SCREENS GROUNDING OF 6-500 kV SINGLE-CORE CABLES: THE DISTANCE FROM JOINTS TO LINK-BOXES

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Cables with cross-linked polyethylene insulation (XLPE) have been widely used for more than 20 years. If cables of both single-core and three-core design are used in medium-voltage networks of 6-35 kV, then in 110-500 kV networks – exclusively single-core.

1. INTRODUCTION

Single-core 6-500 kV cables have a number of features, one of which is the presence of induced currents of industrial frequency 50 Hz in metallic screens and the losses of active power caused by them. To combat power losses in screens there are several options:

- one-side grounding of screens (Fig.1a);
- transposition of screens (Fig.1b) which is also known as cross-bonding of screens.

The issues of designing and operating cables with XLPE insulation, in particular single-core ones, are discussed in detail in a series of standards [1-3], which were prepared and approved by FGC "UES PJSC" a few years ago (they can be downloaded for free from the company's website). For example, the document [3] is devoted to the selection of screens bonding/grounding schemes – the appearance of this and other standards has become a very important step for the country.

The experience gained so far with cables has shown that there are several issues that are not reflected in the current editions of the standards, but which it would be useful to add there when the opportunity presents itself.

In particular, nowhere in the norms for cable lines does it indicate the requirements for the grounding resistance of screens cross-bonging nodes and for the grounding resistance of overhead line towers at the points of transition to cable. Substantiating such requirements and adding them to the standards is a very important task.

Another of the rather acute questions is whether there are restrictions on the length of the connecting wires (CW) with polyethylene insulation that connect the cable terminations (CT) or cross-bonding joints (CBJ) with protective surge arresters (SA, Fig.1) installed in end link-boxes (ELB) or in cross-bonding boxes (CBB).

The lack of clear instructions on lengths in the domestic documentation led to the fact that manufacturers of cable terminations and joints began to refuse warranty obligations and write off cases of damage to their products for violation of one or two of the following dubious rules:

- the length of CW should be less than 10 m (sometimes 15 m);
- the length of the CW should not differ in phases.

For example, at the end of 2015, one domestic manufacturer refused to guarantee replacement of a 110 kV cross-bonding joint that had broken through on the reason that the length of the CW from this joint to the CBB with the SA installed in it was 16 m. The danger of a length of 16 m, as we were told, was checked by manufacturer in a special calculation, which was impossible to obtain due to the " permanent illness of the technical staff".

Such stories are by no means uncommon. Due to the lack of information in the norms and having no clear explanations from the manufacturers, we will try to figure out whether there are actually restrictions on the length of CW and the spread of length across the phases of the cable line.

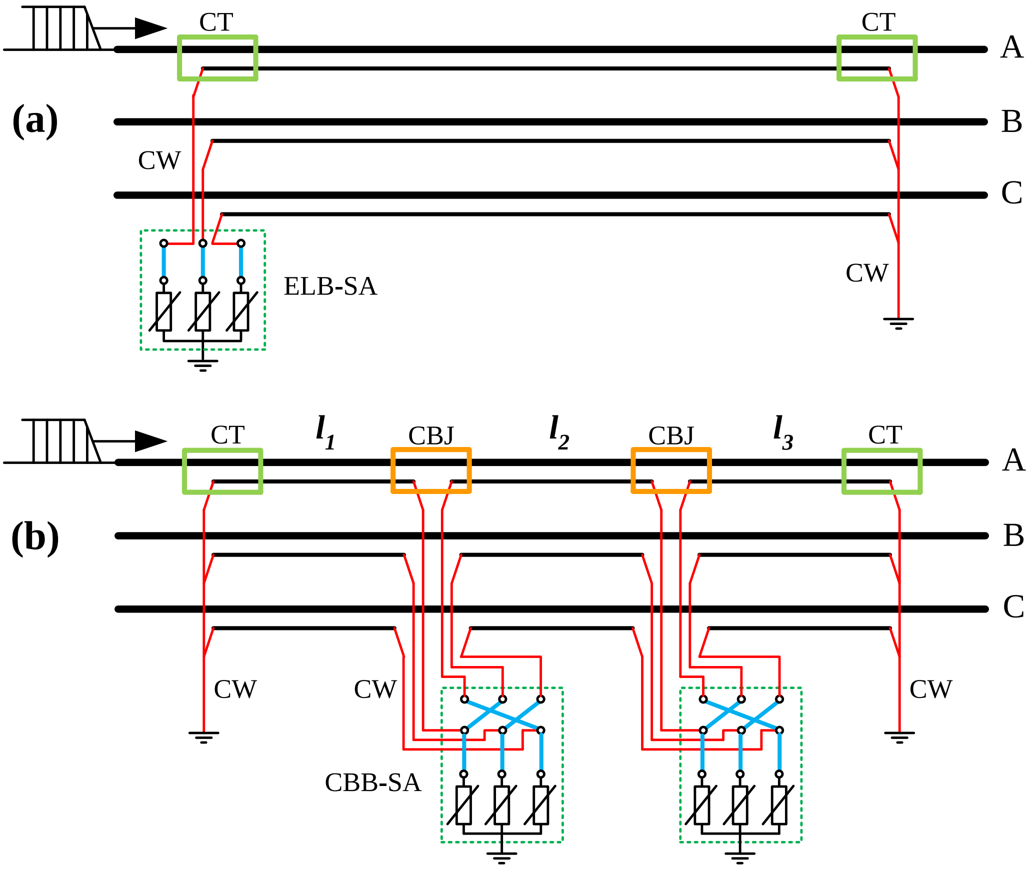

Fig.1. Basic schemes to reduce currents and power losses in single-core cable screens.

