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VOLTAGES INDUCED ON HIGH VOLTAGE CABLE LINES

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Personal safety while working on disconnected overhead lines under induced voltage is relatively well understood. However, unfortunately, this cannot be said about 6-500 kV cable lines, where, as experience shows, the induced voltage is a complete surprise.

The article gives a number of examples that explain the mechanisms of interference on the switched off cable line from the nearby cable or overhead lines.

Keywords: overhead transmission line, cable line, single-core cable, screen bonding, screen grounding, magnetic field, induced voltage, the safety of personnel.

1. THE VOLTAGE INDUCED FROM THE NEIGHBORING CABLE LINE

Modern cable lines (CL) with cross-linked polyethylene (XLPE) insulation of voltage classes from 6 to 500 kV can be designed using:

- three-core cables;
- single-core cables.

Both cable designs have metal screens, one or more. Such screens are superimposed on the cable insulation surface and are most often made of copper wires (although options with aluminum wires or aluminum foil are known). The main purpose of metal screens is:

- equalization of electric field strength in cable insulation;
- elimination of the electric field outside the cable.

In order for the cable screens to perform these functions, they must be grounded at least at one side (for example, at the beginning and/or the end of the CL). The absence of an electric field outside the 6-500 kV cables makes it difficult for neighboring CLs to influence each other due to this field. Therefore, considering the mutual influence of several CLs, we will focus on the influence through the magnetic field.

The magnetic field created by currents of cores and screens of the CL is present both inside and outside entire CL, however, we will focus in more detail only on the magnetic field outside, since it determines the degree of influence of neighboring CLs on each other. It is necessary to distinguish the magnetic field of the CL:

- in symmetrical mode (normal operation mode or the passage of a three-phase short-circuit current in the CL cores);
- in asymmetric mode (emergency mode when current passage only in one or two CL cores, for example, in case of a single-phase or two-phase short-circuit).

The voltage induced in symmetrical mode

If the CL is made by a three-core cable, then there is practically no magnetic field outside the CL in the symmetrical mode of operation. It is explained by the fact that three magnetic fields of the three phases sum up and compensate for each other. Exactly the same situation occurs if the CL is made by a group of three single-core cables laid in a closed triangle (Fig.1a). In cases where single-core cables are located at a distance from each other

(Fig.1b), magnetic fields of the three phases do not compensate each other so well, and therefore the resulting field outside the CL can be very significant, capable of causing appropriate interference to neighboring CL.

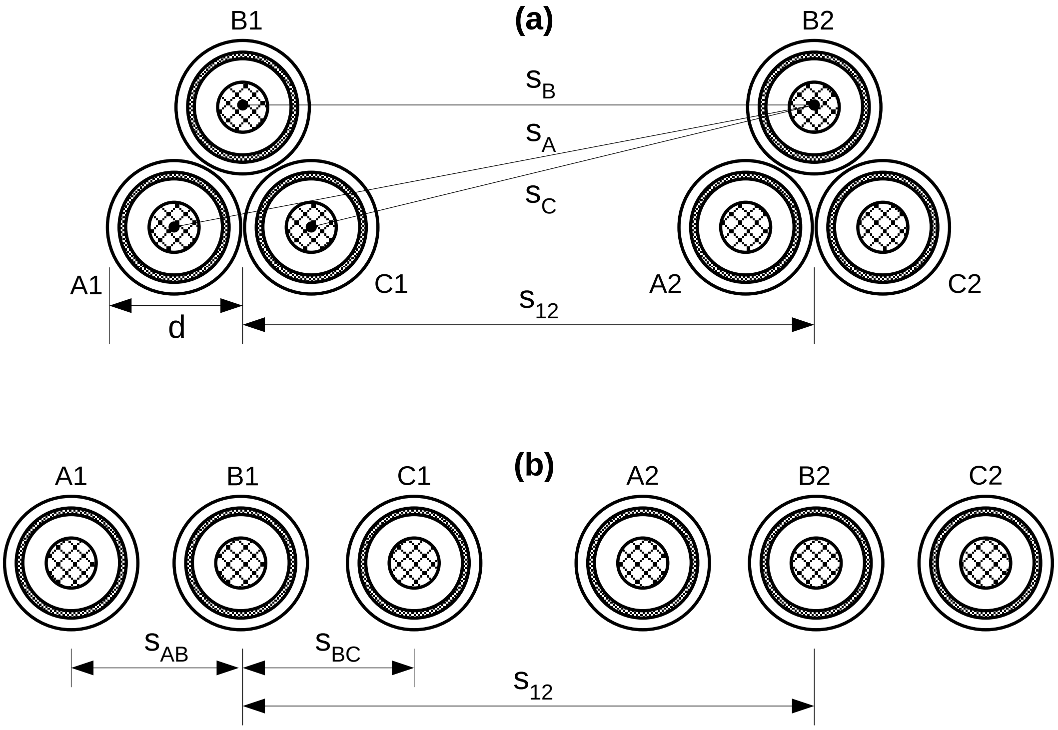

Fig.1. A two-circuit CL:
(a) – phases arranged in a triangle; (b) – phases arranged in a row.

