AN OPTIMAL MUTUAL ARRANGEMENT OF HIGH-VOLTAGE SINGLE-CORE CABLES

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

The article shows that if we consider the whole set of factors, it turns out that it is the mutual arrangement in the form of a trefoil that is the most optimal for almost any cable line.

Keywords: cable line, single-core cable, bonding of cable screens, transposition of cables, induced voltage, zero-sequence current, damage to cable sheath.

I. INTRODUCTION

For a group of three single-core 6-500 kV cables, two main types of mutual arrangement of phases are shown in Fig.1. Although standards [1] and cable catalogues focus only on the current-carrying capacity (ampacity) of the line, it should be understood that this is not the only and not the main argument when choosing the optimal mutual arrangement. The full list of factors requiring consideration should at least include the following:

- ampacity of the cable line (CL);
- the installation and maintenance cost of the bonding/grounding of the cable screens;
- the width of the CL route (width of the trench etc.) and culture of cable installation;
- convenience of cable identification on multi-circuit CL;
- safety of personnel when working on multi-circuit CL;
- the asymmetry of the CL parameters (impedances) in different phases;
- the magnitude of zero-sequence currents in the CL screens and their grounding circuit, as well as the electric potential of the grounding circuit and corrosion of its metal;
- the magnitude of the zero-sequence currents in the CL conductors (cores of the cables) and the false operation of protection in 6-35 kV networks with an isolated neutral;
- detection of cable damages in 6-35 kV networks with isolated neutral;
- the possibility of automatic reclosure on 110-500 kV mixed cable/overhead lines.

The article shows that taking into account all these factors should convince designers rather to lay phases in a trefoil (Fig.1b) than in a flat (Fig.1a).

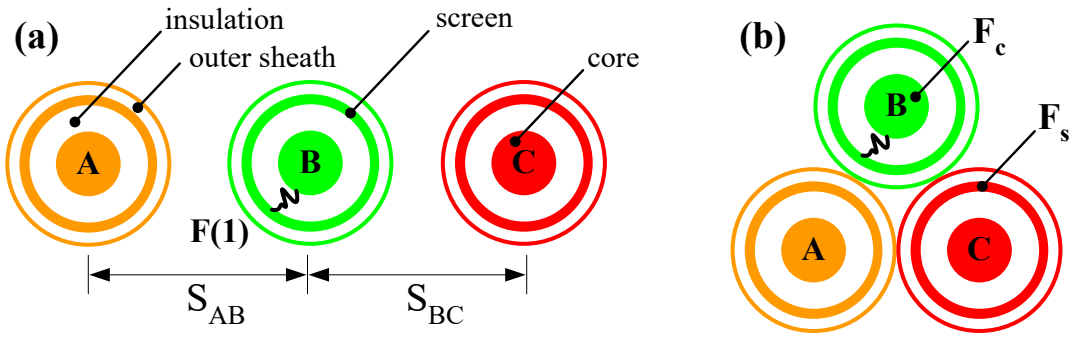


Figure 1 – The main options for laying single-core cables:
(a) – flat formation, (b) – trefoil.

II. BONDING OF THE SCREENS

The CL ampacity 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 flat formation (Fig.1a), the area of contact of the cables with the cooling medium (soil or air) turns out to be larger than when laying a trefoil (Fig.1b). Therefore, it may seem that for a flat formation of phases (flat-formation), the ampacity is greater than for a trefoil. 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, which is not always like that.

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 (let us do not take into account losses in insulation since they are minimal). 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 bonding types.

According to [2,3], three basic screen bonding types are known:

- solid bonding (Fig.2a);
- single-point bonding (fig.2b);
- cross-bonding (Fig.2c).

With solid bonding, power losses occur in screens due to 50 Hz currents induced there by the magnetic field of the cores, 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 [3] that with solid bonding, 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 trefoil to laying in a 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 ampacity when laying the phases (with solid bonding of the screen) in a flat formation may be both higher (due to good cooling) and lower (due to big screen losses) than those when laying a trefoil.