2. CAUSES OF VOLTAGE APPEARANCE ON THE CABLE SCREEN

The AC 50 Hz currents passing through the cable cores, by their magnetic field induce in the cable screens an AC 50 Hz voltages and currents, which causes an active power losses. Induced voltages, currents and power losses depend on the bonding/grounding scheme of cable screens and therefore affect the selection of the screens scheme (methodology [3-5]).

The screens bonding/grounding scheme should be such that the AC 50 Hz voltage on the screen relative to the ground does not exceed:

- 100 V in normal operation mode (clause 5.2.3.1 of [1]);
- 5 kV in case of a short-circuit in the network (p.4.2.1.7 and p.4.2.3.4 of [3]).

If the restrictions on the normal mode are related to the safety of people and animals, then the restriction in case of a short-circuit is due to the desire to minimize the risk of a breakdown of the cable outer sheath from the screen to the ground.

In fact, not only operating currents and short-circuit currents cause induced voltages from the cores to the cable screens. Impulse processes characteristic of lightning discharges or switching are also transmitted from the cores to the screens. Since lightning and switching impulse voltages can lead to a breakdown of the cable sheath from the screen to the ground, protective surge arresters (SA), also known as sheath voltage limiters SVL, are installed in the cable screens at the grounding points (Fig.1a) or at the nodes of cross-bonding (Fig.1b).

Thus, the AC 50 Hz induced voltage on the screens is limited by a rational choice of their bonding/grounding scheme, but impulse (lightning and switching) voltages are limited by placing the SA. So, the purpose of having SA in cable end link-box (CLB) or cross-bonding box (CBB) is protection against impulse voltages and nothing more.

3. SA’s CHARACTERISTICS AND CABLE OUTER SHEATH STRENGTH

Traditionally, in the electric power industry, when protecting networks from impulse overvoltages, it is necessary to decide what is the maximum permissible distance at which the SA can still be placed from the equipment. For example, in Chapter 4.2 of the national electrical installation rules (Standard PUE) for various circuits of 35-750 kV switchgear, such distances are given in tabular form, depending on the main influencing factors.

When dangerous level impulse voltages occur, the SA begins to pass current, and this current creates a voltage drop in the wires with which the SA is connected to the protected equipment. As a result, the voltage on the equipment turns out to be higher than on the terminals of the SA, by the amount of voltage drop in the connecting wires. In the case when the length of the wires is large, the voltage on the equipment is unacceptable, posing a threat to insulation. This explains the desire to reduce the length of the connecting wires (CW).

In order to answer the question at what distance it is possible to place screen SA from the cable terminations or cable joints protected by them, it is at least necessary to know the characteristics of the SA and the strength of the cable sheath (its strength in the termination or joint), because in the same rules of the PUE, the distances depend on the type of protective apparatus and the type of protected equipment.

Surge arrester (SA). As a SA for the screen in our country, SA of voltage class 6 kV with an operating voltage of 7.2 kV is most often used. Almost all manufacturers specify SA residual voltage at impulse current of 8/20 μs form with a value of 10 kV. For this current any SA for cable screen has residual voltages less than 23 kV.

Outer sheath. According to clause 4.5.10 [2], the sheath of any single-core cable of class up to 500 kV is periodically tested with DC voltage of 10 kV for 1 min. Unfortunately, there were no figures in the norms that would help to assess the strength of the outer sheath when exposed to impulses or at least when exposed to AC voltage of 50 Hz. At the same time, without these data, it will be difficult to reason about the permissible distances from the SA to the cable termination/joint. Therefore, let's turn to the experience of testing centers and laboratories. Take, for example, the St. Petersburg Polytechnic University and famous KEMA center.

SPbPU. At the Polytechnic University, under the leadership of A.E. Monastyrsky, tests of the 330 kV cable outer sheath with an industrial frequency voltage were carried out. The cable outer sheath withstood AC 50 Hz voltage of 55 kV for hours and wasn't damaged. It was impossible to increase voltage above 55 kV since partial discharges appeared on both ends of cable samples, which were associated exclusively with the way that was used to cut cable samples (without mounting cable terminations). As for the "breakdown strength", it was estimated by experts to be over 100 kV – with such an AC 50 Hz voltage, a breakdown would be formed in a few minutes. Unfortunately, there were no impulse tests of the outer sheath performed on this laboratory.

