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# New method for the selection of the bonding cable and SVL

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## SUMMARY

HVAC cable lines play a key role in the energy system. Despite the fact that cross-bonding of the screens of single-core cables is considered in a number of documents, some issues still need to be clarified there. The purpose of the article is to show the need to use statistical methods for calculating lightning processes in the cross-bonding nodes, to share operational experience that suggests the need for broader consideration of switching processes, and to propose a new rule for selecting operating voltage of sheath voltage limiters (SVL).

The standard requirement to lay bonding cables as close to each other as possible was confirmed using statistical calculations. For this reason, it is necessary to minimize the use of cable joints (and link boxes) in which the inputs of the screens are made in opposite directions. Statistical calculations also confirmed that the length of bonding cables can safely exceed 10-15 m. These values are deemed to be limiting in regulatory documents.

The article calculates the switching processes on one of the lines, and shows why there are risks of damage to the joints located closest to the circuit breaker supplying voltage to the line. The results of such calculations are confirmed by the operating experience of a number of cable lines, where numerous damages to such joints were recorded.

The article also shows what difficulties personnel have if cross-bonding nodes are equipped with SVLs having a standard operating voltage, which is usually about 3-6 kV. Article suggests slightly increasing the operating voltage of the SVL and explains why this is beneficial.

## KEYWORDS

Cable line, single-core cable, XLPE insulation, screen cross-bonding, cable joint, bonding cable, link box, sheath voltage limiter.

## 1. Introduction

The screen cross-bonding of single-core cables is described in CIGRE publications [1-4] and standards IEEE [5-7]. As an example, Figure 1 shows one complete cycle of cross-bonding of screens, assuming that the line is divided into three sections of approximately equal length. The screens of neighboring sections are connected to each other using jumpers located inside the link box, which also has a set of surge arresters (sheath voltage limiters, SVLs) necessary to protect the outer sheath of cables from lightning and switching impulses. The connection of the link box to the joints of the cable line is carried out by bonding cables.

Let us consider the optimal type of joints and link boxes, determine the requirements for the length of the bonding cables between them, as well as select the operating voltage of SVL.

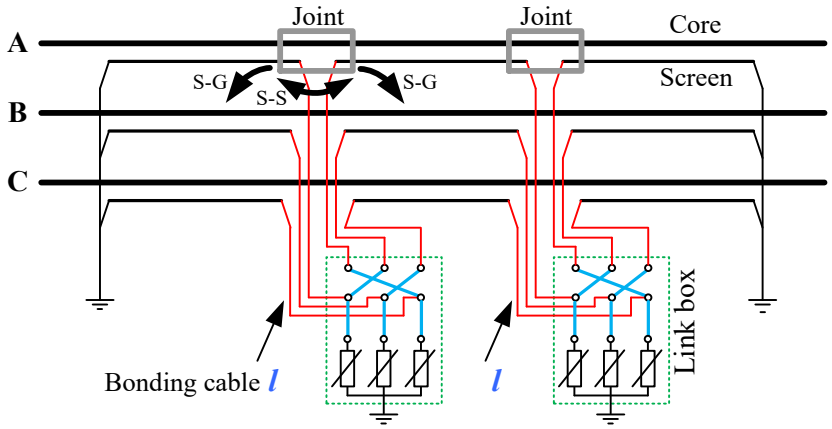



*Figure 1 – One complete cycle of cross-bonding of cable screens*

## 2. Joints, link boxes, bonding cables

Inside cross-bonding joint, cores of two cable sections (left and right) are connected in series to each other. The screens (left and right) are isolated from each other – they are taken out of the joint by so-called bonding cables. There are two possible types of bonding cables:

- coaxial bonding cable which consists of two conductors (core and its screen) of the same cross-section, arranged concentrically (Figure 2a);
- single-core bonding cable which consists of only conductor with no screen (Figure 2b).