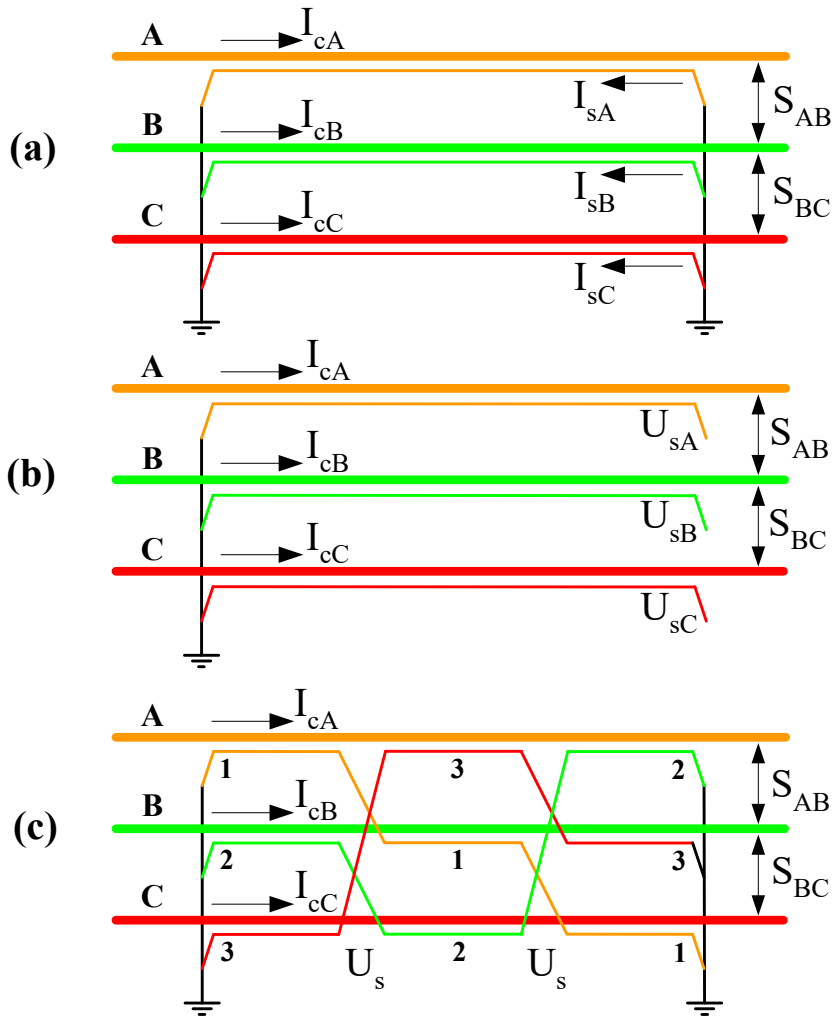


Figure 2 – Main types of screen bonding of single-core cables:
(a) – solid bonding, (b) – single-point bonding, (c) – cross-bonding.

Calculations, reflected, in particular, in the catalogues of leading cable companies, show that for CL with solid bonding of the screens, the highest ampacity is achieved:

- when laying in a flat, if the CL has a small cross-section of screens (25, 35 mm^2);
- when laying in a trefoil, if the CL has a large cross-section of screens (50, 70, 95 mm^2, etc.).

The cross-section of the screens is determined by the level of short-circuit currents of the network, and usually for 6-35 kV 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 bonding the screens on both sides, the maximum ampacity is achieved when laying the phases in a trefoil, and not with a flat.

If the CL screens have single-point bonding or cross-bonding, then in this case there are no losses in the screens, and regardless of the distance S between the CL's phases and the screen cross-section F_s. Then the greatest CL ampacity will be at the flat formation of phases.

It can be seen that laying phases of the CL in a flat (Fig.1a) provides increased ampacity only for those bonding types that provide for no losses in the screens – namely with single-point bonding (Fig.2b) and cross-bonding (Fig.2c). However, for CL with such bonding, one should still

not strive to increase the ampacity 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 [2,3] causes an increase in the 50 Hz voltage U_s induced on the screens by the magnetic field of the cores.

In accordance with [3] 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 single-point bonded screen sections ($K = 1$ on Fig.2b) or increase the number N of full cycles of cross-bonding ($N = 1$ on Fig.2c) – this significantly complicates the construction of the CL and its operation. Thus, even for CLs with bonding types Fig.2b or Fig.2c having no losses in the screens, preference should be given to a trefoil.

