Transient Overvoltage Distribution in Sectionalized Screens of HV Joints

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ABSTRACT

The overvoltages between screens of the sectionalized joints depend not only on the chosen surge voltage limiters, but also on the type of bonding lead cable used to connect them. Connection cables of unipolar type instead of coaxial lead to higher overvoltages. This negative influence is accentuated the longer the length of the bonding lead cable. This article demonstrates the use of unipolar cable is equivalent to increasing the length of the cable more than 5 times that of the coaxial cable. The article also analyses the voltage distribution between each screen of a joint with respect to earth.

KEYWORDS

Sectionalized joints; surge voltage limiters, link-boxes, bonding lead cables, transient overvoltages, lightning.

INTRODUCTION

The protection against fast transient overvoltages between metal sheaths of sectionalized joints used in cross-bonding and single-point bonding system is carried out by means of surge voltage limiters (SVL) arranged inside link-boxes. The selection of the SVL is performed taking into account the maximum temporary overvoltage that can appear in the cable system [1]. Analytical equations for the transient sheath-overvoltages of atmospheric origin were deduced in [2], in which formulas to determine the overvoltage between sheaths of sectionalized joints were presented for different cases, as analytical functions depending on the length of the bonding lead cable between the sheaths and SVL in order to ensure an appropriate protection margin for the insulation of the cable accessories. However no formulas were established for the voltage distribution between one and another sheath of the sectionalized joint.

Furthermore, it is possible to evaluate the overvoltages between sheaths and between sheaths and ground, using electromagnetic transients software (ATP), but it is not easy to determine the voltage distribution that appears on each sheath.

The limited transient overvoltage between sheaths of sectionalized joints depends on the type of bonding lead cable used to connect them to the surge voltage limiters (SVL) placed in the link-box (unipolar bonding lead cable or coaxial bonding lead cable) and its length.

It is known that the overvoltage is lower when coaxial bonding lead cables are used, but it is not well known the voltage distribution between one and another sheath. This voltage distribution depends on whether the metal sheath of each side of the sectionalized joint is connected to the inner conductor or to the outer conductor of coaxial bonding lead cable.

In addition, the voltage distribution between sheaths is different depending on whether it is a joint arranged as a cross-bonding bonding system, where the metal sheath of each side of the joint is connected to a SVL, or whether it is a joint arranged as a single-point bonding system, in which the metal sheath of one side of the joint is connected to a SVL and the other side is directly connected to earth.

The effect of the length of the bonding lead cable in the transient overvoltage distribution should also be considered, as well as the effect of using limiters of different rated voltage to achieve an appropriate limited overvoltage at each sheath.

The paper presents an analysis of the transient overvoltages transmitted through a cable system and how they are distributed at metal sheath of each side of the sectionalized joint taking into account the influence factors indicated above.

ANALYSIS OF OVERVOLTAGE DISTRIBUTION ON CABLE SHEATH

The analysis of the overvoltage distribution on cable sheaths is supported by the results of a set of laboratory tests carried out on a 66 kV cable system (cable + sectionalizing joint). The testing setup is composed by a sample of cable (66kV 1x1000Al+H135) of 50 m length, in which a sectionalizing joint was assembled in the middle of the cable. Lightning impulses 1,2/50 up to 1,5kV were applied between conductor and the cable sheath at one cable end for two configurations of bonding lead cables (coaxial and unipolar) used for cross-bonding or single-point bonding system:

a) Coaxial bonding lead cable to link:
- Each metal sheath of the sectionalizing joint connected to a different SVL simulating a cross-bonding system.
- One metal sheath of the sectionalizing joint connected to a SVL. The other connected to earth, simulating a single-point bonding system.

b) Unipolar bonding lead cable:
- Each metal sheath of the sectionalizing joint connected to a different SVL simulating a cross-bonding system.
- One metal sheath of the sectionalizing joint connected to a SVL. The other connected to earth, simulating a single-point bonding system.

The overvoltages between sectionalized sheaths can be calculated by formulas (1) to (4) introduced in [2] and the ones between cable sheath and earth are given by the in formulas (5) to (8), in which the voltage distribution factor K_{emp_cb} and K_{emp_cb} can't be easily estimated.

Table 1. Overvoltages on cable sheaths.