KEMA. Comprehensive tests of a 220 kV cable line with installed terminations and cross-bonding joints were carried out in the world-famous KEMA laboratory. At AC 50 Hz voltage of 50 kV the breakdown of the cable outer sheath occurred 15 seconds after the start of the tests, and there was no breakdown at voltages of 10, 20, 30, 40 kV. In addition, tests were carried out with a standard lightning impulse of the form of 1.2/50 μs – when exposed to impulses of 170 kV, no breakdown of the sheath was recorded, and further voltage growth in order to find the breakdown voltage was prevented by discharges, which, as in the SPbPU laboratory, were associated with the peculiarities of the end cutting of samples.

Since the thickness of the cable sheath almost doesn't depend on voltage class and is always the same value of about 5 mm (regardless the manufacturer), it is possible to extend the collected test results obtained on several specific cable samples to all others. So, with a certain degree of caution, it can be argued that without any consequences, the outer sheath of any single-core 6-500 kV cable, even slightly damaged during installation, is able to hold:

- over 30 kV of AC 50 Hz voltage "without time limit";
- over 100 kV of the standard lightning pulse of the form of 1.2/50 μs.

Looking at these values, specialists who test cable sheaths on existing cable lines may doubt, because sometimes they fail to raise on the cable sheath even DC voltage of 10 kV, so how then to raise 30 kV (yes, this is AC 50 Hz voltage, but the essence does not change)? Here we can say that in recent years, most of the cases when it was not possible to raise a test DC voltage of 10 kV on the cable outer sheath were not related to the cable itself or its terminations or joints, but to improper installation and subsequent careless operation of the end link-boxes (ELB) and cross-bonding boxes (CBB).

The AC 50 Hz voltage of 30 kV, which is given here, has nothing to do with protection against impulse overvoltages, but is given only to take the opportunity to draw the attention of all interested parties: in case of such a need, it is quite acceptable that in case of network short-circuits, the voltage on the screen relative to the ground is greater than the excessively rigid value of 5 kV specified by standard [3]. From the point of view of the strength of the outer sheath, it would be possible to allow not up to 5 kV, but up to 30 kV and even more. However, at such a high voltage, the 6 kV class screens SA installed in the boxes (with a continuous operating voltage of 7.2 kV) will fail. And at what voltage they will not fail?

Modern SA can withstand AC 50 Hz voltage with a multiplicity of 1.25 pu (relative to their operating voltage) for more than 10 sec, which with a margin exceeds the time of any short-circuit. Therefore, on the screen of any cable for the duration of a short-circuit, it would theoretically be possible to allow AC 50 Hz voltage up to level of $7.2 \cdot 1.25 = 9$ kV. At the same time, cable outer sheath itself withstands more than 30 kV without time limit.

So, when choosing the bonding/grounding schemes of the screens, if necessary, it is possible to increase the limit of AC voltage from 5 kV (as in [3]) to 7 kV and even to 9 kV.

Let us now return to the impulse strength of the sheath – it is assumed that it is at least 100 kV for all 6-500 kV cables when exposed to a standard lightning impulse with a front of 1.2 μs and a half-life of 50 μs. If the residual voltage of SA used in the screens is 23 kV, and the outer is able to withstand 100 kV, then the voltage drop in the connecting wire (CW) between the SA and the termination/joint should not be more than $100 - 23 = 77$ kV, and knowing this value, one could try to estimate the maximum allowed length of the CW.

4. CIGRE TECHNICAL POLICY

Approximately similar arguments are conducted in the relevant working committee of the International Council for Electric Power Engineering CIGRE: knowing characteristics of the SA and the outer sheath, they try to determine the maximum length of the connecting wire (CW) using a very simple formula.

The first thing I want to say is that the main recommendations of CIGRE concern only the cross-bonding nodes, and there is almost no information about one-side grounding of screens. Secondly, when talking about CWs between cable joints and cross-bonding box (with SAs inside), the CIGRE recommendations are focused not on the use of six single-core CWs (as shown in Fig.1b), but on the use of three coaxial CWs (Fig.2). In other words, not two single-core CWs come out of each joint, but one coaxial CW (the inner conductor of coaxial CW is connected to the screen of one section of the power cable entering the joint, and the outer conductor of coaxial CW is connected to the screen of another section).

In the country, CWs are used mainly at facilities where joints of the French company NEXANS are used, while most other manufacturers are focused on single-core CWs that have a small external radius, bend and cut easier. Since CIGRE's headquarters is also located in France, and the main language is French, and only then English, it is not surprising that CIGRE focuses on NEXANS technical solutions. My task is to draw attention of interested parties to the fact that CIGRE materials cannot be widely used in our country, since they are designed for technical solutions which are uncharacteristic for us. Not to mention the fact that they do not have the status of a regulatory document in the country.