III. SAFETY OF WORK ON DOUBLE-CIRCUIT LINES

Usually, CLs 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, consider the following three questions to double-circuits CLs:

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

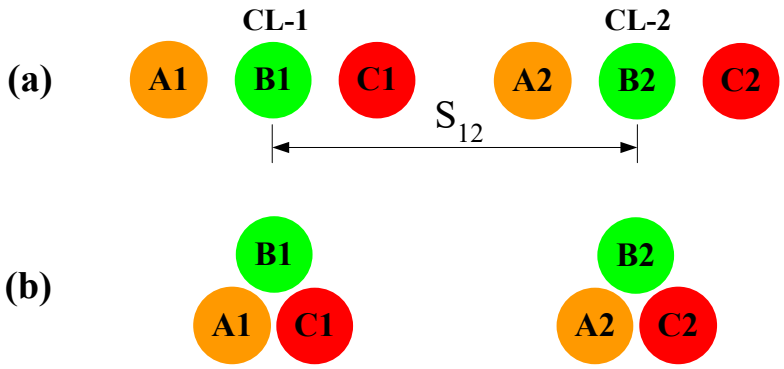


Figure 3 – The main options for laying the phases of a two-circuit CL:
(a) – flat formation, (b) – trefoil.

Circuit identification

When laying the phases of a double-circuit CL in a flat (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 circuit are laid in a trefoil (Fig.3b), periodically fixed together with ties or cleats, equipped with identifying tags, then the probability of personnel error is reduced. Also, the trefoil laying of the phases makes it possible to slightly reduce the width of the CL corridor.

Induced voltage

For the personnel servicing the disconnected circuit, the value of the 50 Hz voltage, which is induced from a nearby working circuit, is important [3,4].

In the design of a cable, the presence of a grounded screen (with near-zero electric potential) leads to the fact that there is no electric field outside the cable. However, 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 of three different phases are laid together, and their 50 Hz 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 trefoil.

In two-circuit CL, the presence of a magnetic field of a CL circuit in operation leads to the fact that the disconnected circuit is under the influence of an induced 50 Hz voltage. As an example, Fig.4 shows that the 50 Hz induced voltage occurs on the disconnected circuit in the place prepared for the installation of the cable joint. The voltage occurs both on the cable 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.

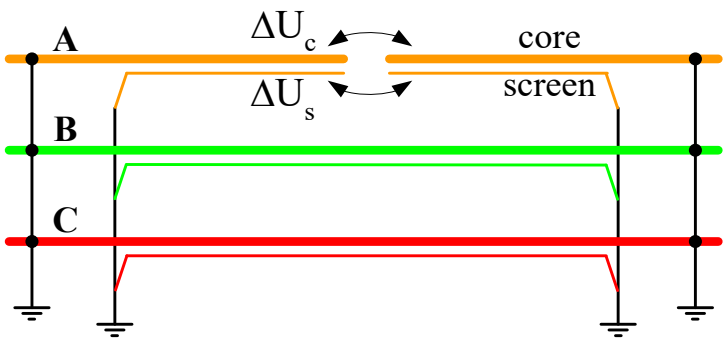


Figure 4 – The 50 Hz voltage induced on the disconnected circuit of the double-circuit CL.

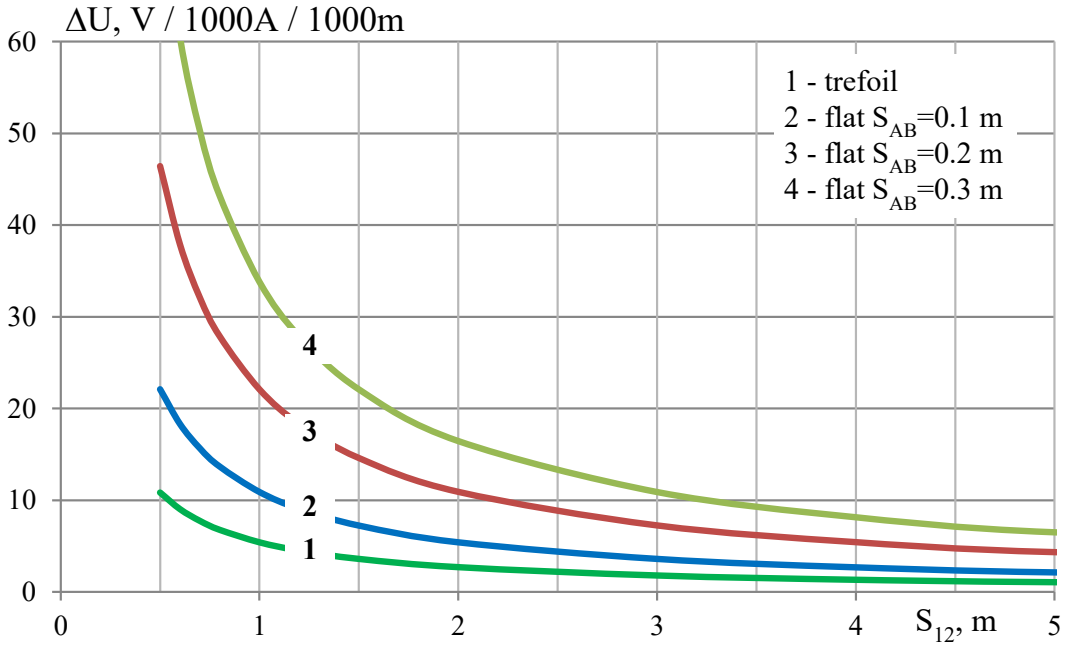


Figure 5 – 50 Hz voltage induced on the disconnected circuit of a double-circuit CL.

