CHOOSING AN OPTIMAL POSITION OF SINGLE-CORE CABLES FOR 6-500 kV CABLE LINES

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Regulatory documents on cable lines, as well as catalogs consider the arrangement of single-core 6-500 kV cables in a row and in a closed triangle as two equal methods of laying, differing from each other only by the value of the current capacity. At the same time, when choosing the phase arrangement, many other factors should be taken into account.

Keywords: cable line, single-core cable, cable screen, screen grounding, screen cross-bonding, cable outer sheath protection

INTRODUCTION

Two main ways of phase mutual arrangement for a three-phase group of single-core 6-500 kV cables are shown in Fig.1. Although regulatory documents and factory catalogs focus only on the cable current capacity, it should be understood that this is not the only and not the main argument when choosing the phases relative position. According to the author, the full list of factors requiring consideration should at least include the following:

– the value of the long-term cable line (CL) current capacity;
– the installation and maintenance cost of the screens grounding and cross-bonding;
– CL route width and culture of cable installation;
– convenience of cable identification on multi-circuit CL;
– safety of work on multi-circuit CL;
– the asymmetry degree of the CL parameters by phases;
– the magnitude of zero-sequence currents in the CL screens and in the screens grounding circuit, as well as the potential of the grounding circuit and corrosion of its metal;
– the magnitude of the zero-sequence currents in the CL cores and the false operation of relay protections in 6-35 kV networks with an isolated neutral;
– detection of cable damages in 6-35 kV networks with insulated neutral;
– the possibility of automatic reclosure on 110-500 kV mixed cable and overhead lines.

The article shows that taking into account all these factors should incline designers rather to lay phases in a closed triangle (Fig.1b) than to lay phases in a row (Fig.1a).

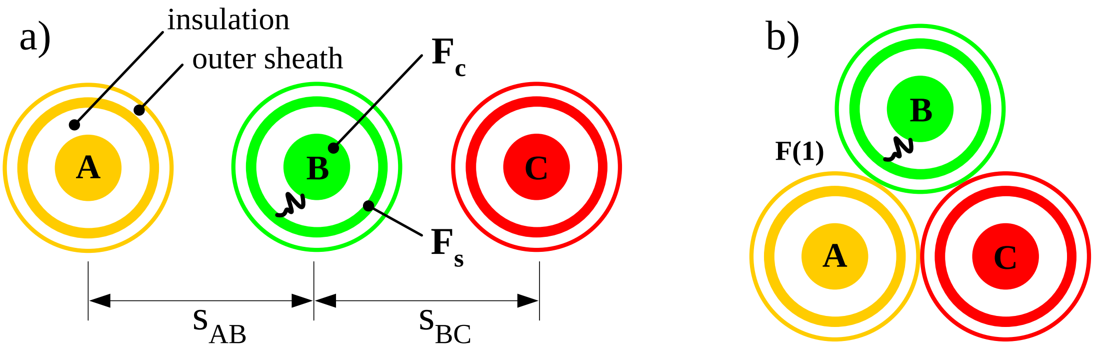

Fig.1. The main options for laying single-core cables:
(a) – in a row, (b) – in a closed triangle.

CABLE CURRENT CAPACITY AND SCREENS GROUNDING

The CL current capacity is determined during thermal calculations and depends on the active power losses in the CL phases and the intensity of their cooling by adjacent soil or ambient air.

When laying three phases in a row (Fig.1a), the area of contact of the cables with the cooling medium (ground or air) turns out to be larger than when laying a closed triangle (Fig.1b). Therefore, it may seem that for an in-row arrangement of phases (flat-formation), the current capacity is greater than for a closed triangle. This would indeed be the case if the active power losses in single-core cables did not depend on the distance *s* between the phases, and in some cases, they still do (for example, for two-side grounding, Fig.2a).

Active power losses in a three-phase CL made by single-core cables are defined as the sum of losses in the cores and losses in the screens. If the losses in the cores do not depend on the relative position of the three phases (we neglect the proximity effect), then for screens a lot is determined by phases relative position (the distance between phases) and screens grounding/bonding scheme.