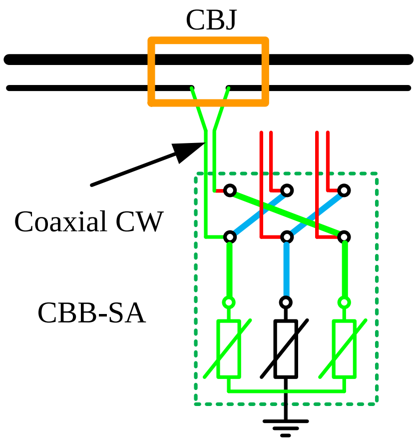

Fig.2. Cross-bonding join is connected with the box by coaxial connecting wire (CW).

In case of using a coaxial CW, a specific task arises – to determine for which impulse voltage the insulation between its two concentrically arranged current-carrying parts should be calculated. To solve it, CIGRE committee proposed the "famous" well-known formula (the designations are preserved):

$$E_{1b} = 2 \cdot \left[U_R + 0.45 \cdot L_b \cdot l_w \cdot \frac{I}{\tau} \right] \qquad (1)$$

where U_R – is the residual voltage of the SA (kV); I is some "incoming" current (kA); τ – the duration of the current wave front (μs); l_w – is the length of the CW of coaxial type (m); L_b – is the inductance of the unit length of the coaxial CW (μH/m).

Formula (1) is not difficult to obtain according to the 2nd Kirchhoff law, written for the contour highlighted in green in Fig.2. The only peculiarity is that in (1), in contrast to the textbook on high voltage engineering, there is an empirical coefficient of 0.45, which was obtained by CIGRE specialists after processing the results of calculations using EMTP.

Having carried out calculations according to (1), CIGRE gives recommendations [6] on the coaxial CW insulation strength (see Table 1). It can be seen that the requirements for the insulation strength of this coaxial CW increase with an increase in its length and with an increase in the voltage class of the power cable. The dependence on CW length is obvious, and the influence of the voltage class is also easy to understand, because for higher voltage lines possible lightning impulses on the cable core are significant, and therefore the induced impulse voltages from the core to the screen are also large, i.e. I/τ in (1).

Although the quality of Table 1 does not cause much doubt, how specific figures were obtained remains a mystery, because it is not clear which in (1) the linear inductance L_b and the rate I/τ of change of the current should be taken.

Table 1. CIGRE recommendations on the insulation strength E_{1b} of the coaxial CW on a standard lightning impulse of the form 1.2/50 μs.

Main insulation class according to GOST 1516.3-96	Lightning impulse according to IEC for main insulation	Coaxial CW insulation requirements	
		Wire up to l_w = 3 m	Wire up to l_w = 10 m
6-35 kV	<325 kV	60 kV	60 kV
110 kV	380-750 kV	60 kV	75 kV
220 kV	850-1050 kV	60 kV	95 kV
330 kV	1175-1425 kV	75 kV	125 kV
500 kV	1550 kV	75 kV	145 kV

The linear inductance L_b of the coaxial CW can be calculated based on data on its design and is usually in the range of values from 0.1 to 1.2 μH/m. The authors (1) claim that the value of 0.24 μH/m was used more often, which corresponds to surge impedance 50 Ω and a wave velocity of about 200 m/μs.

If it is more or less clear with the inductance L_b, then what to take the rate of change of the current I/τ (kA/μs) – not a word is said anywhere. At the same time, the lightning current can have a rate of change at the front from 5 kA/μs to 100 kA/μs. Such a significant spread of current parameters makes it impossible to use (1), and against this background, the figures from Table 1 looks unreasonable and untrustworthy. It is by no means accidental that the requirements of the PUE (national electrical installation rules) for the lightning protection of switchgear were obtained not by formulas at all, but with the involvement of statistical calculations. On the other hand, CIGRE provides us with the formula only.

The CIGRE materials mention a reasonable rule – the shorter the CW from the SA to the joint, the better, but CIGRE does not provide any adequate methods for finding specific limit lengths. The lengths of 3 and 10 m indicated in Table 1 are obviously considered only as an example of using formula (1) and do not mean at all that it is impossible to have CWs with a length of 15, 20, 25 m. Also, nowhere does it say that the lengths of the wires cannot differ in phases, and what to do if the connecting wires (CW) are not coaxial.

For these reasons, the CIGRE materials will not be further considered as they are not containing useful information on the issue of interest.

5. CALCULATION OF IMPULSE VOLTAGES FOR 110 kV CABLE

The mechanism of the appearance of impulse voltages in screens is described, for example, in the 10th chapter [4]. If there were no on-screen SAs at the cable line end (Fig.1a) or at the cross-bonding node (Fig.1b), then the resulting impulse voltage on the cable screen relative to the ground could reach half the voltage on the core and even more. Therefore, there is no doubt about the need to install on-screen SA, but the effectiveness of their work, unfortunately, is reduced due to the presence of CWs that separate the SA from the protected cable termination or cable joint.

As an example, we will calculate the voltage at the cross-bonding node of a 110 kV line 3 km long with 1000/240 mm^2 cables having one full cycle (Fig.1b). We will perform process modeling in the EMTP program, where we will vary the length of the single-core CWs connecting cable joints with SAs which have an operating voltage of 7.2 kV.