The voltage (50 Hz, RMS) that can be induced on the disconnected circuit is shown in Fig.5 (taken from [3]), depending on the distance S_{12} between the circuits and phase arrangement (flat, trefoil). The induced voltage is proportional to the length of the CL and the current in the core of the circuit in operation (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 per 1000 m, 1000 A. If the length of the CL is, say, 4000 m, and the core current is 500 A, then the 50 Hz voltage affecting the personnel will be $22 \cdot (4000/1000) \cdot (500/1000) = 44$ V.

It follows from Fig.5 that a noticeable reduction in the induced voltage can be achieved if a flat formation phase laying is abandoned, and the phases are arranged in a trefoil. 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 trefoil.

If laying phases in a trefoil 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 cables. The diagram is shown on Fig.6 (as an example, the CL screens have solid bonding of the screens), and the photo from the real object is shown in Fig.7.

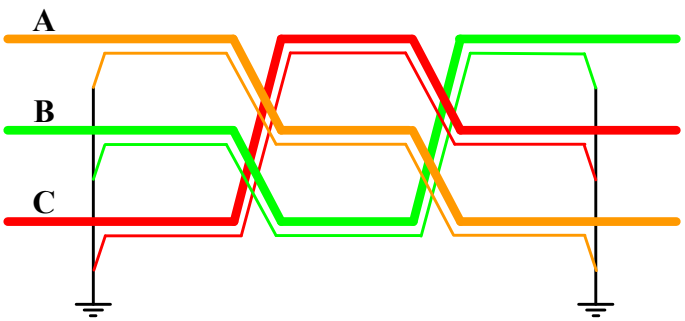


Figure 6 – Transposition of single-core cables (in case of solid bonding of cable screens).



Figure 7 – Transposition of the single-core cables.

The design of the screens' cross-bonding nodes

To reduce the risks of electrical injury, it would be useful to reduce the number of cases when personnel descend into the cross-bonding manholes and open the cross-bonding link boxes. This turned out to be possible by equipping the link boxes with new type of sheath voltage limiters (SVL), which have continuous operating voltage of 8.2 kV against the previously common 7.2 kV. The increase in the operating voltage of the SVL 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 SVL retains a non-conductive state. This means that it is no longer necessary to open the link boxes and disable the SVLs. Moreover, the application of a 10 kV DC voltage to the CL sheath, even if there are connected 8.2 kV SVLs, allows to check not only the sheath, but also these SVLs, because only serviceable 8.2 kV SVL will remain in a non-conductive state when exposed to a 10 kV DC voltage.

Note that a slight increase in the SVL 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 outer sheath is determined mainly not by the SVL characteristics, but by the voltage drop on the bonding cables (auxiliary cables between main cable joint and the link box, and between link box and the grounding contour), which can reach several tens of kilovolts.

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

- the use of a separate cross-bonding manholes (cross-bonding nodes) for each of the several circuits, so that the personnel, while servicing the link box of the disconnected circuit, could not touch the cross-bonding link box of the working circuit;
- the use of dielectric polymer materials (for example, Fig.8) instead of concrete ones;
- the use dielectric plastic link boxes (Fig.8) instead of metal ones.



Figure 8 – Modern screen cross-bonding node: polymer link-box in the polymer manhole.

IV. PHASE ASYMMETRY

Laying 6-500 kV single-core cables in a flat formation leads to the fact that the phases differ in longitudinal impedance. 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) will not be the same in three phases. In addition to the described asymmetry, other effects of it are possible. In particular, as it was shown in [3], if the three phases of the CL are in a flat formation, and the screens have a solid bonding (or cross-bonding), then zero-sequence currents $3I_{s0}$ arise.

For single-circuit CL, the zero-sequence screen currents $3I_{s0}$ are passed through the ground (Fig.9a), leading to corrosion of the grounding contour and appearance of a 50 Hz potential on it.