Two cable lines CL-1 and CL-2 through their magnetic fields affect each other in the case when both are in operation, and in the case when only one of them is in operation and second is disconnected. From a practical point of view, the case of a disconnected circuit is more interesting, since it is directly related to the safety of installations and repairs.

For a disconnected circuit, induced voltage can occur both on screens and on cores. Here we will consider only the voltage induced on screens. The interest in targeting screens is not accidental, but is due to the proximity of screens to the outside surface of cables, that is, any screen is the part of the cable that is most likely to be touched. For example, when performing fairly common work on repairing the cable outer sheath of a disconnected CL, personnel can easily touch the screen, and it will be unexpected for them to have an AC voltage of 50 Hz on the screen, induced from a nearby CL.

The magnetic field of the CL-1 under current leads to the appearance of an induced electromotive force (EMF) in the screens of the disconnected CL-2. If the CL-2 screens have a two-side grounding (Fig.2a) or their cross-bonding (Fig.2b), then under the action of the induced EMF in the CL-2 screens, currents $I_S > 0$ of frequency 50 Hz will occur, and the screens voltage $U_S \approx 0$ will be absent. If screens of CL-2 are one-side grounded (Fig.2c), then, on the contrary, $I_S \approx 0$ and $U_S > 0$ will be.

Although there are several different schemes for bonding/grounding the CL-2 screens, we will consider only one-side grounding (Fig.2c), since the voltage U_S here is exactly equal to the value of the induced EMF and, therefore, scheme Fig.2c is convenient to study the degree of influence of the working CL on the disconnected one.

The voltage values U_S obtained for the scheme Fig.2c, in fact, will give an idea of the danger in the schemes Fig.2a and Fig.2b. For example, let's imagine the situation when the personnel should put the new cable joint in some of the CL places with two-side grounding. In order to get to the core of the CL, he must first cut the cable screen and separate its ends to the side. It is in this place between the "left" and "right" parts of the screen that the voltage U_S will arise (under the influence of this voltage U_S, even before the installation of the cable joint, the current I_S was flowing in the two-side grounded screen). This induced voltage U_S will exactly correspond to the voltage U_S shown on the scheme Fig.2c.