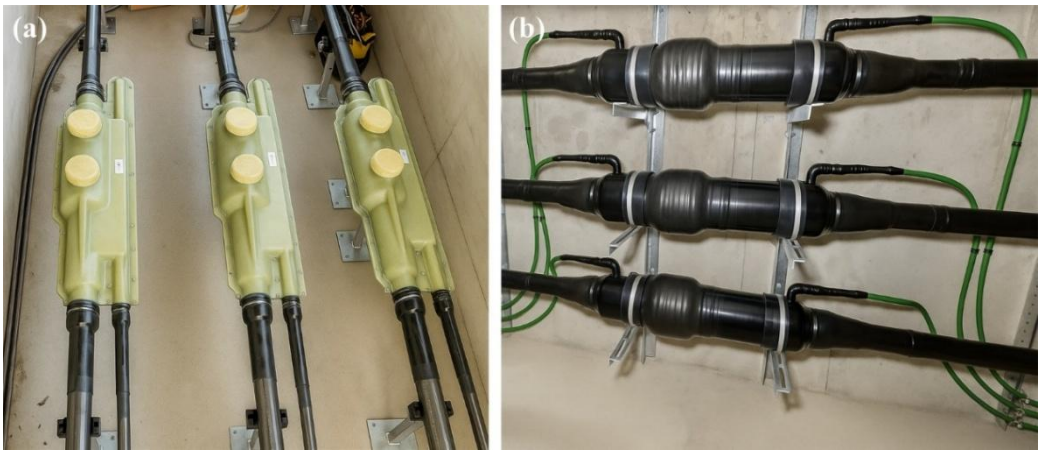



*Figure 2 – Cable joints with bonding cables of different types:*
*(a) – coaxial type; (b) – single-core type*

Bonding cables of single-core type can be taken out from the joint not just in two opposite directions (as shown in Figure 2b), but also in the same direction, and in this case the technical solution turns out to be close to shown in Figure 2a.

A number of different link box designs are known, which differ in the material of the casing, dimensions, number of bolts on the lid, and the way the bonding cables are connected. Let us focus on the way the bonding cables are connected to the link box, from the point of view of location of connection points (holes or bushings) on the box casing. Issues of reliability and tightness of connections to the box will be omitted here.

There are three options:

- for bonding cables of coaxial type: there are three "holes" for inserting bonding cables inside the box, where these cables are cut and connected to six support insulators, which are bonded by jumpers according to the cross-bonding diagram (Figure 3);
- for bonding cables of single-core type: there are six "holes" (or bushings) on the same side of the box casing for inserting wires inside (Figure 4a);
- for bonding cables of single-core type: six "holes" (or bushings) are divided into two equal groups and placed on two opposite side walls of the box casing (Figure 4b).

One additional bonding cable is also connected to each link box (Figure 3-4), which is necessary for grounding of SVLs installed inside the box, but its position does not matter.

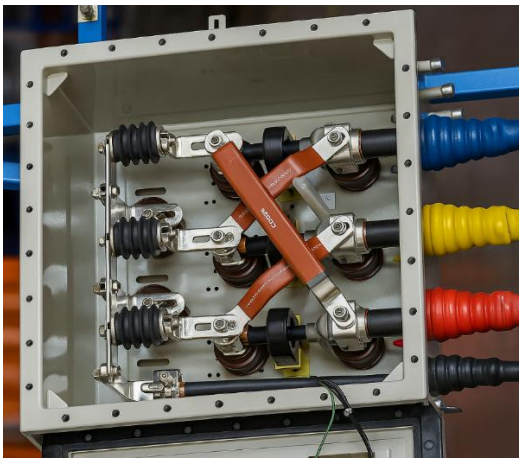


*Figure 3 – Link box for bonding cables of coaxial type*

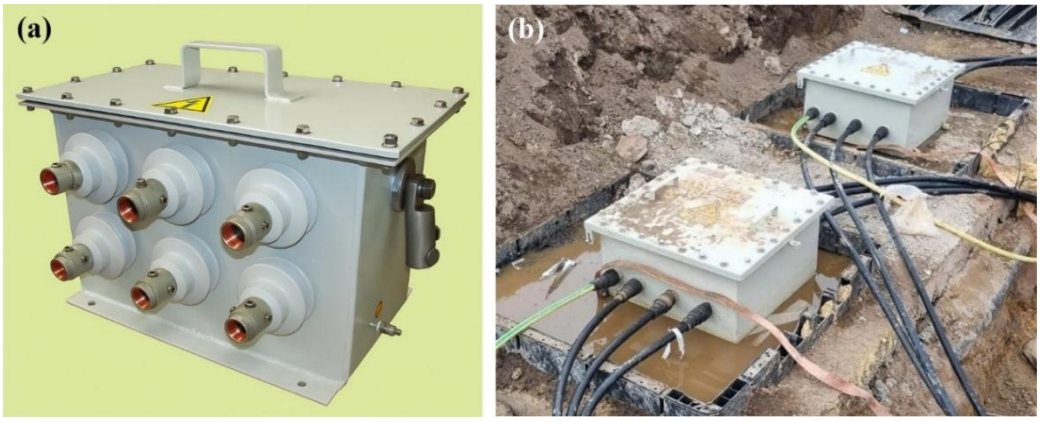



*Figure 4 – Link boxes for bonding cables of single-core type:*
*(a) – bushing on the same side of the box; (b) – bushings on two opposite sides of the box*