According to [1], three basic screen grounding/bonding schemes are known:

– two-side grounding (Fig.2a);
– one-side grounding (fig.2b);
– transposition of screens so-called screen cross-bonding (Fig.2b).

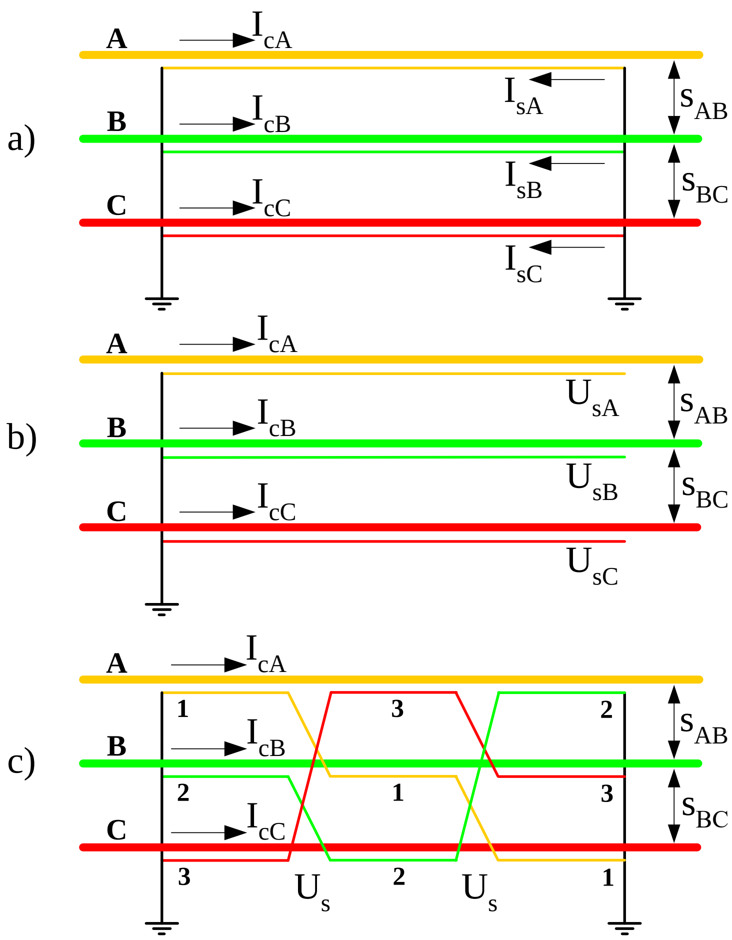

Fig.2. Grounding schemes of single-core cable screens:
(a) – two-side grounding, (b) – one-side grounding, (c) – cross-bonding.

With two-side screens grounding, active power losses occur in them due to industrial frequency AC currents induced from the core, and these losses depend on:

– the distance between the phases s;
– the screen cross-section F_s;
– the screen material (Cu, Al, Pb, etc.).

It is shown in [1] that with two-side screen grounding, active power losses in screens increase significantly with increasing distance s and cross-section F_s. Therefore, when switching from laying three phases of the CL in a closed triangle to laying in a row (flat-formation), although the cooling of the phases improves, but the power losses in the phases do not remain at the same level, but also increase. As a result, the CL current capacity when laying in a row of CL with double-sided grounding of the screens may be both higher (due to good cooling) and lower (due to big screen losses) than those when laying a triangle.

Calculations, reflected, in particular, in the catalogs of leading companies, show that for CL with two-side screen grounding, the highest current capacity is achieved:

– when laying in a row, if the CL has a small cross-section of screens (25, 35 mm^2);
– when laying with a closed triangle, if the CL has a large cross-section of screens (50, 70, 95, 120, 150 mm^2, etc.).

The cross-section of the CL screens is determined by the level of short-circuit currents of the network, and usually for 6-35 kV cables it is at least 50 mm^2, and for 110-500 kV cables – at least 95 mm^2. These cross-sections are such that when grounding the screens on both sides, the maximum CL current capacity is achieved when laying the phases with a closed triangle, and not with row (flat-formation).

If the CL screens have one-side grounding or transposition, then in this case there are no losses in the screens, and regardless of the distance s between the phases and the screen cross-section F_s. Then the greatest current capacity will be at the row arrangement of phases.