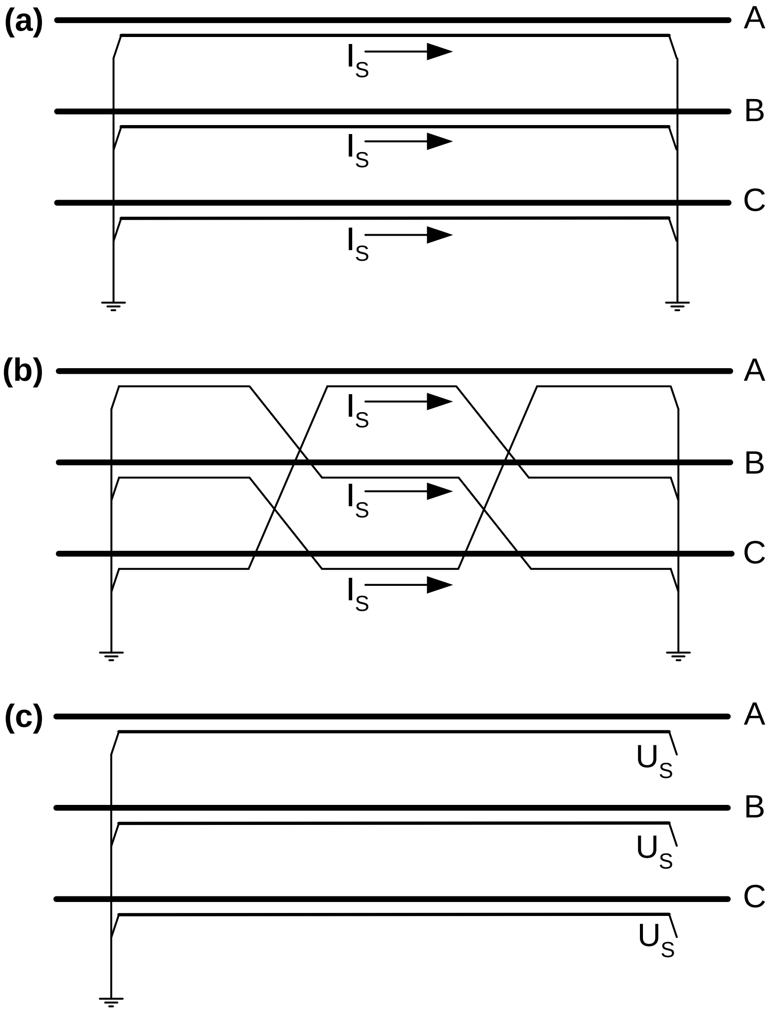

Fig.2. Basic screen schemes for CL with single-core cables:
(a) – two-sides grounding; (b) – screens cross-bonding; (c) – one-side grounding.

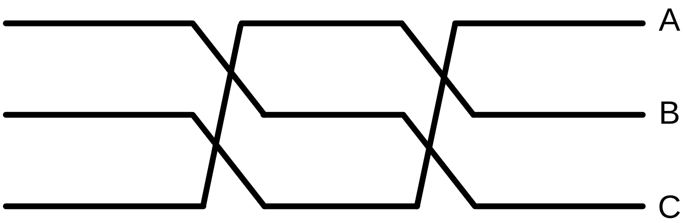

Fig.3. The cross-bonding (transposition) of the single-core cables themselves (or OHL's wires).

So, let's assume that there are two parallel lines CL-1 and CL-2, each of them has a one-side grounding of the screens. Consider the voltage induced from the CL-1, which is in operation under load current, to the screens of the disconnected CL-2. The magnitude of the induced voltage U_S will differ slightly depending on which of the three screens of the CL-2 is in question (A, B, C). For convenience, consider the screen of the middle phase "B", since in the conditions of Fig.1 the distance s_{12} between circuits CL-1 and CL-2 just corresponds to the distance between "B" cables of these circuits. Let there be no transposition of single-core cables themselves (no cross-bonding shown on Fig.3).

The voltage U_S of the CL-2 screen "B" is an AC voltage of frequency 50 Hz, it can be found by a complex method based on the currents $\dot{I}_A$, $\dot{I}_B$, $\dot{I}_C$ of the CL-1 cores:

$$\dot{U}_S = jX_A \cdot \dot{I}_A + jX_B \cdot \dot{I}_B + jX_C \cdot \dot{I}_C, \tag{1}$$

where $X_A = \omega \cdot M_A$, $X_B = \omega \cdot M_B$, $X_C = \omega \cdot M_C$ are mutual inductive impedances between the CL-2 screen "B" and CL-1 cores "A, B, C",

$\omega = 2\pi f$ is the circular frequency ($f = 50$ Hz), $j = \sqrt{-1}$ is an imaginary unit.

As in [1], the mutual inductances M_A, M_B, M_C can be found:

$$M_A = \frac{\mu_0}{2\pi} \cdot l_{CL} \cdot ln\frac{D_G}{s_A} \qquad M_B = \frac{\mu_0}{2\pi} \cdot l_{CL} \cdot ln\frac{D_G}{s_B} \qquad M_C = \frac{\mu_0}{2\pi} \cdot l_{CL} \cdot ln\frac{D_G}{s_C} \tag{2}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant of the vacuum,
l_{CL} is the length of the section where CL-1 and CL-2 laid in parallel to each other,
s_A, s_B, s_C are the distances (m) shown in Fig.1,
D_G is the depth of penetration of the magnetic field into the ground:

$$D_G = 2.24 \cdot \sqrt{\frac{\rho_G}{\mu_0 \cdot \omega}} \tag{3}$$

where ρ_G is the soil resistivity (Ω·m).

As the currents of the CL-1 cores are in a symmetrical mode (normal mode or mode when three-phase short-circuit currents pass through these cores), the following currents can be taken, forming a positive-sequence:

$$\dot{I}_A = I_{CL} \qquad \dot{I}_B = \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right) \cdot I_{CL} \qquad \dot{I}_C = \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) \cdot I_{CL} \tag{4}$$

where I_{CL} is the effective value of the current in the core of the CL-1 (A).

Calculations (1)-(4) are convenient to carry out with the core current $I_{CL} = 1000$ A and the length of the parallel section $l_{CL} = 1000$ m. The voltage value $U_S = |\dot{U}_S|$ obtained in this way is shown in Fig.4 and is given for two main cases:

- the phases of each CL are laid in a closed triangle (Fig.1a);
- the phases of each CL are laid in a row with a certain distance $s_{AB} = s_{BC}$ (Fig.1b).