Overvoltage on cable sheaths	Cross-Bonding	Single-point
Between sheaths for coaxial bonding lead cable:	$U_{ss\_c\text{-}cb}$ (1)	$U_{ss\_c\text{-}sp}$ (2)
Between sheaths for unipolar bonding lead cable	$U_{ss\_u\text{-}cb}$ (3)	$U_{ss\_u\text{-}sp}$ (4)
Between sheath and earth for coaxial bonding lead cable:	$U_{se\_c\text{-}cb}$ (5)	$U_{se\_c\text{-}sp}$ (6)
Between sheath and earth for unipolar bonding lead cable	$U_{se\_u\text{-}cb}$ (7)	$U_{se\_u\text{-}sp}$ (8)

$$U_{ss\_c\_cb} = 1.035 \cdot \left(2 \cdot U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot L_b}{Z_1} \cdot \frac{BIL}{\tau} \right) \quad (1)$$

$$U_{ss\_c\_sp} = 1.035 \cdot \left(U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot L_b}{Z_1} \cdot \frac{BIL}{\tau} \right) \quad (2)$$

$$U_{ss\_u\_cb} = 2 \cdot U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot L_b}{Z_1} \cdot \frac{BIL}{\tau} \quad (3)$$

$$U_{ss\_u\_sp} = U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot L_b}{Z_1} \cdot \frac{BIL}{\tau} \quad (4)$$

$$U_{se\_c\_cb} = K_{emp\_cb} \cdot U_{ss\_c\_cb} \quad (5)$$

$$U_{se\_c\_sp} = K_{emp\_sp} \cdot U_{ss\_c\_sp} \quad (6)$$

$$U_{se\_u\_cb} = K_{emp\_cb} \cdot U_{ss\_u\_cb} \quad (7)$$

$$U_{se\_u\_sp} = K_{emp\_sp} \cdot U_{ss\_u\_sp} \quad (8)$$

Where:

- U_{ss}: overvoltage between cable sheaths on the sectionalized cable joint.
- U_{se}: overvoltage between a cable sheath and earth on the sectionalized cable joint.
- U_{res}: residual voltages of the surge voltage limiter.
- L_b: inductance per unit length of the bonding lead.
- L: length of the bonding lead.
- Z_1: characteristic impedance of the power cable.
- BIL: insulation level at lightning impulse.
- τ : front time of a standardized lightning impulse.
- PM_c: minimum protection margin (p.u)
- β_0 is the refraction coefficient of the lightning impulse.

The k_s factor can be introduced in the previous formulas in order to take into account the relationship between the actual inductance per unit length of a generic bonding lead and a perfect connection using a coaxial bonding lead $L_{b\text{-}coaxial}$. This factor depends on how the sectionalizing joint is designed from the point of view of the way the bonding lead is connected to the sectionalized sheaths: directly or by means of additional unipolar cables and the type of the bonding lead (coaxial or unipolar). Formulas (1) to (4) change to the new expressions:

$$U_{ss\_c\_cb} = 1.035 \cdot \left(2 \cdot U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot k_s \cdot L_{b-coaxial}}{Z_1} \cdot \frac{BIL}{\tau} \right) \quad (1bis)$$

$$U_{ss\_c\_sp} = 1.035 \cdot \left(U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot k_s \cdot L_{b-coaxial}}{Z_1} \cdot \frac{BIL}{\tau} \right) \quad (2bis)$$

$$U_{ss\_u\_cb} = 2 \cdot U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot k_s \cdot L_{b-coaxial}}{Z_1} \cdot \frac{BIL}{\tau} \quad (3\text{-bis})$$

$$U_{ss\_u\_sp} = U_{res} + \frac{\beta_0}{(1+PM_c)} \cdot \frac{L \cdot k_s \cdot L_{b-coaxial}}{Z_1} \cdot \frac{BIL}{\tau} \quad (4\text{-bis})$$

It is important to note that the inductance per unit length of the bonding lead is made up of an internal part of the connection, k'_s and an external part, k''_s, which represents the bonding lead itself. The weight factor w takes into account the relationship between the lengths of both parts. The following expression allows keeping in mind the influence of these two terms

$$k_s = k'_s + k''_s \quad (9)$$

where

$$k'_s = \frac{L_{b-joint} \cdot w}{L_{b-coaxial}} \; ; k''_s = \frac{L_{b-lead}}{L_{b-coaxial}}$$

The parameter k'_s depends on the design of the sectionalizing joint, the better the lower this coefficient is, while the parameter k''_s depends on the type of connection established in the installation project for the bonding lead, for an optimal installation project $k''_s=1$ (bonding lead is a coaxial cable).