It can be seen that laying three phases of the CL in a row (Fig.1a) provides increased current capacity only with some screen schemes without screen power losses – namely with one-side grounding (Fig.2b) and with screens cross-bonding (Fig.2c). However, for CL with such schemes, one should still not strive to increase the current capacity by separating the three phases of the CL at a great distance s from each other, since an increase in the distance between three phases according to [1] causes an increase in the AC voltage U_s induced on the screens.

In accordance with [1] exceeding by the voltage U_s the permissible levels (100 V for normal operation and 5-7 kV for external short circuits outside the CL) leads to the need to increase the number K of one-side grounded screen sections ($K = 1$ on Fig.2b) or increase the number N of full cycles of screen cross-bonding ($N = 1$ on Fig.2c) – this significantly complicates the construction of the CL and its operation.

Thus, even for CLs with screen grounding schemes Fig.2b or Fig.2c having no screen power losses, preference should be given to the closed triangle.

SAFETY OF WORK ON DOUBLE-CIRCUIT CL

In very many cases, CL have a double-circuit design (Fig.3), which allows to provide power supply to consumers in conditions when one of the circuits is disconnected for the purpose of its repair or testing. Speaking about the safety of CL, consider the following three questions of double-circuits CLs:

– cable identification;
– the induced voltage to the disconnected circuit;
– construction of screen cross-bonding nodes.

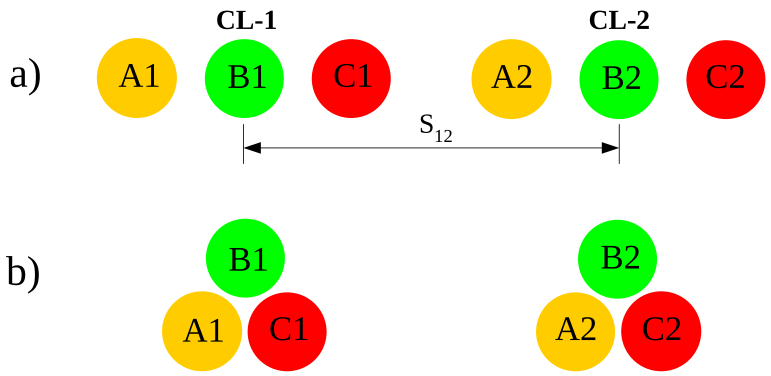

Fig.3. The main options for laying the phases of a two-circuit CL:
(a) – in a row, (b) – in a closed triangle.

Circuit identification

When laying the phases of a double-circuit CL in a row (Fig.3a), there are cases when single-core cables of the 1st circuit and single-core cables of the 2nd circuit overlapped with each other at turns of the route. As a result, repair personnel who go out on the route may incorrectly identify the phases of the disconnected circuit and get under voltage.

If the phases of each CL circuit are laid in a closed triangle (Fig.3b), periodically fixed together with plastic clamps or belts, equipped with identifying tags, then the probability of personnel error is reduced. Also, the triangular laying of the phases makes it possible to slightly reduce the width of the CL route.

Induced voltage

For the personnel servicing the disconnected CL circuit, the value of the sinusoidal AC voltage of the industrial frequency of 50 Hz, which will be induced from a nearby working CL circuit, is important. Research on this topic is given in the article [2].

The presence of a grounded screen in the design of a single-core cable leads to the fact that there is no electric field outside the cable. The magnetic field is there and can reach dangerous values. The reduction of the magnetic field is helped by the fact that three single-core cables are laid together at once, their sinusoidal AC currents are equal to each other in magnitude and have a shift of 120°. The best compensation of the magnetic fields of the three phases occurs when they are laid in a closed triangle.

In two-circuit CL, the presence of a magnetic field of a CL circuit under current leads to the fact that the disconnected circuit is under the influence of an induced AC voltage of an industrial frequency of 50 Hz. As an example, Fig.4 shows that the induced voltage occurs on the repaired disconnected circuit in the place prepared for the installation of the cable joint. The voltage occurs both on the core and on the screen, and despite the fact that at the time of the work they (both the core and the screen) were grounded simultaneously at both ends.