For two-circuit CL, the currents are passed differently – they pass in a contour formed by the screens of the first and the second circuits of the CL (Fig.9b). If, at the same time, the cores of the circuits are combined for parallel operation (sectional circuit breakers are closed), then the zero-sequence current of the cable screens $3I_{s0}$ induces a zero-sequence current in the cable cores $3I_{c0}$, 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 effects caused by them if the phases of the circuits of the CL are laid not in a flat, but in a trefoil.

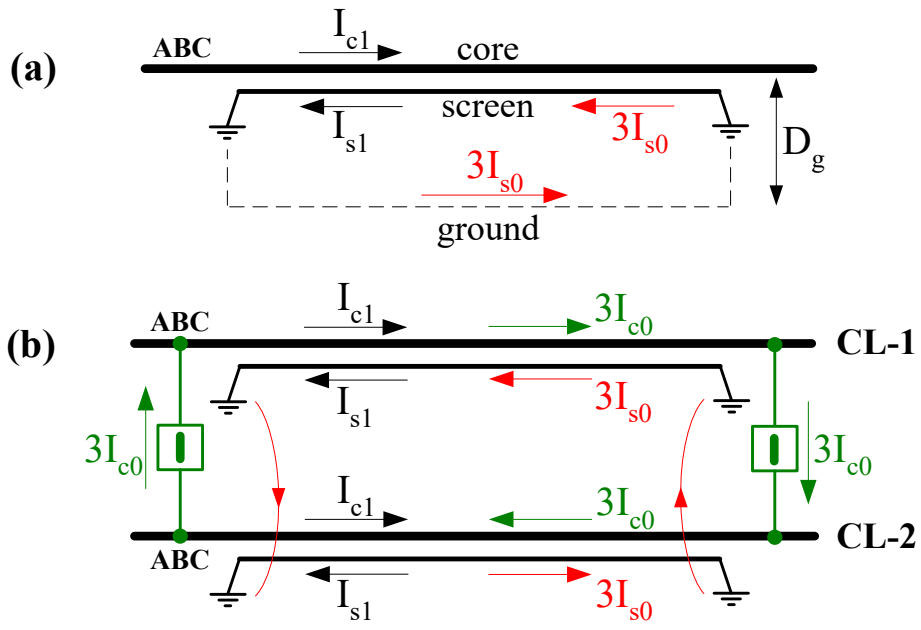


Figure 9 – Contours for the passage of currents of positive sequence (1) and zero (0): (a) – single-circuit CL, (b) – double-circuit CL.

V. RISKS OF SPREADING THE DAMAGE

The selection 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 the ground fault. Protection, due to the small magnitude of the fault current, is not

always able to identify the damaged section of the network and put it out of operation. Laying single-core cables in a trefoil 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.1), and this in turn means the transition of a ground 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 damage, but there are some difficulties with mixed cable/overhead lines, where it is necessary to establish an automatic reclosure (AR). As shown in [3,5], there are three possible options:

- 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 line is allowed if the short circuit happened on the section of the overhead line, and is prohibited if the short circuit happened on the cable section).

On mixed lines, 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 section, but on the cable, the voltage will be re-applied to the line and the short-circuit current will pass again through the damaged point of the cable, an arc will arise again. In order for the arc combustion products not to damage the adjacent cables (phases), they should be located at a distance from each other, i.e. rather in a flat formation than in a trefoil.

As can be seen, in the AR issues, the arrangement of the cable phases is crucial only in one case – if the AR is always allowed on the mixed line, and in this case, it is desirable that the cables are laid in a flat (Fig.1a). As noted in [3,5], the unconditional permission of the AR is allowed only in rate case – when the cables are short in length and the repair of the cable is not difficult.

VI. CONCLUSIONS

The mutual arrangement of single-core cables is determined not only by the need to achieve the maximum ampacity of the cable line. There is a whole list of factors discussed in the article that should be taken into account when choosing the arrangement of the phases. The analysis of these factors shows that in most cases it is advisable to give preference to laying cables in a trefoil.

REFERENCES

[1] IEC 60287 "Electric cables – Calculation of the current rating".
[2] IEEE Std 575-2014 "Guide for bonding shields and sheaths of single-conductor power cables rated 5 kV through 500 kV".
[3] M. Dmitriev "High voltage cable lines". -Porto, 2021. -690 p.
[4] CIGRE TB 801 "Guidelines for safe work on cable systems under induced voltages or currents", April 2020. –90p.
[5] IEEE 1793-2012 "Guide for Planning and Designing Transition Facilities between Overhead and Underground Transmission Lines".