Conversion to other I_{CL} and l_{CL} can be performed using the formula:

$$U_S = U_S{}^{FIG} \cdot \frac{I_{CL}}{1000} \cdot \frac{l_{CL}}{1000} \tag{5}$$

According to Fig.4, with a typical distance between two CL circuits $s_{12} = 0.7$ m, the induced voltage U_S, depending on the relative position of cables, will be from 6 up to 50 V for each 1000 A and 1000 m.

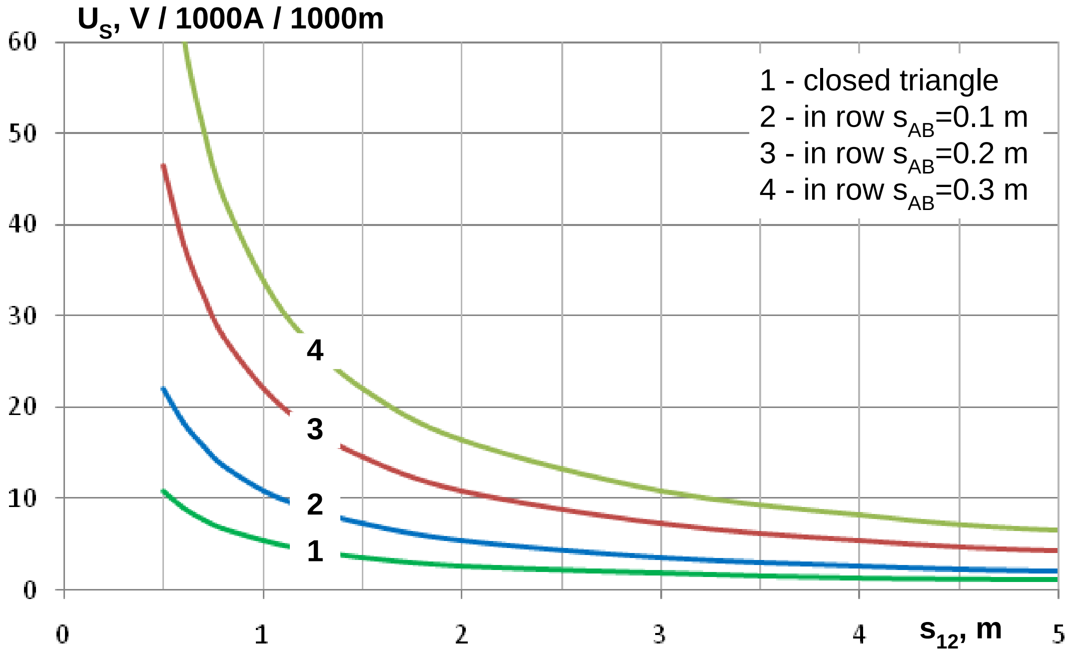

Fig.4. The voltage induced on the screen of the disconnected CL-2 in symmetrical mode due to the action of the magnetic field of the working CL-1 (see Fig.1).

For example, if a double-circuit CL (of any voltage class) has in row arrangement of phases $s_{12} = 0.7$ m, $s_{AB} = s_{BC} = 0.2$ m, length $l_{CL} = 3000$ m, core current $I_{CL} = 500$ A (for a period of time when only one of the two circuits remained in operation), then the AC 50 Hz voltage induced on the screens of the disconnected circuit, will be:

$$U_S = 30 \cdot \frac{500}{1000} \cdot \frac{3000}{1000} = 45\ V$$

representing a real danger to personnel who will have it "in their hands". However, if the single-core cables of each CL (CL-1 and CL-2) are laid in a closed triangle, then the induced voltage is significantly reduced:

$$U_S = 6 \cdot \frac{500}{1000} \cdot \frac{3000}{1000} = 9\ V$$

As can be seen, the safety issues of work on multi-circuit CL require that single-core cables be laid mainly in a closed triangle, and the distance between the circuits is as large as possible.

It happens that for some reason (for example, to increase the permissible current of the CL core), it is better to place the CL’s cables not in a triangle, but in a row at a distance from each other. In this case, to ensure the safety of work, it is recommended to provide for the transposition of the single-core cables themselves – see diagram Fig.3. Although this is a rather complicated and inconvenient technical solution, but in some cases, it is worth implementing. The cable transposition must be performed for each of the following CL in parallel, because any of them can be in the role of a disconnected line.

The voltage induced in asymmetrical mode

Asymmetric modes (primarily short-circuit), although usually short-lived, may be accompanied by the passage of significant currents in the CL individual cables. Since these currents are not present in all three phases, there is no need to talk about compensation of the magnetic fields of the phases, and a significant resulting field appears in the CL, leading to commensurate induced voltages on neighboring CL.