The AC voltage that can be induced on the disconnected circuit is borrowed from [2] and shown in Fig.5. Here the distance between the circuits s_{12} varies, as well as the phase arrangement (row, closed triangle). The induced voltage level is proportional to the length of the CL and the core current of the working circuit (in Fig.5, for convenience, the voltage is indicated at 1000 m and 1000 A).

For example, when laying with $s_{AB} = 0.2$ m (curve No. 3) and $s_{12} = 1$ m, we have a 22 V voltage for 1000 m and 1000 A. If the length of the CL is, say, 4000 m, and the core current is 500 A, then the AC voltage affecting the personnel will be $22 \cdot (4000/1000) \cdot (500/1000) = 44$ V.

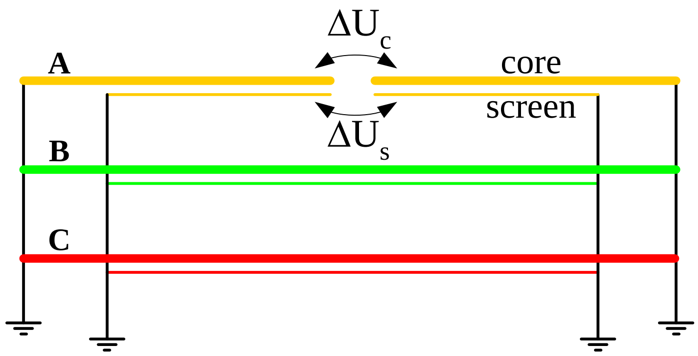

Fig.4. The 50 Hz voltage induced on the disconnected circuit of the double-circuit CL and affecting the personnel performing the installation of the cable joint. The cores and screens of the disconnected circuit are grounded at both sides.

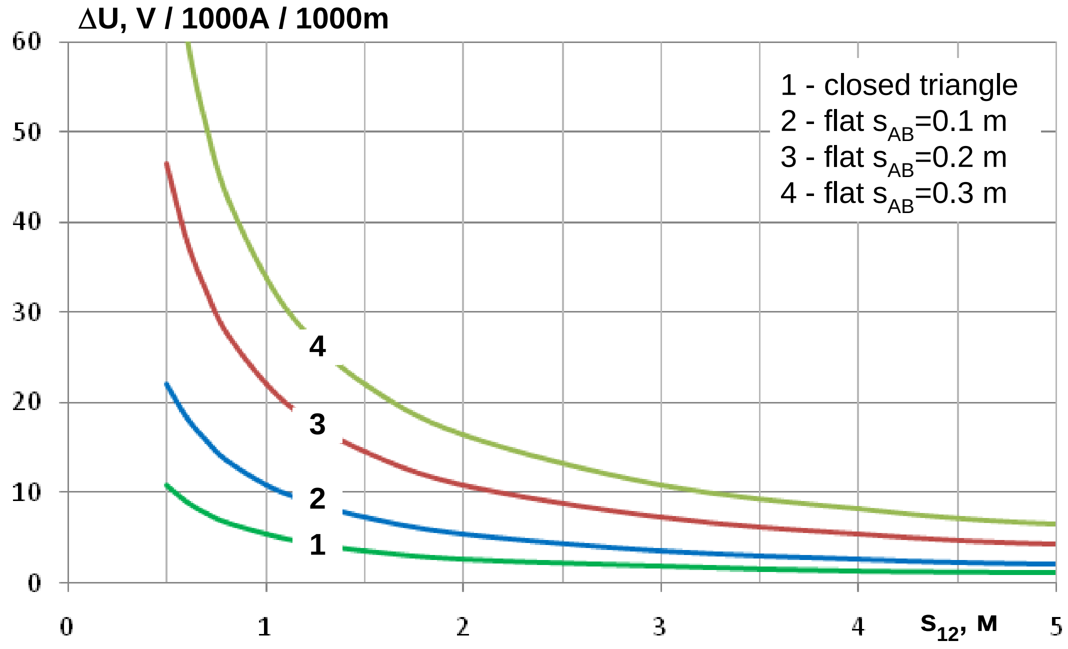

Fig.5. 50 Hz voltage induced on the disconnected circuit of a double-circuit CL.