Joints shown in the Figure 2 can be connected to boxes shown in the Figure 3-4 using bonding cables of coaxial or single-core type. Possible options for such a connection are shown in Figure 5. Note that if the bonding cables of single-core type are taken out from the joint not in opposite directions (Figure 5b), but in the same direction (from the same side of the joint), then the option Figure 5b will become similar to the option Figure 5a.

At first glance, three options shown in Figure 5 seem to be equal, achieving the same result – screen cross-bonding. However, in fact, these options differ significantly, and to explain this, we will refer to regulatory documents and a series of calculations.

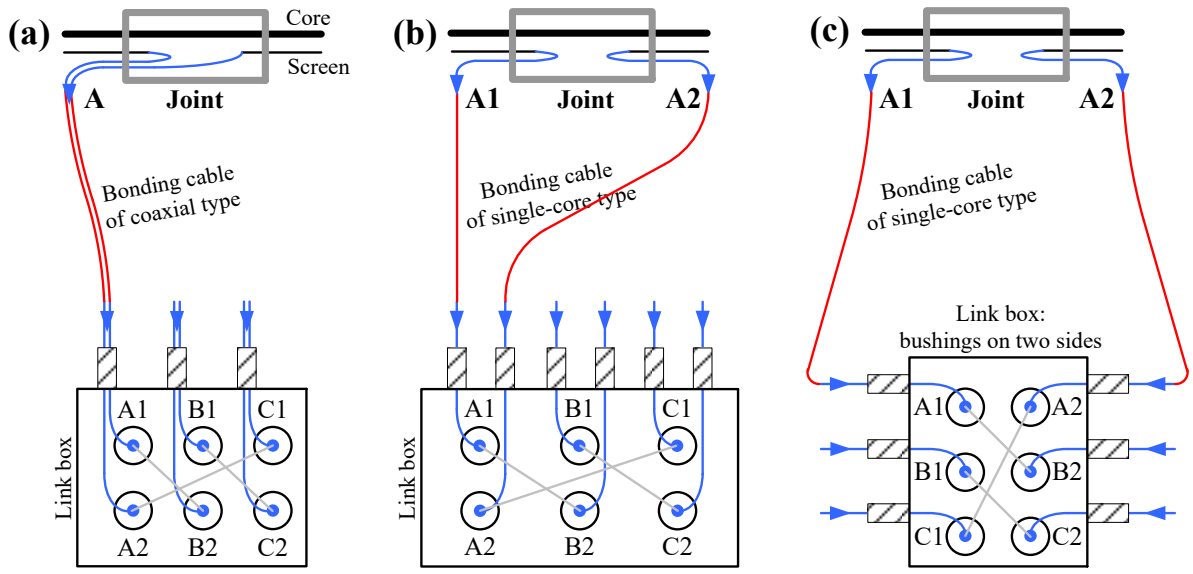



*Figure 5 – Options for arranging the screen cross-bonding node:*
*(a) – bonding cables of coaxial type;*
*(b) and (c) – bonding cables of single-core type.*

## 3. Review of regulatory documents

Comparative analysis of the three options shown in Figure 5 is given in IEEE [5], where clause 7.5.2 clearly states to give preference to bonding cables of coaxial type. Also, in [5] there is a brief guide on how to select the proper bonding cable type to use:

- for bonding cable lengths up to 3 m, single-core bonding cables can be used;
- for lengths from 3 to 10 m, for every joint, two single-core bonding cables twisted around each other should be used, and if it is impossible to twist the cables, then at least they should be placed close to each other and fastened together with ties;
- for lengths from 10 to 15 m, it is strongly recommended to use coaxial bonding cables;
- lengths above 15 m should be excluded.

It can be seen that IEEE [5] recommends placing the bonding cables of the same joint, as close to each other as possible, and it would be ideal combining them into a single bonding cable of a coaxial type. Thus, of the three options shown in Figure 5, standard recommends option (a), while option (b) is allowed only for short bonding cables of not more than 3 m, and option (c) should be excluded. Since the length of the bonding cable usually reaches 10-15 m, it should be recognized by [5] that option (b) cannot be applied as well.