In a 110 kV network, the operating voltage can reach 127 kV, and the amplitude of the phase voltage is $127 \cdot \sqrt{2}/\sqrt{3} \approx 100$ kV. When the line is connected to the network, the network operating voltage appears on cores in form of a "step" and its maximum value can reach value of 100 kV. The largest impulse voltage on cable screen will occur on that screen which corresponds to that core where at the time of cable switching the voltage on the cable core was close to the amplitude value (100 kV).

Figure 3a shows two voltage waveforms at the cross-bonding node – one corresponds to the zero length of the single-core CW, and the other corresponds to a huge 100 m length. The actual lengths of the CWs are in the range from 0 to 10-20 m, and the length of 100 m was taken only for the purpose of illustrating the processes more clearly. According to Fig.3a, the screen voltage at the cross-bonding node does not exceed only 40 kV, even for CW of a large length of 100 m. It is also seen that it is about 0.4 of the core voltage.

From Fig.3a, it may seem that screen impulses repeatedly reach the value of 40 kV. It should be said here that traditionally in such calculations it is customary to focus only on the first oscillations. Other impulses (subsequent ones) are not taken into account, since in practice they will not be due to the serious effect of losses and the attenuation they introduce, which, alas, cannot be reliably taken into account in computer programs like EMTP.

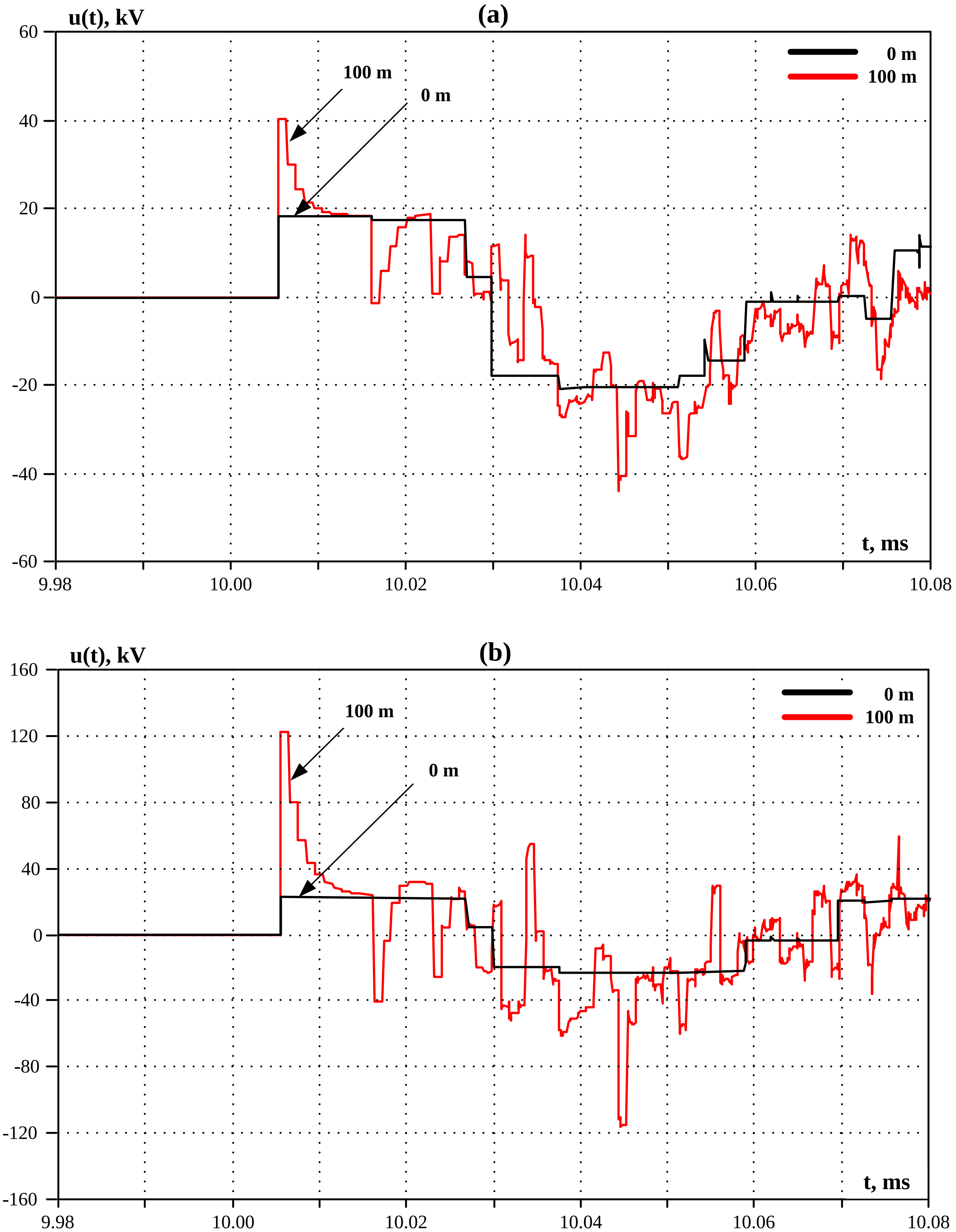

Fig.3. The voltage on the screen of the 110 kV cable line at the screens cross-bonding node, depending on the length of the single-core connecting wire (CW):

(a) – when switching the cable;

(b) – when lightning discharge.