It follows from Fig.5 that a noticeable reduction in the induced voltage can be achieved if the in-row phase laying is abandoned, and the phases are arranged in a closed triangle. In the areas where the cable terminations or joints are installed, the cable phases have to be separated at a distance from each other. You should not be afraid of this, because the induced voltages are determined by the average distance between the phases along the CL route, and it, despite the terminations and joints sections, will still be dictated by the way that dominates along the CL route, i.e. by a closed triangle.

If laying phases in a triangle along a significant part of the CL route for some reason is not possible, then to reduce the interference to the disconnected circuit, it is recommended to perform a solution called transposition of the single-core cables themselves. The scheme is shown on Fig.6 (as an example, the CL screens have two-side grounding), and the photo from the real object is shown in Photo 1.

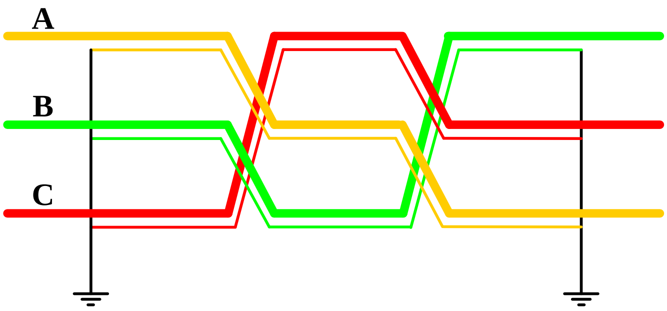

Fig.6. Transposition of single-core cables themselves (on the example of two-side screen grounding).

Photo 1. Transposition of the single-core cables themselves.

Screen cross-bonding nodes design

The induced voltage manifests itself not only during repairs on the CL route (during installation of cable termination or joint), but also in other situations: for example, personnel servicing the screen cross-bonding nodes on the disconnected CL circuit may encounter it.

To reduce the risks of electrical injury, it would be useful to reduce the number of cases when personnel descend into the cross-bonding wells and open the cross-bonding boxes. This turned out to be possible by equipping the boxes with new metal oxide surge arresters (MOA), which have continues operating voltage of 8.2 kV against the previously common 7.2 kV. The increase in the AC operating voltage of the MOA to 8.2 kV led to the fact that during periodic tests of the CL outer sheath with a 10 kV DC voltage, provided for by regulatory documents, the MOA retains a non-conductive state. In other words, the new 8.2 kV MOA, unlike the old 7.2 kV MOA, do not interfere with checking the sheath, which means that it is no longer necessary to open the cross-bonding boxes and disable the MOA installed inside. Moreover, the application of a 10 kV DC voltage to the CL sheath, if there are unconnected 8.2 kV MOA in the cross-bonding nodes, allows you to check not only the CL sheath itself, but also these MOA, because only serviceable 8.2 kV MOA will remain in a non-conductive state when exposed to a 10 kV DC voltage.

It is important to understand that a slight increase in the MOA operating voltage from 7.2 kV to 8.2 kV will not lead to a deterioration in the protection of the CL outer sheath from overvoltages, since the voltage level on the CL outer sheath (sheath between the screen and the ground) is determined mainly not by the MOA characteristics, but by the voltage drop on the connecting wires and grounding circuit, which can reach several tens of kilovolts.

Recommendations on equipping the CL screen cross-bonding boxes with new 8.2 kV MOAs were adopted in 2018 at the Scientific and Technical Council at PJSC ROSSETI (the biggest grid company) and apply to all branches, subsidiaries and affiliates.

The transition to the new 8.2 kV MOA is an important step, but it cannot completely exclude the need to open the screens cross-bonding boxes. For example, opening the boxes may be required when locating for a place of CL outer sheath damage, if it was detected during tests with a 10 kV DC voltage. Therefore, it is important for the staff to descend into the well and work with the boxes as safely as possible. To improve the safety of personnel in recent years, the country has been switching to the following technical solutions:

– the use of a separate cross-bonding well for each of the CL’ circuits, so that the personnel, while servicing the box of the disconnected circuit, could not touch the cross-bonding box of the working circuit;
– the use of not classic concrete cross-bonding wells, but special dielectric polymer wells of the PKET type (photos 2, 3);
– the use of not metal cross-bonding boxes, but dielectric plastic boxes of the KTP type (one three-phase box – on photo 2, three single-phase boxes – on photo 3).