The reason for the need for careful selection of the bonding cable design is explained in another document – CIGRE technical brochure [1]. Here, in clause 4.5.4, the formula for the voltage peak in the joint is given, where voltage is equal to the sum of the residual voltage on the SVL installed in the box and the voltage drop on the bonding cable. According to [1], as well as according to [2], the voltage drop across the bonding cable is directly proportional to:

- the length of the bonding cable (m);
- the linear inductance of the bonding cable (μH/m);
- the steepness of the current front in the bonding cable (kA/μs).

For a cable joint, the inductance of a pair of bonding conductors depends on bonding cable type (one coaxial or two single-core) and the distance between the bonding cables in the pair (if they are of a single-core type). In [1], a very wide range of linear inductance from 0.1 to 1.2 μH/m is indicated, which makes it difficult to use the formula to calculate the voltage in the joint. Another problem with the formula from [1-2] is the statistical nature of the lightning parameters, and, for example, the current steepness required for calculations according to clause 4.2.1 [1] varies in a wide range from 24 to 80 kA/μs and even more.

It can be seen that it is not possible to use the formula [1-2] to calculate the voltage in the joint and verify the validity of the requirements [5] about the length of the bonding cables, their optimal type and position. For this reason, we will check the requirements of IEEE [5] using detailed computer modeling of processes, taking into account the statistical nature of the parameters of the lightning current, as well as taking into account the design of the bonding cables (their inductance will be not set, but calculated automatically by software).

The results of calculations of lightning processes depend on the models of lightning current and circuit elements (overhead line, cable line, ground). These models have been described in many sources and go beyond the scope of this article, the main purpose of which is not to give specific numbers, but to show that almost any model will be more developing for the industry than the established practice of [1-2], according to which the problem is solved by multiplying the cable inductance and the steepness of the lightning current.

## 4. Modeling of lightning processes

Overhead line near switchgear (or near transition tower) normally has a lightning shield wire. This makes it possible to significantly reduce the probability of lightning strike to the phase wire, and to focus the main attention in research on lightning strikes to shield wire or towers.

An additional reason why lightning strikes to shield wire and towers are interesting is that it is precisely with them that lightning waves with an infinitely steep front can form on the phase wires – due to an overlap from the grounded tower to the phase wires, called a back flashover. As a result of the insulation back flashover, the electric potential of the phase wire "instantly" increases from relatively small value to the high potential of the tower, and for this reason a voltage surge with an infinitely steep front appears on the phase wire relative to the ground. Such waves with a steep front propagate along phase wires and the cores of the connected cable, which means they initiate the corresponding steep-front processes in the cable screens creating significant voltage drops on the inductance of bonding cables in cross-bonding nodes. In such processes the steepness of the current impulse in bonding cable can be higher than 24-80 kA/μs discussed in documents [1-2] creating dangerous voltages inside cable joints.

Lightning processes in the cross-bonding node occur when the cable line is connected to an overhead line (OHL), as shown in Figure 6. It is convenient to perform modeling of this circuit in software [8], following the recommendations [9] aimed at statistical calculations. According to [9], the model consists of an OHL and cable, and has an ability to generate lightning strikes to the OHL with parameters according to the statistical data on the lightning current (peak, front, and duration), taking into account many other factors. In fact, we are talking about using the Monte Carlo method to calculate the processes in the cable lines and its cross-bonding nodes. Using this model, it is possible to find the probability of lightning surges of a dangerous peak U on a cable core or screen, including a joint (screen-to-screen or screen-to-ground voltages).

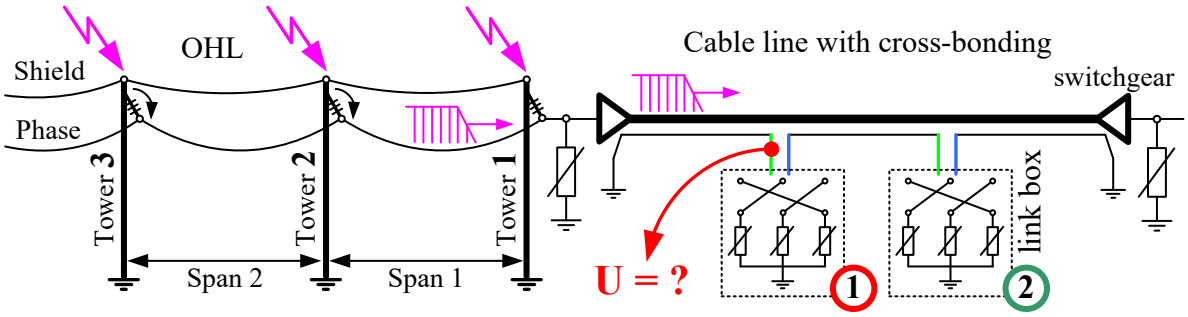



*Figure 6 – The schematic diagram for statistical calculations of lightning overvoltages*