The voltage of Fig.3a is unlikely to pose a danger to the cable sheath and joint, since:

- impulse of more than 100 kV is allowed for the outer sheath, but here we have 40 kV;
- the strength of the outer sheath is tested on a lightning impulse with a duration of 50 μs, and here it is of no more than 3 μs.

Now let's consider lightning processes – they can be evaluated as follows. It is known that if the cable is laid in a network containing overhead lines, then power SAs are installed near the cable terminations to protect them from lightning overvoltages. The residual voltage of the SA 110 kV does not exceed 300 kV, and therefore, to calculate the lightning impulses on the screen in the cross-bonding node, it is enough to switch on the cable core under a DC voltage of 300 kV.

The calculation result is shown in Fig.3b. The highest voltage value on the screen is 120 kV, which is close to the strength of the cable outer sheath, but still hardly dangerous due to the short pulse duration (only 3 μs against the test value of 50 μs). Nevertheless, it is obvious that lightning impulses are more powerful than switching ones and require more detailed study. It can also be noted that in Fig.3b, as in Fig.3a, the impulse voltage on the screen is about 0.4 of the core voltage.

Figure 4a shows the first lightning voltage impulse on the screen, and how it changes as the length of the single-core CW increases from 0 to 100 meters. It can be seen that the maximum voltage value does not change, and all that happens is that the impulse duration gradually increases (the time before its half-life), reaching 3 μs (at 100 m).

A lightning wave that has entered the cable core has a steep front when it was formed as a result of a lightning discharge close to the cable – into the grounded part of the overhead line and subsequent back flashover from the grounded part of the overhead line to the phase conductor. In other cases, the lightning wave does not have a zero-duration front, but some other, finite one. As an example, Fig.4b shows calculations for the case when the lightning voltage on the cable core increased to 300 kV not instantly, but during 2 μs.

Fig.4b shows that an increase in the duration of the wave front from 0 to 2 μs caused a decrease in voltage on the screen, especially noticeable at small CW lengths. For example, with a length of 5 m, the decrease occurred from 120 kV to 30 kV only.

The waveforms of Fig.4a, 4b do not allow us to draw any specific conclusion, except for the already well-known: "the shorter CWs, the better". No one knows where the lightning will strike and what its parameters are, which means no one can be sure whether to substitute a wave front of 0 μs, or 2 μs, or some other in the calculations. Here statistical calculations are required that can take into account all the variety of parameters of lightning waves coming into the cable from the overhead line. They are not difficult to carry out, but they will require time and funding.

In conditions of a significant difference in the shape of real impulses in the screens (short) and test (long), in conditions of uncertainty with the strength of the cable sheath, in conditions of the statistical nature of lightning and its discharge locations, looking at Fig.4a, 4b, it is impossible to draw an unambiguous conclusion that the length of the connecting wire, for example, 5 m is still permissible, and let's say 20 m – no. All that remains is to recommend the use of minimum length, but there can be no question of any prohibition of the use of CWs longer than 10 (15) m: if the circumstances on the construction site required the use of CWs longer than 10 (15) m, then there are no grounds that could prohibit this.