For example, if the passage of a single-phase short-circuit current through a cable core is considered as an asymmetric mode, then the magnetic field of the short-circuit will not depend on whether the phases lie in a row or are assembled in a closed triangle. The only influencing factor is the distance from the CL-1, where the short-circuit current passes, to the disconnected CL-2, where the induced voltage appears.

To calculate induced voltages for single-phase short-circuits, it is enough to take formulas (1)-(4) and substitute $\dot{I}_A \approx 0$, $\dot{I}_B = I_{CL}$, $\dot{I}_C \approx 0$ in them. The choice of the CL-1 phase "B" as a special one is convenient because the distance from the phase "B" of the working CL-1 to the phase "B" of the disconnected CL-2 exactly corresponds to the distance s_{12} between the axes of the cables.

Fig.5 (Curve 1) shows the calculation results for (1)-(4) induced voltage $U_S = \left|\dot{U}_S\right|$ at single-phase short-circuit. It can be seen, for example, that even at a large distance between CL-1 and CL-2, equal to $s_{12} = 50$ m, the induced voltage is about 200 V, and at small distances it reaches 500 V. For example, if at short-circuit the current in the CL-1 core is only $I_{CL} = 10$ kA, then at length of $l_{CL} = 3000$ m the induced voltage will be:

$$U_S = 500 \cdot \frac{10000}{1000} \cdot \frac{3000}{1000} = 15000\,V$$

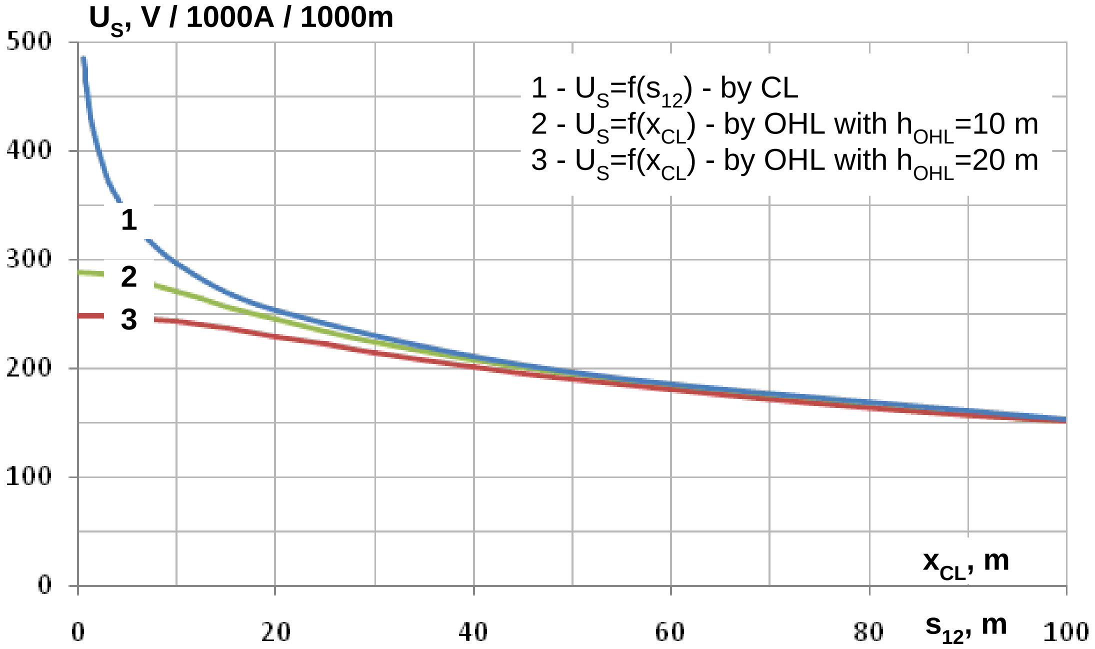

Fig.5. The voltage induced on the screen of a disconnected CL in asymmetrical mode (single-phase short-circuit) due to the action of the magnetic field of a working CL (curve 1) or a working OHL (curves 2,3).

2. THE VOLTAGE INDUCED FROM THE NEIGHBORING OVERHEAD LINE

Let's consider options for parallel following of a single-circuit CL together with an overhead transmission line (OHL) – which could be either single-circuit (Fig.6) or double-circuit (Fig.7). For example, such following may occur on approaches to the switchgear of an electric station or substation, where part of the connected lines has an overhead design, and part is cable. Another example may be the case when several parallel OHL are gradually redesigned into CL, and at some stage it turned out that one of these lines is still OHL, and another have already been transferred from the air to cable design.