As an example, let us consider a 3 km long 110 kV cable line with a 1200 mm$^2$ copper core and one complete cycle of screen cross-bonding (three sections of 1 km each). Let the cable line be connected to a single-circuit 110 kV OHL which has a lightning shield wire (above three phase wires A, B, C) and a distance between the towers of 300 m. A grounding impedance of the towers is assumed to be 0.5 Ω for Tower 1 (transition tower) and 10 Ω for all other towers.

At the junction of the overhead line and the cable line (and at the end of the cable line where it is connected to switchgear) there are surge arresters (residual voltage of 250 kV at 8/20 μs current impulse with a peak of 10 kA). At cross-bonding nodes 1 and 2, there are SVLs installed in link boxes (residual voltage of 23 kV at 8/20 μs current impulse with a peak of 10 kA).

Other parameters of the model, not mentioned above, were taken from [9]. The lightning current was modelled as an impulse with zero initial derivative, the insulation of every insulator string was presented by its volt-second characteristic, OHL towers were as a set of inductances, OHL wires had an impulse corona, surge arresters and SVLs were resistors with nonlinear voltampere characteristics. If required, it was possible to take parameters other than [9].

Figure 7 shows the results of calculations of the probability P that the peak value of the screen-to-ground lightning impulse U in the joint will exceed the value from the abscissa axis. The location of the lightning discharge to the overhead line varies in the calculations.

The impulse strength of the outer sheath (of the cable and joint) is always a debatable issue. Based on provisions [10], let us assume there that a lightning impulse with a peak value of 75 kV is acceptable between the screen and the ground for a 110 kV joint (this is higher than per [5]). Then, with the help of Figure 7, we can see that dangerous surges (greater than 75 kV) occur only in the case of a lightning discharge to Tower 1, that is, to the transition tower.

The calculations of Figure 7 were carried out for the case when bonding cables were of single-core type and arranged in pairs, close to each other. The length of bonding cables was

assumed to be 30 m, despite the fact that, in practice, such lengths couldn't be found. It was done to show that even with such significant lengths, only lightning strike directly to the tower of the transition point (Tower 1) pose a danger to the joints, and not to subsequent Towers 2, 3. At the same time, the probability of 0.04, shown in Figure 7, means that the danger to the joints occurs only in one case out of 1/0.04=25 lightning discharges to Tower 1. Having data on lightning activity in the area (a number of lightning discharges per line tower per year or over the lifetime of the line), we can recalculate the axis ordinate (probability P) to absolute values.

Figure 8 is valid only for the case of lightning discharge to the transition Tower 1, since it poses the main danger to the joint. There are two options presented in Figure 8:

- two single-core bonding cables in a pair (of the same joint) are located close to each other (the marked point for the length of 30 m is the same as shown in Figure 7);
- two single-core bonding cables in a pair (the same joint) are located at a 0.5 m distance.

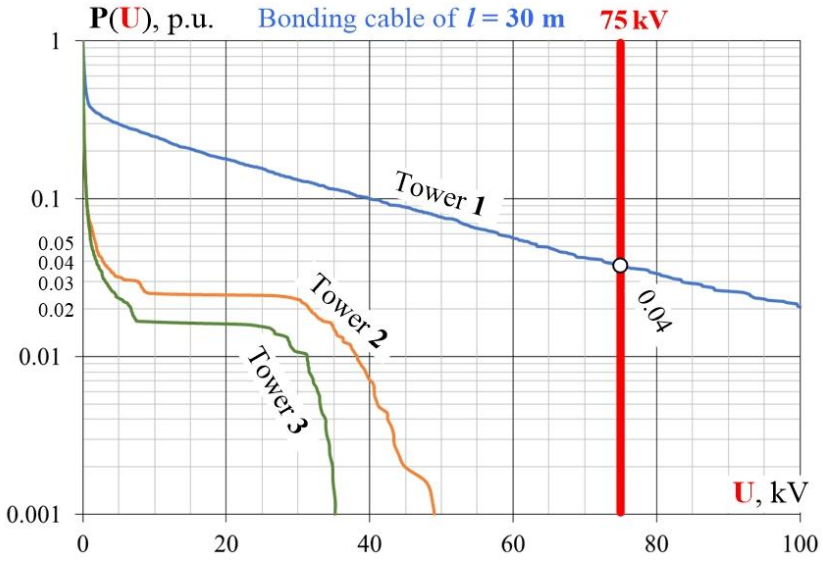



*Figure 7 – The probability of damage to the cable joint during lightning discharges into different towers of overhead line (bonding cables of single-core type have a length of 30 m)*