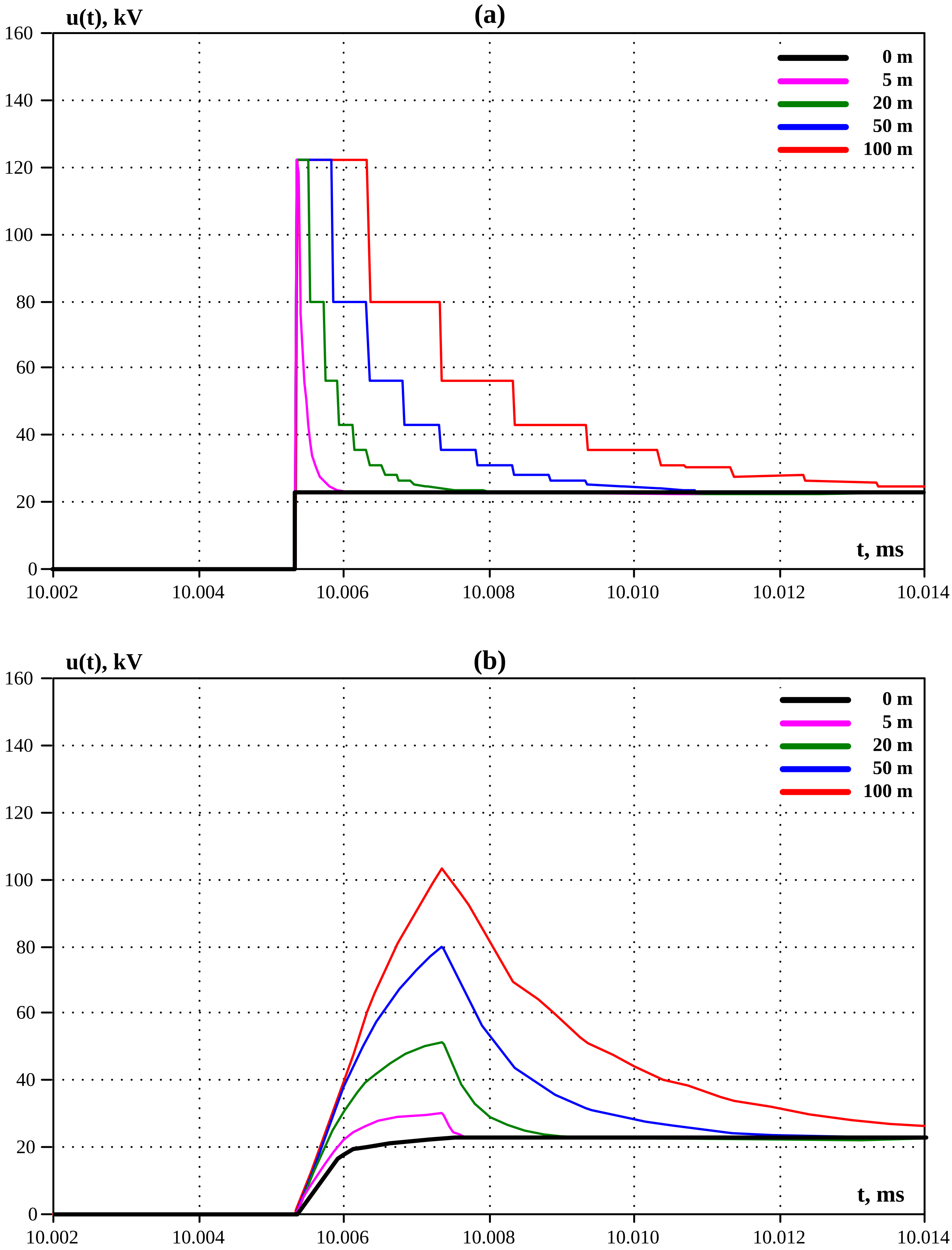

Fig.4. The voltage on the screen of the 110 kV cable line at the screens cross-bonding node, depending on the length of the single-core connecting wire (CW):
(a) – a lightning wave with a front of 0 μs;
(b) – a lightning wave with a front of 2 μs.

6. ESTIMATION OF IMPULSE VOLTAGES FOR 220-500 kV CABLES

Let's look at how the waveforms of Fig.4 change, if we are talking about a 220 kV cable and higher. To protect the 220 kV cable, a 220 kV SA is used with a residual voltage of about 500 kV, and then the voltage at the cross-bonding node can be estimated as $0.4 \cdot 500 = 200$ kV, achieved only in the case of a lightning wave with a zero-duration front. However, for 220-500 kV overhead lines, the insulation strength of overhead lines is so high that the risk of back flashovers is minimal, which means that it is necessary to substitute not a zero-duration front, but another, finite one, in the calculations of processes in the cable, which will reduce the voltage on the sheath from the level of 200 kV to less dangerous.

According to Chapter 4.2 of the PUE, measures should be taken to reduce the risk of overhead line insulation back flashovers and the occurrence of lightning waves with a steep front that can cause dangerous overvoltages on the insulation of switchgear equipment of 35 kV class and above. To do this, small grounding resistances (no more than 10-20 Ω) are provided on the overhead line towers closest to the switchgear, and 1-2 lightning protection wires are also installed.

It was shown above that the risk of back flashovers directly determines the effects on the sheath of the cable adjacent to the overhead line. Consequently, in cases where there is an overhead line of 35 kV class and above, the transition point (tower) between overhead line and cable should also be perceived as a kind of switchgear, and then, as required by the PUE, several overhead line towers adjacent to the transition point should have a grounding resistance of no more than 10-20 Ω and they should be with 1-2 lightning wires. Otherwise, SAs in the screens, even with CWs length of only 5 m, will no longer be able to protect the cable outer sheath and termination/joint, especially for voltage classes of 220, 330, 500 kV.

7. PERMISSIBLE VARIATION IN THE LENGTHS OF CONNECTING WIRES

Several times I heard from people that lengths of all connecting wires (CWs) at the same screens bonging/grounding node should be the same. First of all, considerations are expressed about cross-bonding schemes (Fig.1b), and one can only guess about the reasons for such requirements and the place of their publication (this is definitely not CIGRE).

Impulse processes in each CW occur almost separately from the wires of other phases. Therefore, it all leads to the fact that on the sheath of that phase of the cable and joint, where the CW to the SA is shorter, impulses of reduced magnitude and/ or duration will occur, but there is no problem in this.

At AC 50 Hz, all the CWs, being extensions of the cable screens, are combined into one common connected system, and here, theoretically, one can understand the desire to have all the wires of the same length, because thanks to this, all three cable screens will also be of equal length and will behave like an ideal cross-bonding system. These considerations are essentially a variation on the common misconception that, they say, the screens cross-binding is workable only if the lengths of the three sections l_1, l_2, l_3 are equal (Fig.1b).