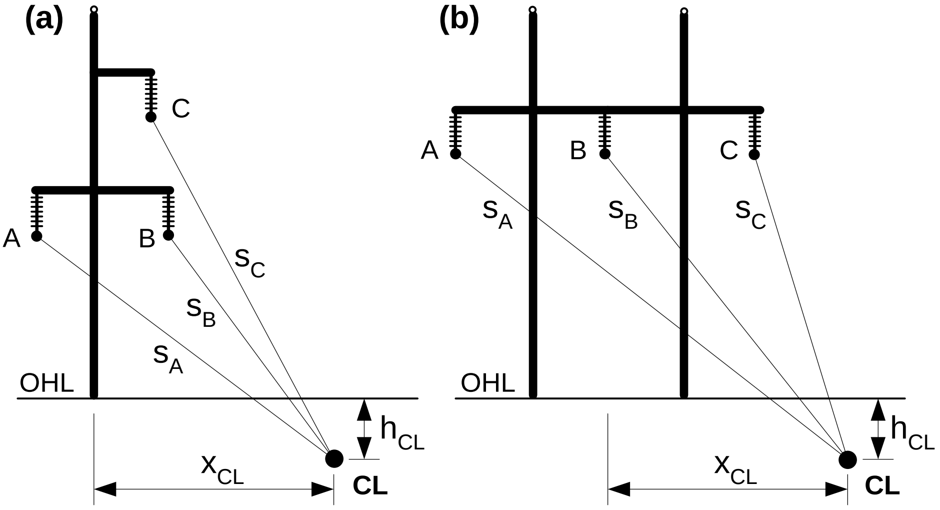

Fig.6. Parallel following of a single-circuit CL and a single-circuit OHL:
(a) – OHL has a triangular arrangement of phase wires; (b) – OHL has a horizontal arrangement.

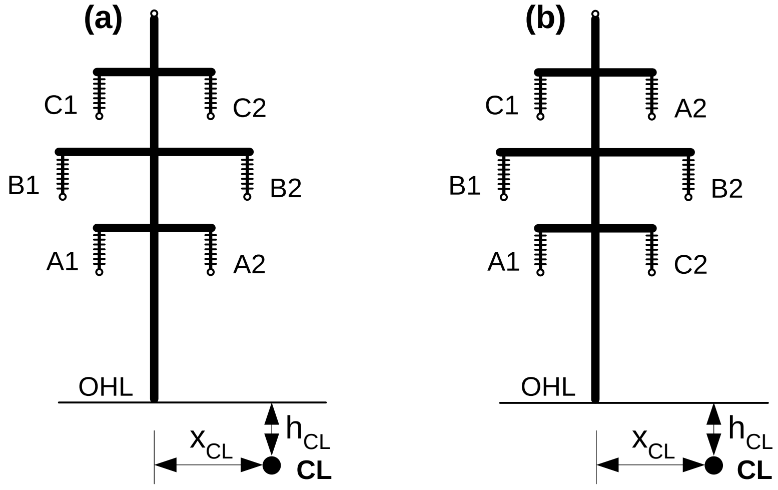

Fig.7. Parallel following of single-circuit CL and double-circuit OHL:
(a) – OHL has a vertical arrangement of phase wires; (b) – OHL has a reverse vertical arrangement.

The OHL, unlike the CL, has not only a magnetic field, but also an electric one, which means that the mechanism of the influence of the OHL on neighboring CL, in the general case, turns out to be more complicated than was considered for the two circuits of the CL in Fig.1. Despite this, when studying the OHL influence on CL, it is enough to consider only the magnetic field. The fact is that CLs are most often laid in the ground at a depth of up to

1.5 m or more, and the ground surface, as is known, is considered to be a surface of zero electric potential. Thus, the electric field of the OHL cannot affect the CL for the reason that the CL is shielded by the ground. Therefore, to calculate the voltage induced from the OHL to the CL, it is sufficient to use formulas (1)-(4). Correction of the formulas will be required only if the OHL is double-circuit – then in (1)-(4), instead of three components, write six.

The voltage induced in symmetrical mode

The voltages $U_S = |\dot{U}_S|$ induced from OHL to CL were calculated by (1)-(4), and the results obtained are given:

- for single-circuit OHL in Fig.8;
- for double-circuit OHL in Fig.9.

When calculating the U_S voltage, the OHL design was assumed to be typical for its rated voltage class (support height, distance between phases). As for the CL, the depth of its location in the ground was always assumed to be equal to $h_{CL} = 1.5$ m. Also note that for double-circuit OHL it was assumed that the currents of the circuits are the same.

Comparing Fig.8-9 and the previously obtained Fig.5, it can be seen that in general, in both cases (CL-CL and OHL-CL), the induced voltages are close to each other, amounting to tens of Volts for every 1000 A and 1000 m.