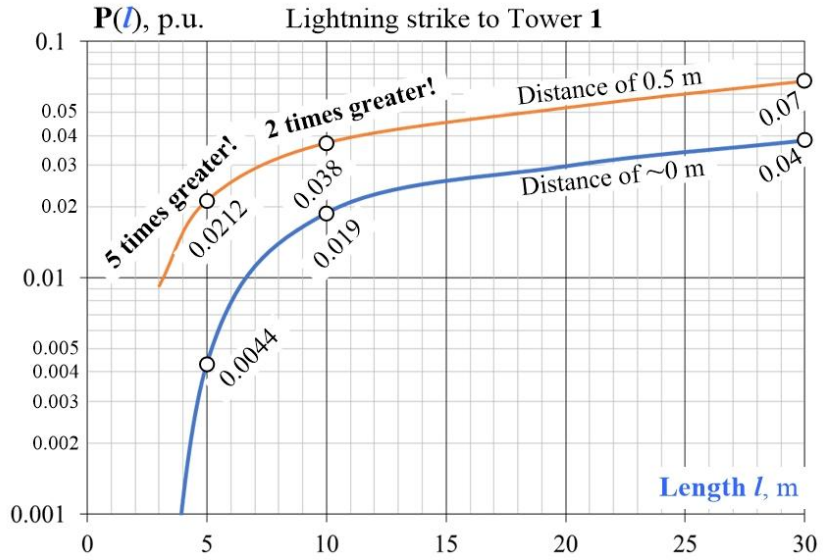



*Figure 8 – The probability of damage to the cable joint during lightning discharges into Tower 1 (bonding cables of single-core type have a variable length)*

It can be seen from Figure 8 that increasing the distance between the bonding cables (from 0 to 0.5 m) increases the probability of occurrence of dangerous lightning impulse in the joint, by several times (up to 5). Thus, it is possible to confirm the provisions of IEEE [5], which strongly recommend laying a pair of bonding cables of the same joint as close to each other as possible, and ideally replacing two bonding cables with one bonding cable of a coaxial type.

One of the conclusions that can be draw there, based on IEEE [5] and Figure 8, is that the following options are not so good to have:

- cable joint of the design shown in Figure 2b;
- link box of the design shown in Figure 4b.

Another interesting conclusion can be drawn from Figure 8, which, however, to some extent contradicts IEEE [5] and CIGRE [1-2] – even if the bonding cable length is $l = 30$ m (that is 2-3 greater than recommended limit of 10-15 m), nothing special will happen. The only thing is that the probability P will increase by 2 times (from 0.02 to 0.04) but it's not much to worry about. So, statistical calculations of lightning processes show the need for revision of the rule which almost prohibits to have bonding cable length of more than 10-15 m. It can be seen from Figure 8 that, if required, the length of the bonding cable can be higher than 10-15 m, without fatal consequences (the limiting length will depend on the model being used). However, for a definitive answer to this question, it is important to take into account not only lightning, but also switching processes (which for some reason are not mentioned at all in IEEE and CIGRE).

## 5. Processes when switching the line

As it was shown above, documents [1-7], determining the length and type of bonding cables, mainly consider lightning processes. At the same time, most of the lines are in the centre of the megapolis, without the possibility to have lightning, and then it remains unclear what guidelines to follow when selecting the length of the bonding cables? As part of the answer to this question, it was proved in [10] that the main factors to select the design of cross-bonding nodes are:

- lightning processes, for lines of 110 kV and below;
- switching processes, for lines of 220 kV and above.

Such assumptions are confirmed by operational experience. For example, Figure 9 presents the damaged 220 kV joint of cross-bonding type from one of the city lines. There were several damages on this line at the same conditions – they happened at the moment of turning the line on, and all of these joints were closest to the circuit breaker that supplied voltage to this line. The line was in the center of the megapolis, without possibility to have lightning processes. It is important to note that joints were made by one of the leading European manufacturers, and installed by highly qualified specialists. The length of the bonding cables was less than 10 m.