TESTING SETUP

Figure 1.a and 1.b show the sectionalizing joint assembled in the middle of the power cable (25 m at each side of the sectionalizing joint), the link box with connected SVL's (case of a cross bonding configuration is shown) and the different points where transient measurements were conducted for coaxial and unipolar bonding lead respectively.

Lightning impulses are injected at a cable end, while for the other cable end a matching resistor (~18Ω) is connected. Overvoltages at both sectionalized cable sheaths and at the SVL's are measured to evaluate k_s and K_{emp}.

Table 2 shows the main characteristics of the components used of the testing setup: Power cable, coaxial and unipolar bonding leads and the sectionalizing joint.

Table 2. Power cable, coaxial and unipolar bonding lead cables characteristics.

Component	Denomination	Manufacturer
Power Cable	66 kV: RHZ1-RA+2OL(AS) 36/66 kV 1x1000KAl+H135	GENERAL CABLE
Coaxial bonding lead cable	RHZ1-2OL 12/20 kV 1x150/150 mm2 Cu2	GENERAL CABLE
Unipolar bonding lead cable	RHZ1 (S) 6/10 kV 1x185 mm2 Cu2F	GENERAL CABLE
Sheath-sectionalizing joint	MSA72-XKR/S	PFISTERER

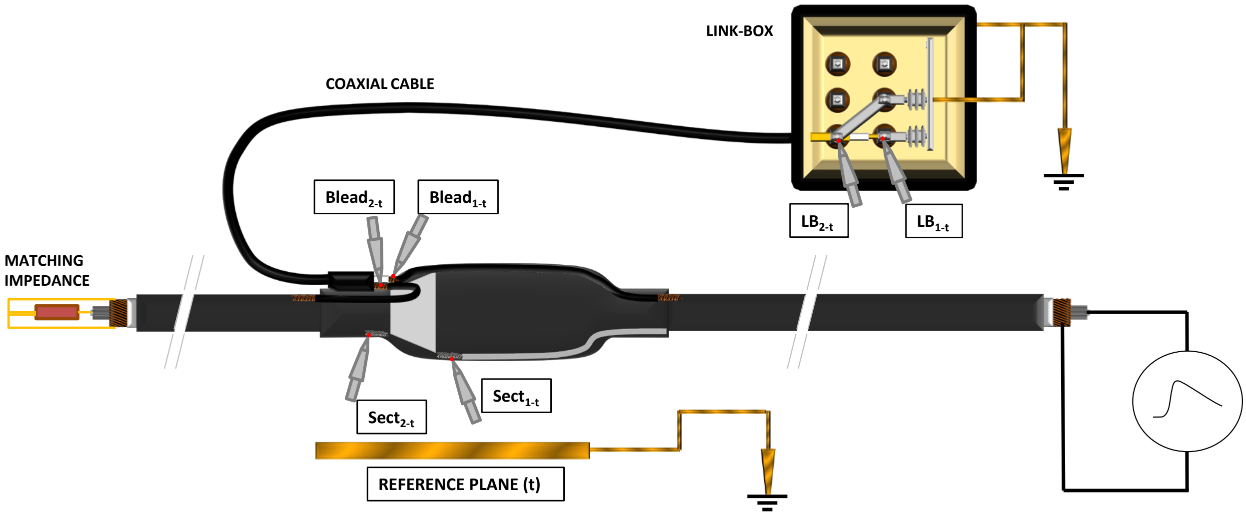


Fig. 1.a. Test setup for coaxial bonding lead.