Of particular interest is the influence of the OHL design on the induced voltage. So, the smallest CL screen voltages are characteristic of OHL with a triangular arrangement of wires, and the largest – for OHL with a horizontal one. It is also important that the induced voltages increase as the OHL rated voltage class increases, since the distances between the phases become bigger and bigger, and their magnetic fields compensate each other worse.

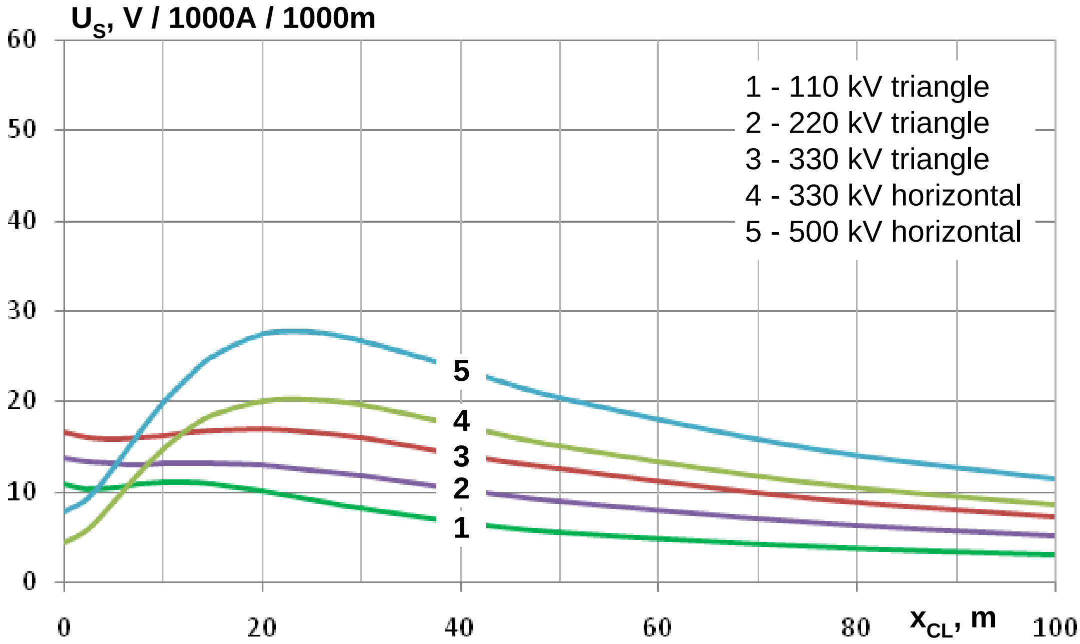

Fig.8. The voltage induced on the screen of the disconnected CL in symmetrical mode due to the action of the magnetic field of the working single-circuit OHL (see Fig.6).

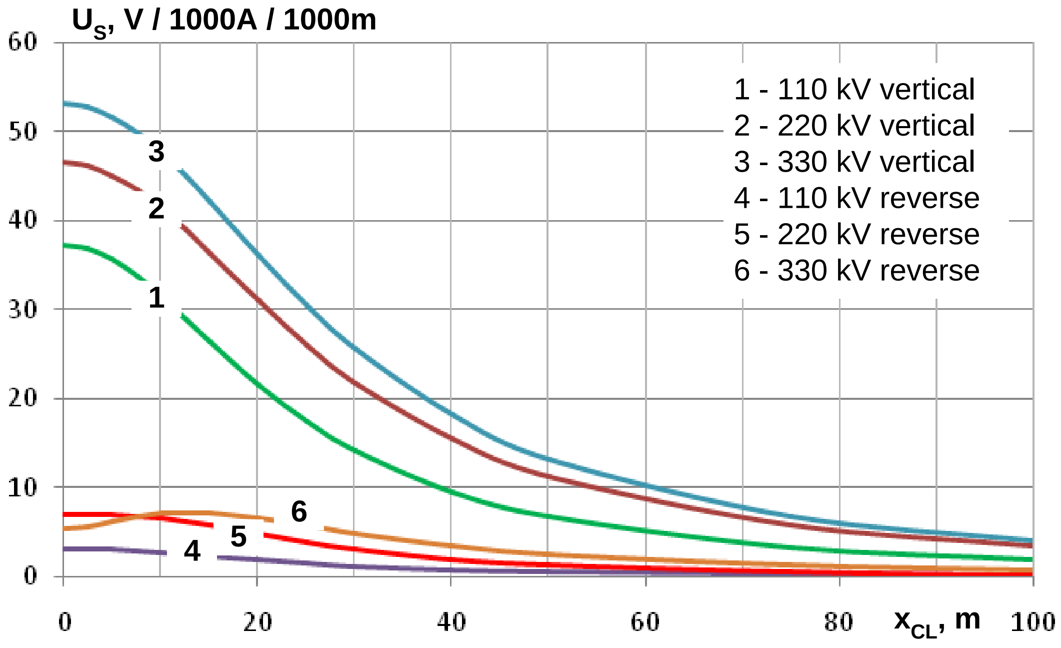

Fig.9. The voltage induced on the screen of the disconnected CL in symmetrical mode due to the action of the magnetic field of the working two-circuit OHL (see Fig.7).