The repeated damages to joints can be explained as follows – when switching the line on, the phase-to-ground voltage wave (created by the circuit breaker) initially has an infinite steepness. As this wave propagates along the line, its front loses steepness. So, the cable joint located first on the way of the switching wave along the line was damaged – since the network voltage wave came without having enough time to reduce its high steepness.

It can be shown that the steepness of the impulse arriving at cross-bonding node 1 may even be infinite, or at least many times higher than during lightning. Then why do IEEE and CIGRE only mention lightning processes which are impossible to have for most of cable lines?



*Figure 9 – Cable joint (closest to circuit breaker) after switching on the 220 kV cable line*

In general, the steepness of the switching impulse on the screens at the cross-bonding node depends on many factors, including:

- the number and rated power of transformers on the busbars of switchgear;
- the number of other cable lines on the busbars of switchgear;
- the distance to the first cross-bonding node (node 1);
- the type of switching process (the presence of initial electric charge on the line);
- the circuit breaker adjustment (the time shift between the phases A, B, C).

Speaking about the shift in the operation of circuit breakers of phases A, B, C, it should be understood that we can talk not only about the different operation of the motor drives, but also about the fact that due to a 120° shift in the phase processes, the breakdown of the gap between the contacts in each of the phases A, B, C can occur at its own unique moment.

An example of a calculation for the switching impulse inside the joint (at a screen-to-screen gap) is shown in Figure 10, obtained by [8] for a 3 km long 220 kV line. It can be seen that the most dangerous impulses appear in the first cross-binding node (closest to the circuit breaker).

Figure 10 shows clearly that attention should be paid not only to lightning processes, but also to switching (or just switching, because lightning processes simply don't exist for most cable lines). Consideration of switching processes is especially important for 220-500 kV cable lines, and under certain conditions such processes can be dangerous, first of all, for those joints that are closest to the circuit breaker, even despite the small length of the bonding cables.

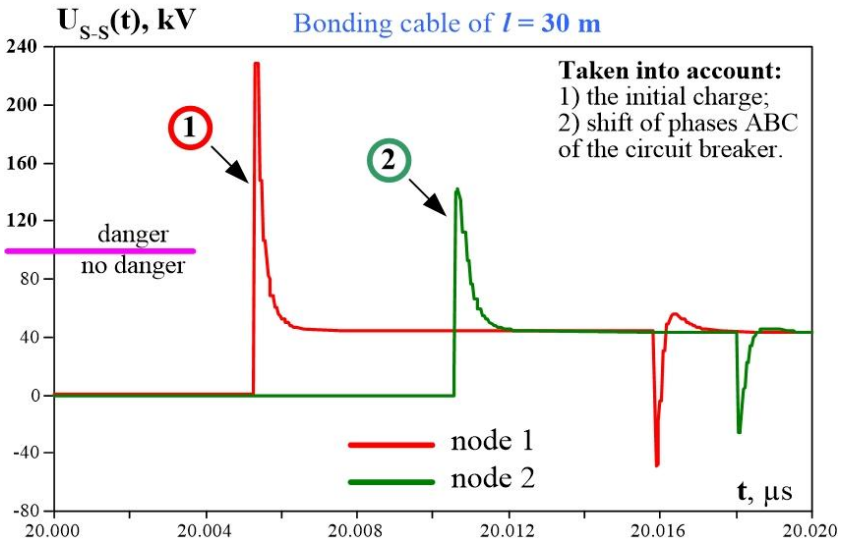



*Figure 10 – Processes in cross-bonding nodes 1 and 2 when energizing a 220 kV, 3 km line*

## 6. Selection of SVL

One of the important issues related to the design of cross-bonding node is the selection of SVL, or rather its operating voltage and energy absorption capability [10]. Usually, the higher the SVL operating voltage, the lower the impulse currents pass through the SVL and the lower the energy released in the SVL. Usually, SVLs with an operating voltage of 3 to 6 kV are used.

The integrity of the outer sheath of power cables must be checked on different stages of the cable line construction and, then, periodically after its commissioning. To do this, the cable is disconnected, the screen is ungrounded at both sides of the line, and a DC voltage of 10 kV is applied between the screen and the ground, usually for 1 minute. The problem is that SVLs of 3-6 kV installed in link boxes open from such a DC test voltage, conduct current, and the line seems to be defective. To prevent this, every time before applying DC 10 kV, it is required to open all the boxes and disconnect all the SVLs from them. This is a lot of work, especially if there is not one complete cross-bonding cycle (Figure 1), but several (many boxes).