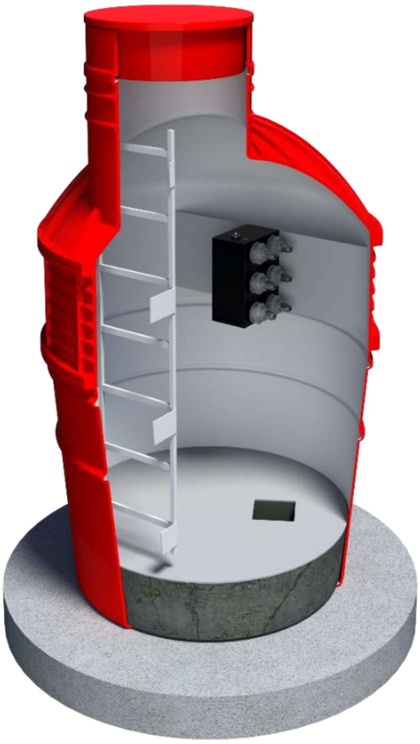

Photo 2. Polymer well of screen cross-bonding with one three-phase plastic box.

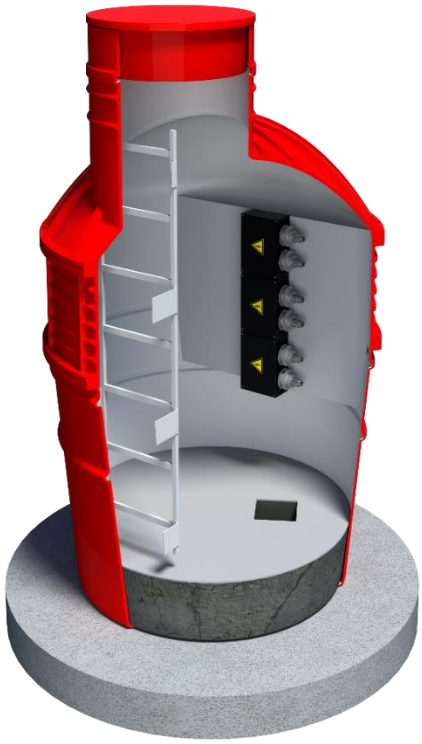

Photo 3. Polymer well of screen cross-bonding with three single-phase plastic boxes.

PHASE PARAMETERS ASYMMETRY AND ZERO-SEQUENCE CURRENTS

Laying 6-500 kV single-core cables in a row leads to the fact that the phases differ in longitudinal inductance. This means that the three phases of the CL will have a different voltage drop from the load current and therefore the voltage levels at the end of the CL (at the consumer) in the three phases will not be the same. In addition to the described asymmetry, other effects of it are possible. In particular, as it was shown in the article [3], if the phases of the CL are stacked in a row, and the screens have a two-side grounding (or cross-bonding), then zero-sequence currents $3I_{s0}$ arise in the screens.

For single-circuit CL, the zero-sequence screen currents $3I_{s0}$ are passed through the ground (Fig.7a), leading to corrosion of the grounding circuit, as well as to the appearance of an industrial frequency AC potential on it.

For two-circuit CL, the currents are passed differently – they pass in a circuit formed by the screens of one CL circuit and the second CL circuit (Fig.7b). If, at the same time, the cores of the circuits are combined for parallel operation (sectional switches are closed), then the zero-sequence current of the screens induces a zero-sequence current in the $3I_{c0}$ cores, which at some 6-35 kV facilities has already led to false operation of earth fault protections.

It is possible to minimize zero-sequence currents in the screens and the negative consequences caused by them if the phases of the CL circuits are laid not in a row, but in a closed triangle.