It should be noted that induced voltage on the CL does not depend on how its single-core cables lie – in a row or in a closed triangle. The voltage will be almost the same for the screen of each CL phase and is determined mainly by the OHL design and the distance x_{CL} to it. Thus, if in the case of two parallel CLs, laying the phases in a triangle made it possible to reduce induced voltages, then here, in the case of OHL and CL, there are no opportunities to reduce the voltage induced on the CL. Therefore, unfortunately, when working on the CL, next to which OHLs pass, personnel should always be aware of the danger of getting under induced voltage.

For example, when servicing a disconnected 330 kV single-circuit OHL, built in St. Petersburg, the staff accidentally found an induced voltage on the CL cable screens, the source of which was a 330 kV OHL passing nearby. The facility has been built, and it was impossible to correct the situation, except that there could be a rule for future maintenance of the CL – to carry it on only during the hours of minimum OHL loading.

Strictly speaking, there are still some ways to reduce voltages induced from OHL to CL laid in parallel. In particular, the influence of a double-circuit OHL can be minimized if it organizes counter-phasing of all the wires of the OHL's circuits according to the scheme shown in Fig.7b. However, hardly anyone will go so far as to change the order of the phases of the OHL in order to reduce the induced voltage on CL.

The so-called transposition (cross-bonding) of three OHL phase wires (Fig.3) can be considered a theoretical option for reducing induced voltages from OHL to CL. However, this solution is complex, and it is used mainly on long overhead lines, that is, the distance along the line route between transposition towers (pylons) is usually tens or even hundreds of kilometers. Since the length of the CL is obviously less than the numbers mentioned, and the section of parallel following of OHL and CL may be only tens (thousands) meters long, the use of transposition of OHL wires in this short section is essentially excluded.

The voltage induced in asymmetrical mode

As before, if, in the role of an asymmetric mode, we consider the passage of a single-phase short-circuit current through the OHL wire, then the induced voltage to the CL will be determined only by the distance s_{12} from the phase of the OHL with the short-circuit current to the CL phase of interest.

The value of s_{12} depends on the horizontal distance x_{CL} between the OHL and the CL, as well as on the height of the phase wire h_{OHL} and the depth of the cable h_{CL}. The formula for calculating s_{12} is as follows:

$$s_{12} = \sqrt{{x_{CL}}^2 + (h_{OHL} + h_{CL})^2} \tag{6}$$

The results of the calculation of the voltage $U_S = |\dot{U}_S|$, induced from OHL to CL, depending on the height of the phase wire h_{OHL} (10 or 20 m) are shown in Fig.5 (curves 2 and 3). The voltage is close to the situation when the source of the voltage is CL (curve 1).

3. CONCLUSIONS

Calculations given in the article showed that cores and screens of a disconnected CL can be under an AC voltage of 50 Hz induced by neighboring line (CL or OHL) passing in parallel. This voltage may pose a danger to personnel when performing installation or repair work, for example, when testing cable outer sheath or locating the place where it is damaged.

In the case of two parallel CL, induced voltages arise, first of all, if these CL are made not by three-core, but by single-core cables. It is possible to reduce voltages induced from one CL to another CL to a safe level if cables of each CL are arranged in a closed triangle. In the case of in-row laying of CL cables, it is recommended to perform the transposition (cross-bonding) of three cables themselves to reduce interference.

In the case of parallel CL and OHL, it is hardly possible to reduce the voltage induced on the CL, which means that the construction of CL in the corridors of existing OHLs is not recommended, even with a large distance between CL and OHL reaching 50-100 m.

In all situations, CL’s voltages will be dangerous when induced from the short-circuit currents passing through the cores of neighboring CL or the wires of neighboring OHL. Therefore, it is necessary to avoid working on disconnected CL circuits during the hours of increased risk of short-circuits in the network – for example, during a thunderstorm, during the scheduled switching in the network, equipment testing, etc.

Unfortunately, there is no regulatory document, where the issues of safety of work on cables in conditions when they are under induced voltage would be considered. Against this background, a translation, for example, of the Australian standard [2], which considers ways to ensure the protection of personnel from induced voltages during the installation of cables, their testing and repair, would be very useful.

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