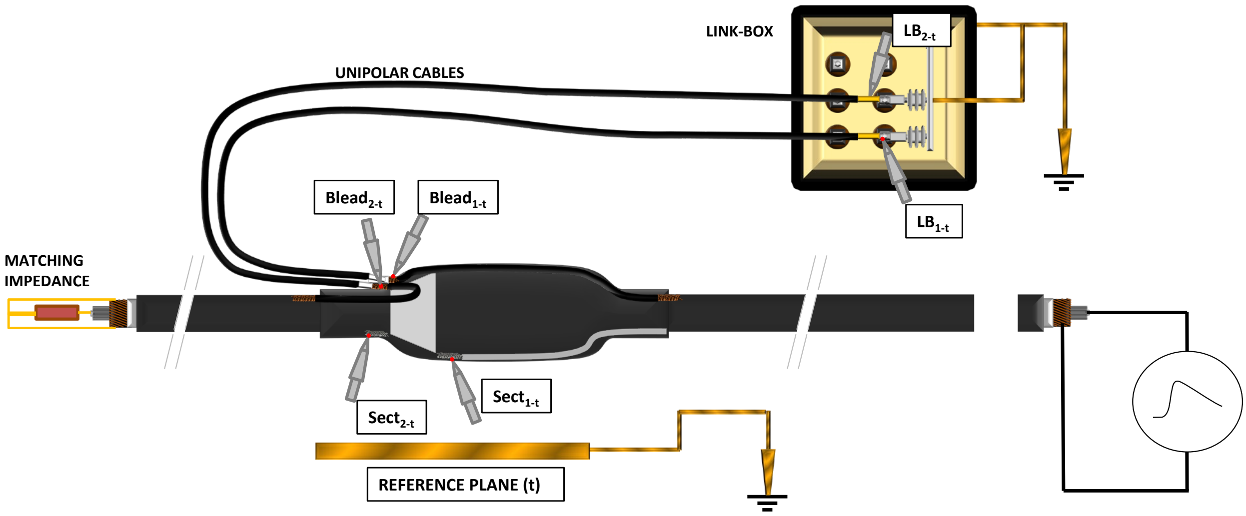


Fig. 1.b. Test setup for unipolar bonding lead.

TESTS AND MEASUREMENTS

Preliminary tests

A set of preliminary measurements were conducted in order to obtain the characteristic impedance, Z_1 of the power cable and the per unit length inductance, L_b of the bonding lead. For this purpose, frequency sweeps were carried out between 100 Hz and 100 kHz (see figure 2).

The characteristic impedance of the power cable, Z_1, was determined by means of the cable parameter values measured for the frequency of 100 kHz (see Figure 2). The obtained value was of 17.8 Ω.

The 100 kHz results of the inductance per unit length of a coaxial bonding lead are summarized in Table 3 and for two unipolar bonding leads in Table 4. In the Table 4 different L_b values are presented because L_b depends on the different kind of layouts of the unipolar bonding leads.

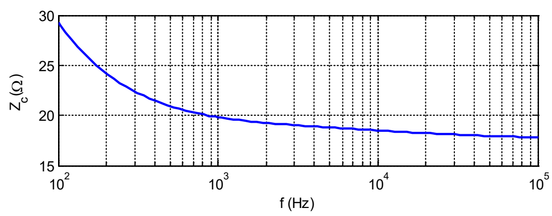


Fig. 2 Characteristic impedance Z_1 of the power cable versus frequency.

The results of these two tables show the increase of the inductance when unipolar cables are used instead of coaxial cable, (see *k"s* parameter of Table 4). This inductance varies between *4.8* to *12.2* times the inductance of the coaxial cable depending on the installation mode. Taking into account formulas (1) to (4), this increase in inductance causes an increase in the term complementary to the voltage limited by the SVL's.

Table 3. Measured inductance in per unit length L_b, characteristic impedance Z_c, coaxial bonding lead, at a frequency of 100 kHz.

Type	Voltage (kV/kV)	L_b (μH/m)	Z_c (Ω)
Coaxial	12/20	0.181	27.8

Table 4. Measured inductance values L_b in per length unit of unipolar cables, at a frequency of 100 kHz and for several layouts and cable lengths.

length (m)	9.2	9.2	2.2	4.2	6.2	9.2
Bonding Layout	In parallel and touching	In parallel with 2m separation	Laid between joint and link box during tests			
L_b (μH/m)	0.86	1.50	1.16	1.96	1.88	2.20
k''_s	4.8	8.3	6.4	10.9	10.4	12.2

The lowest inductance value for unipolar bonding leads was reached for the idealized case when both leads were installed in parallel and touching between them. For the actual layouts used during transient overvoltage tests, the inductance had a dependence on the bonding leads length, due to the need to separate both leads when they were connected to the link-box and to the joint, and therefore, a part of the bonding leads formed a loop that increased considerably the inductance.