A link box can be placed above the ground (Figure 11a) or below (Figure 11b). In the second case, the box is often flooded. To open the box, personnel have to pump out the water from the manhole. This makes it even more difficult to prepare for the DC 10 kV sheath tests. Moreover, a repeated opening/closing of the lid of the box leads to a gradual loss of its tightness, and, as a result, water penetrates into the box and interferes with operation of cross-bonding. Also, there is a problem that water from the box, using a bonding cable, may penetrate the joint.

Our experiments showed that an SVL does not interfere with the sheath DC tests, if operating voltage of SVL is increased from typical 3-6 kV to 8.0-8.5 kV. It was proven that an SVL with an AC 50 Hz operating voltage of 8.0-8.5 kV, when exposed to a DC voltage of 10 kV, passes a DC current of only a few tens of μA, which is not enough to interfere with cable sheath tests. This means that it is not necessary to climb into the boxes and break their tightness.

Such a special SVL protects the cable outer sheath from impulses a little worse compared to a typical SVL. However, this is barely noticeable, because the voltage inside the joint is mainly determined not by SVL's residual voltage, but by the voltage drop on the bonding cables. This conclusion was confirmed by statistical calculations of transient processes, similar to those shown in Figures 7-8. Such calculations, due to a limited space, were not included in this article, but show that the indicated slight increase in the operating voltage of the SVL has no noticeable effect on the probability P of dangerous overvoltages in the cable joint.




*Figure 11 – Typical installation locations of link boxes:*
*(a) – above the ground; (b) – underground, in a manhole*

It is important to note that, if the special SVL remains connected inside the box during 10 kV DC sheath tests, then personnel should check the sheath and the SVL simultaneously. Tests of the sheath and the SVL turn into one common procedure which simplifies line maintenance.

## 7. Conclusions

Statistical calculations of lightning processes in cross-bonding nodes have noticeable advantages over calculations using a formula [1] where it is required to put a specific value of the steepness of the lightning current (which is difficult to be sure of) and ignore other parameters of the lightning, such as its peak value and duration. An example of statistical calculations performed is presented in the article and shows, for example, that from the point of view of lightning processes, the length of the bonding cable, if necessary, can be more than 10-15 m (stated in [5]) without any fatal consequences for the joints.

It is shown that when analyzing the processes in the cross-bonding nodes of 220-500 kV cable lines, it is important to pay attention to switching processes, which is not reflected in the standards. Such processes lead to the formation of waves with a steep front, which can be more dangerous to joints than during lightning processes. The joints closest to the circuit breaker are at greater risk than others, almost regardless of the bonding cable length.

It is proposed to adjust the SVL operating voltage selection rule so as to simplify testing of the cable outer sheath with DC 10 kV voltage and to reduce the number of operations with SVLs and link boxes. It will also reduce the risk of water entering the box and cable joints.

**BIBLIOGRAPHY**


[1] CIGRE Technical Brochure TB 283 "Special bonding of high voltage power cables", October 2005.

[2] A. Khamlichi, G. Denche. F. Garnacho and others. "Location of sheath voltage limiters (SVLs) used for accessory protection to assure the insulation coordination of cable outer sheath, sectionalizing joints and terminations of high voltage cable systems". CIGRE session, Paris 2016, paper B1-108.

[3] CIGRE Technical Brochure 797 "Sheath bonding systems of ac transmission cables – design, testing, and maintenance", March 2020.

[4] CIGRE Technical Brochure 889 "Installation of underground HV cable systems", January 2023.

[5] IEEE Std 575-2014 "Guide for bonding shields and sheaths of single-conductor power cables rated 5 kV through 500 kV".

[6] C 55 "Insulated sheath power cable systems", Energy Network Association (ENA), UK, 2014.

[7] STO 56947007-29.060.20.071-2011 "High voltage 110-500 kV cable lines. Conditions of creation. Norms and requirements", Moscow, 2011.

[8] EMTP – Electro-magnetic transient program.

[9] M. Dmitriev "Lightning overvoltages in high voltage switchgear"– Porto, 2025. -68 p.

[10] M. Dmitriev "High voltage cable lines". -Porto, 2021. -690 p.