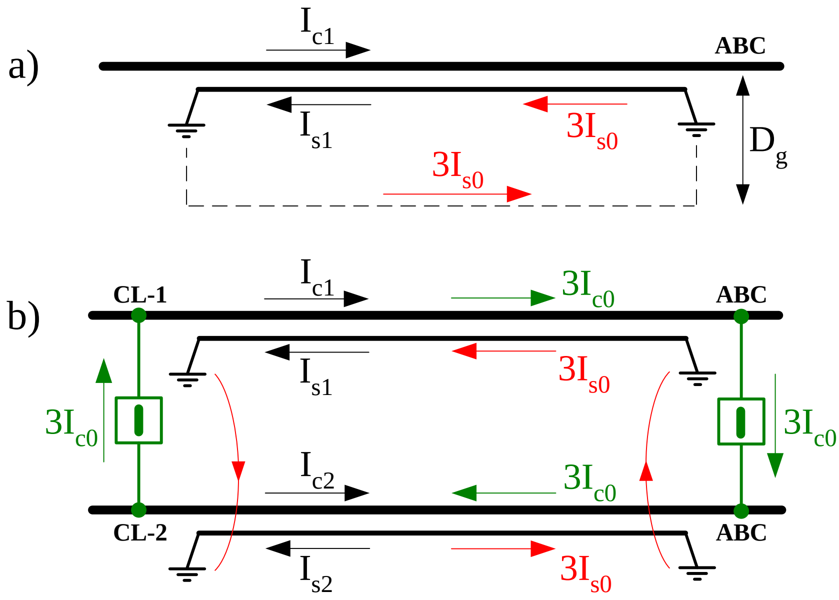

Fig.7. Circuits for the passage of direct-sequence (1) and zero-sequence (0) currents: (a) – single-circuit CL, (b) – double-circuit CL.

RISKS OF SPREADING THE DAMAGE

The choice of the optimal method for the mutual arrangement of the phases of the CL is determined, among other things, by whether a situation is useful or undesirable when a damage at one of the phases spreads to neighboring phases that are initially intact.

In networks with an isolated (compensated) neutral of 6-35 kV, there is a problem of finding the place of occurrence of a single-phase earth fault in the network. Relay protection, due to the small magnitude of the fault currents, is not always able to identify the damaged section of the network and put it out of operation. Laying single-core cables in a closed triangle can be useful because in this case damage to one of the phases over time due to the action of the arc and the heat released can cause damage to the second and third phases in the same place of the CL route (see fault F(1) phase B in Fig.1b), and this in turn means the transition of a single-phase earth fault into a two-phase or three-phase short circuit, which will no longer be difficult to detect and disable.

In networks with a 110-500 kV grounded neutral, there is no problem of finding the place of a CL damage, but there are some difficulties with mixed cable and overhead lines (ML), where it is necessary to establish an automatic reclosure cycle (AR). As shown in the article [4], there are three possible options for ML:

- AR is always allowed (regardless of where the short circuit was);
- AR is always prohibited (regardless of where the short circuit was);
- AR selective (reclosure of the ML is allowed if the short circuit happened on the section of the overhead line, and is prohibited if the short circuit happened on the CL section).

On ML, where AR is always prohibited or is selective, reclosure the line in case of a damage on the cable section is impossible, and therefore there is no need to fear for the cable. If the AR is always allowed, then the situation is different, because even if the short circuit occurred not on the air, but on the cable section, the voltage will be re-applied to the ML and the short circuit current will pass through the cable damage point again, an arc will arise again. In order for the arc combustion products not to damage the adjacent phases, they should be located at a distance from each other, i.e. rather in a row than in a closed triangle.

As can be seen, in the AR issues, the relative arrangement of the CL phases is important only in one case – if the AR is always allowed, and here it is desirable that the CL phases are laid in a row (Fig.1a). As noted in [4], the unconditional permission of the AR is allowed only when the cable section of the ML has a short length and the repair of the CL is not difficult. In other versions of the AR (when it is either prohibited or made selective), the relative position of the phases of the CL does not matter and, therefore, it is possible to lay the phases in a closed triangle.

CONCLUSIONS

The mutual arrangement of single-core cables is determined not only by the need to achieve one or another current capacity of the CL. There is a whole list of factors discussed in the article that should be taken into account when choosing the location of the phases. The analysis of these factors leads the author of the article to the opinion that in most cases it is advisable to give preference to laying single-core cables with a closed triangle.

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