Tests for Transient overvoltage on cable sheath

These transient overvoltages tests have two objectives: 1) to calculate the values of k_s through expressions (1) to (4), and 2) to obtain the overvoltage distribution between both sides of the sectionalized sheaths, K_{emp}.

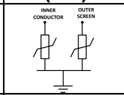
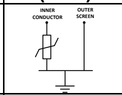
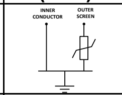
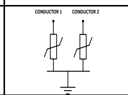
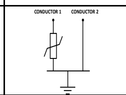
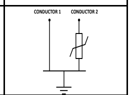
Tests to analyze the k_s factor

In order to consider all different scenarios of the formulas (1) to (4) the three possible configurations were tested for both coaxial and unipolar bonding leads:

- CB: cross-bonding configuration.
- SP1: single-point configuration with the SVL connected to the inner conductor of the coaxial bonding lead when a coaxial cable is used or to one of the two unipolar lead cables when unipolar bonding lead cables are used.
- SP2: single-point configuration with the SVL connected to the outer screen of the coaxial bonding lead when a coaxial cable is used or the other of the two unipolar lead cables when unipolar bonding lead cables are used.

For each configuration tested different lengths of the bonding lead cable were used (from 2 m to 10 m, in steps of 2 m) to analyse the influence of the weight coefficient, w of the internal bonding connection k_s' on k_s factor (9). Furthermore, in order to demonstrate that k_s factor is independent on the surge voltage limiter chosen, three types of surge voltage limiters, SVL_1, SVL_2 and SVL_3 with different rated voltages were used. The rated voltage of SVL_3 is three times the rated voltage of SVL_1 and rated voltage of SVL_2 is twice the one of SVL_1. Table 5 summarizes the different configurations used for the tests.

Table 5. Configuration applied for the transient tests.

Bonding lead		Cross-bonding (CB)	Single-Point 1 (SP1)	Single-Point 2 (SP2)
Type	length(m)			
COAXIAL				
	10.0	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	6.5	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	4.0	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	2.0	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
UNIPOLAR				
	9.2	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	6.2	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	4.2	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3
	2.2	SVL_1	SVL_1	SVL_1
		SVL_2	SVL_2	SVL_2
		SVL_3	SVL_3	SVL_3

Tests to analyze the K_{emp} factor

The same six configurations used to analysis the k_s factor were used to determine the voltage distribution between both sides of the sectionalized sheaths.

ANALYSIS OF THE RESULTS OF TRANSIENT OVERVOLTAGES

Analysis of the k_s factor

The data collected from the six configurations tested were analysed applying the formulas (1) to (4) to determine the k_s as the unknown parameter. The results for coaxial bonding lead cable are shown in Figure 3 (formulas (1) and (2)) and the results corresponding to unipolar bonding lead cable are shown in Figure 4 (formulas (3) and (4)). Each figure ratifies a good compatibility between the formulas (1) vs (2) and (3) vs (4), because the deviation of k_s values for the three different configurations (CB, SP1 and SP2) is negligible.

The curves draw in Figures 3 and 4 show the dependency of the weight coefficient, w, of the internal bonding lead, k_s', from the k_s factor, as predicted in formula (9).

By analysing both figures, lower k_s values are reached for the coaxial bonding leads compared to the k_s values reached for unipolar bonding leads.

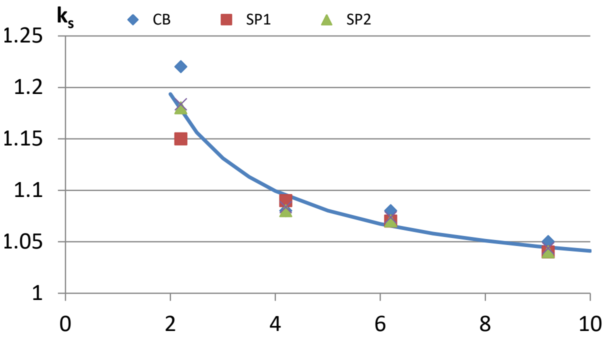


Fig. 3 Average value of k_s factor and fitting curve, obtained for all tests carried out with coaxial bonding lead (formulas (1) and (2).