Let's consider examples showing that screens cross-bonding perfectly performs all its functions even in the case of a significant difference in the three lengths of l_1, l_2, l_3. For convenience, we borrow the basic data from the example of article [5], where a 10 kV cable line with a length of 6 km was made with 630/95 mm^2 cables laid in a closed triangle, and it turned out to be sufficient for the line to equip one full cycle of screens cross-bonding. The linear voltage induced on the screen was 50 V for every 1000 m of cable length and 1000 A of current in the core.

Example #1. Let a 6 km line be divided into sections of length $l_1 = 2500$ m, $l_2 = 2500$ m, $l_3 = 1000$ m (Fig.1b). Then, in normal mode with the core current $I_C = 800$ A, the AC 50 Hz voltage induced on the screen will be: in the 1st section $U_{S1} = 50 \cdot 2.5 \cdot 0.8 = 100$ V, in the 2nd section $U_{S2} = 100$ V, in the 3rd section $U_{S3} = 50 \cdot 1.0 \cdot 0.8 = 40$ V.

Coefficient of cross-bonding (transposition) [3,4]:

$$K_T = \frac{\sqrt{[U_{S1} - 0.5(U_{S2} + U_{S3})]^2 + \left[0.5\sqrt{3}(U_{S2} - U_{S3})\right]^2}}{U_{S1} + U_{S2} + U_{S3}} = 0.25$$

According to [5], without cross-bonding at all, the relative value of the screen current is $D_I = 0.25$ pu, the absolute value of this current $I_S = D_I \cdot I_C = 0.25 \cdot 800 = 200$ A. After applying the cross-bonding with three sections of different lengths l_1, l_2, l_3., the current in the screen will decrease, not to zero but to a certain value corresponding to the unbalance of the three induced voltages U_{S1}, U_{S2}, U_{S3}.

In conditions of non-ideal cross-bonding, the relative value of the current induced in the screen is $I_S/I_C = D_I \cdot K_T = 0.25 \cdot 0.25 = 0.0625$ pu, absolute value $I_S = (I_S/I_C) \cdot I_C = 0.0625 \cdot 800 = 50$ A. As you can see, due to a non-ideal cross-bonding, the current in the screen decreased from $I_S = 200$ A not to zero, but to $I_S = 50$ A, i.e. 4 times. Consequently, the power losses in the screens decreased by $4^2 = 16$ times – so much so that the main goal of the cross-bonding has certainly been achieved.

Example #2. Suppose, in the conditions of Example #1, on the 3rd section with a length of $l_3 = 1000$ m, the cable phases are laid in a closed triangle only on a segment of 250 m, and 750 m are laid in a bundle of polymer pipes with a diameter of 225 mm each.

For a triangle, the linear induced voltage is 50 V for every 1000 m and 1000 A, and for the pipe section, the ratio $s/d_S = 225/40 = 5.625$ and according to Fig.3 of [5], the linear voltage induced on the screen will already be 150 V. Then, with a normal mode core current of 800 A, the AC 50 Hz voltage induced on the screen for the 1st and 2nd sections, as in Example #1, will be 100 V each, and on the 3rd section there will be $U_{S3} = 50 \cdot 0.25 \cdot 0.8 + 150 \cdot 0.75 \cdot 0.8 = 100$ V, that is, it will coincide with the first two.

The transposition coefficient [3,4] $K_T = 0$, the current in the screen $I_S = 0$, the losses in the screen $P_S = 0$, or, in other words, in the considered case, the cross-bonding behaves as ideal, although the lengths of its 3 sections are seriously different (2500, 2500, 1000 m).

These two examples show that it makes no sense to achieve equality of cable lengths between the nodes of the cross-bonding, if at the same time you do not ask about the methods of laying the phases of the cable and the distances between them. It is also obvious that the difference in lengths in meters and even tens of meters is completely insignificant, because in the examples the difference in lengths reached $l_1 - l_3 = 2500 - 1000 = 1500$ m, and this did not prevent the successful operation of the cross-bonding.

8. CONCLUSIONS

In the bonding/grounding schemes of 6-500 kV cable screens, the wires connecting the on-screen SA with terminations or joints should preferably have a short length of several meters. However, there are no grounds for prohibiting the use of connecting wires longer than 10 (15) m, including in international CIGRE documents.

To increase the reliability of cable lines, especially 220-500 kV, it is recommended to carry out measures on overhead lines next to cable lines: reduce the grounding resistance of the towers to a level of no more than 10-20 Ω, install 1-2 lightning protection wires.

There is no reason to require that in the grounding schemes of 6-500 kV cable screens, the lengths of the connecting wires (CW) should be the same for different phases of the line. One-side grounding of screens or screens cross-bonding remain effective measures to reduce currents and losses in screens, even in cases where the lengths of connecting wires or cables themselves differ by hundreds of meters.

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