A" of the three-core cable line CL1. This sequence of events makes it necessary to choose the cross-section of each screen of a three-core cable line CL1 for the following currents:

- for the cable Fig.5,a it should be the entire current F(1,1);
- for the cable Fig.5,b it should be 1/3 of the current F(1,1), since screens touch each other and work in parallel dividing F(1,1) current.

The neutral is grounded through a resistor

In a network with a resistive neutral grounding, if a three-core cable get fault F(1), it is likely that it will be disconnected faster than it will go to F(2) or F(3). Therefore, here the cross-section F_S of each of the three cable screens (Fig.5,a) should be selected for the current $\sqrt{I_C{}^2 + I_R{}^2}$ taking into account the time of its passage. If screens touch each other (Fig.5,b), then it is enough to calculate each of them only by 1/3 of current $\sqrt{I_C{}^2 + I_R{}^2}$.

4. SELECTION OF SCREEN CROSS-SECTION AND GROUNDING SCHEME

Selection of the screen cross-section

The cross-section of the copper screen F_S (mm^2), the short-circuit current I_F (kA), the shutdown time t_F (sec) must satisfy the well-known expression:

$$I_F \leq K_S \cdot \frac{F_S}{\sqrt{t_F}}$$

where K_S is the coefficient, which according to [2] is usually assumed to be equal to 0.174 $\mathrm{kA}\sqrt{\mathrm{s}}/\mathrm{mm}^2$, I_F is the calculated current determined according to Table 1, t_F is the time that is agreed with relay protection specialists (it is impossible just take it equal to 1 sec).

When compiling Table 1, as in [1], it was assumed that in a network with an isolated (compensated) neutral, the double-fault-to-ground current F(1,1) reaches $\sqrt{3}/2 = 0.87$ of the three-phase current F(3) on the switchgear busbars (the end of the line is taken where the current F(3) the largest). In addition, in Table 1, the capacitive current I_C of the network is used, as well as the active current I_R of the neutral resistor.

Table 1. The calculated current I_F for selecting the cross-section F_S of each of the three screens of the 6-35 kV cable line with XLPE insulation.

Cable construction	**Neutral of 6-35 kV network**	
	Isolated (compensated)	**Resistive with fast disconnection of F(1)**
	Rated current I_F for F_S selection	
Single-core, Fig.1	$I_{F(1,1)} = 0.87 \cdot I_{F(3)}$	$I_{F(1)} = \sqrt{{I_C}^2 + {I_R}^2}$
Three-core, Fig.5,a	$I_{F(1,1)} = 0.87 \cdot I_{F(3)}$	$I_{F(1)} = \sqrt{{I_C}^2 + {I_R}^2}$
Three-core with touching screens, Fig.5,b	$I_{F(1,1)} = 0.29 \cdot I_{F(3)}$	$I_{F(1)} = 0.33 \cdot \sqrt{{I_C}^2 + {I_R}^2}$

Let's consider the influence of the screens grounding scheme on the choice of screen cross-section F_S. To do this, turn to Fig.2. Values I_{S1} and I_{S2} of currents in screens depend on the place of cable line fault (at its beginning, in the middle or at the end) and on the screen grounding scheme.

In cases when screens are grounded at each end of the cable line (this happens with a simple screen two-side grounding or when they are cross-bonded), currents I_{S1} and I_{S2} pass to the left and right of the fault phase screen (together they make up the fault current I_F, Fig.2). Calculations show that even if the fault occurred exactly in the middle of the cable line, then $I_{S1} > I_{S2}$, since it is always more profitable for the current to pass from the place of fault towards busbars, where screens of all cable lines of the network are assembled.

If the fault does not occur in the middle of the cable line, but near its beginning (near busbars), then $I_{S1} >> I_{S2}$ and therefore $I_{S1} \approx I_F$. Thus, the screen cross-section F_S should always be selected for the entire fault current I_F, and not for any part of it. Moreover, this is true if screens have not two-sides grounding, but one-side.

It is difficult for cable plants to produce three-core 6-35 kV cables of the type Fig.5,a, whose screens would withstand F(1,1) current of a network with an isolated (compensated) neutral. The discrepancy of the actually produced cross-sections with the actual short-circuit currents F(1,1) of the network is a known problem. To solve it, it is necessary to switch to the use of cables of the type Fig.5,b, having increased resistance to short-circuit currents due to the parallel operation of individual screens of three phases.

Selection of the screens grounding scheme

For single-core cables, calculations are carried out according to the method [1] and allow you to choose one of three typical grounding schemes: two-side grounding, one-side grounding, screens cross-bonding. In the case of resistive grounding of the neutral according to the Table 1, it is sufficient to have a small screen cross-section F_S, which, in combination with laying three phases with a closed triangle, makes it possible to have a simple grounding of screens on both sides and not worry about losses in the screens due to their insignificance (see Table 2).

For three-core cables, screens should always have just a simple both-side grounding. Alternative schemes of screens (one-side grounding or screens cross-bonding) for three-core cables are not applied. For three-core cables (Fig.5,b) these circuits are not needed because there are no screen contours on which voltage could be induced and where currents could pass. As for other cables (Fig.5,a), here, with two-side grounding, there are still currents and losses in screens, but they are not dangerous, since phases are located close (almost a closed triangle) and the screen cross-section F_S is small (plants cannot produce otherwise).

Table 2. Selection of screens grounding scheme for 6-35 kV cable line with XLPE insulation and the amount of active power loss in screens in normal operation mode.

Cable construction	**Neutral of 6-35 kV network**	
	Isolated (compensated)	**Resistive with fast disconnection of F(1)**
	Optimal screen bonding/grounding scheme	
Single-core, Fig.1	Selection by method [1]	Two-side grounding (There are only small screen losses if single-core cables are laid in closed triangle)
Three-core, Fig.5,a	Two-side grounding (There are screen losses)	Two-side grounding (There are small screen losses)
Three-core with touching screens, Fig.5,b	Two-side grounding (There are no screen losses at all)	Two-side grounding (There are no screen losses at all)

5. CONCLUSIONS

The paper considers basic designs of 6-35 kV cables with XLPE insulation. Analysis of processes in networks with such cables allowed us to give a method for selecting screen cross-sections (Table 1) and their optimal grounding schemes (Table 2).

It has been shown that in 6-35 kV networks with isolated (or compensated) neutral, it is desirable to use not single-core cables, but three-core (especially if they have "touching" screens). As for single-core cables, they are mostly designed for electrical networks with resistive neutral grounding (or direct neutral grounding), where relay protection switches off the first fault-to-ground, doing it selectively and fast.

REFERENCES

1. Dmitriev M.V. "Bonding and grounding of power cable screens" // Publishing House of Polytechnic university, St. Petersburg, 2010, 152p.
2. Dmitriev M.V. "Metallic screen selection for 6-500 kV cables taking into account the aperiodic current" //The "Electrical Engineering News" magazine, 2014, No.4, pp.34-37.