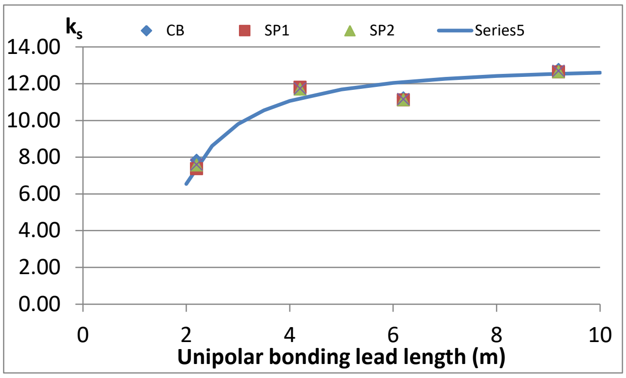


Fig. 4 Average value of k_s factor and fitting curve, obtained for all tests carried out with unipolar bonding lead (formulas (3) and (4).

For coaxial bonding leads, the worst result was reached for short lengths of bonding lead cable, for which k_s around 1.2 is reached, while for unipolar cables the worst results were reached for large lengths. For unipolar bonding leads, k_s results in higher k_s values as the bonding length increases above 4 m, to become a constant value around 12. Comparing Figure 3 with Figure 4 it can be seen that the use of unipolar cables instead of coaxial cables is equivalent to multiplying the cable length around 5 times (6/1.2) more in lengths close to 2 m and up to 12 times (12.5/1.05) for 9 m lengths.

Furthermore, figure 3 shows that the effect of the internal design of the cable joint has a negative effect on the coaxial bonding lead, since k_s increases the shorter the length of the coaxial cable. It means that the manufacturer plays an important role in overvoltages between sectionalized screens of a cable joint.

The curve of Figure 4 of is compatible with the preliminary results derived from the table 4 for k_s" on the basis of inductance measurements of unipolar bonding lead at 100 kHz. It allows ratifying the k_s results because they have been determined by two different measuring ways.

Analysis of the K_{emp} factor

The data collected from the six configurations tested were analysed applying the formulas (5) to (8) to determine the K_{emp} factor as the unknown parameter. The results for coaxial bonding lead cable are shown in table 6 (formulas (5) and (6)) and the results corresponding to unipolar bonding lead cable are shown in table 7 (formulas (7) and (8)). Each table ratifies a good compatibility between the formulas (5) vs (6) and (7) vs (8), because the deviation of K_{emp} values for the three different configurations (CB, SP1 and SP2) is negligible.

By analysing both tables (coaxial and unipolar bonding lead cables), similar K_{emp} coefficients were obtained for the coaxial bonding leads and for unipolar bonding leads. In both cases CB configuration gave a more homogenous voltage distribution than single-point configurations, in which a cable sheath has a slightly lower overvoltage (<47%) than the other (<60%).

Table 6. Average values of K_{emp} factors for both sides of the sectionalized sheaths, obtained for coaxial bonding lead tests.

	CB		SP1		SP2	
l(m)	K_{emp_cb1}	K_{emp_cb2}	K_{emp_cb1}	K_{emp_cb2}	K_{emp_cb1}	K_{emp_cb2}
10.0	0.48	0.52	0.40	0.60	0.53	0.47
6.5	0.50	0.50	0.45	0.58	0.58	0.43
4.0	0.54	0.47	0.46	0.54	0.54	0.46
2.0	0.51	0.49	0.44	0.59	0.56	0.47
Average	**0.51**	**0.49**	**0.44**	**0.59**	**0.55**	**0.46**

Tables 2 and 3 show there is no dependency of the length of the bonding lead cable on the K_{emp} factor.

Table 7. Average values of K_{emp} factors for both sides of the sectionalized sheaths, obtained for unipolar bonding lead tests.

	CB		SP1		SP2	
l(m)	K_{emp_cb1}	K_{emp_cb2}	K_{emp_cb1}	K_{emp_cb2}	K_{emp_cb1}	K_{emp_cb2}
9.2	0.49	0.51	0.47	0.54	0.51	0.49
6.2	0.51	0.50	0.48	0.53	0.54	0.47
4.2	0.51	0.49	0.46	0.54	0.53	0.47
2.2	0.52	0.48	0.48	0.54	0.57	0.43
Average	**0.51**	**0,50**	**0.47**	**0.54**	**0.54**	**0.46**

Overshooth at the sectionalized joints of a CB

The voltage-time curves at both cable sheaths of a sectionalized joint, between the sectionalized sheaths and at both surge voltage limiters for coaxial and unipolar bonding lead cables are shown in figures 4 and 5.

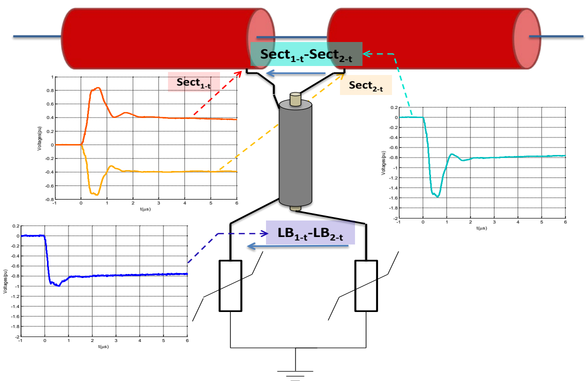


Fig. 4: Wave-shapes in per unity values, of measured voltages at sectionalizing joint and at SVL's terminals. Case of a Cross-Bonding configuration, with 10m of coaxial bonding lead and SVL1.

When unipolar connection cables are used, a much higher overshoot appears on the sectionalized screens of a CB than when unipolar cables are used, as shown figures 4 and 5. It can be observed in figure 4 that for the case of coaxial connection the voltage between screens is 1.6 times the voltage that appears in terminals of the limiters, while for the case of unipolar connection of figure 5, the voltage between screens is 4.5 times higher.

To consider the actual stress caused by these transient overshoots an attenuation k factor depending oscillation frequency must be considered.

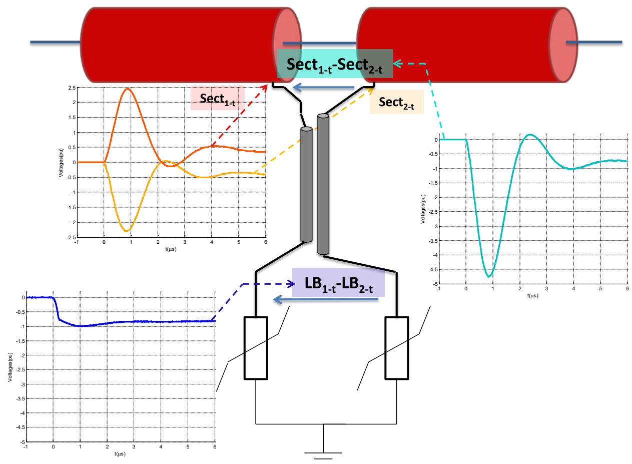


Fig. 5: Wave-shapes in per unity values, of measured voltages at sectionalizing joint and at SVL's terminals. Case of a Cross-Bonding configuration, with 9.2m of unipolar bonding lead and SVL_1.

CONCLUSIONS

Coaxial cables are much more suitable than unipolar cables for bonding lead of SVL in order to limit overvoltages in the screens of the sectionalized joints. The use of unipolar cables is equivalent to increasing the length of the bonding lead cable between 5 times, for short lengths of about 2 m, and up to 12 times, for lengths of about 9 m. In the case studied it was observed that the overvoltage in the screens of the sectioned joint reached 1.5 times the voltage limited by the SVL when a coaxial cable was used and reached 4.5 times the voltage limited by the SVL when unipolar cable was used, that is, the effect of the cable type was a multiplicative factor of the overvoltage of 3.It has also been demonstrated that the design inside the cable joint is also very important to limit surges between sectioned screens.

Finally, it has been shown that the distribution of the overvoltage in one or another screen of a coaxial or unipolar bonding lead cable does not exceed 60% of the overvoltage between screens of the sectionalized joint.

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