Study of the protection of screen interruption joints against fast-front over-voltages

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Abstract—When underground cables are cross-bonded, the cable sheaths are earthed at both ends of the route (and at the end of each major section in case of sectionalized cross-bonding). In order to protect the screen interruption joints, surge arresters are installed at cross-bonding locations. This paper studies the efficiency of these arresters against Fast Front Over-voltages (FFO), based on EMTP-RV simulations. The case of a 225 kV siphon is considered. The paper focuses more particularly on the choice of the rated voltage of arresters, considering that arresters with higher rated voltage may authorize in some cases the design of longer minor sections.

The elements presented in this paper are part of a study conducted at EDF R&D aiming at knowing if an increase of the rated voltage of the arresters protecting the sheaths of a specific 225 kV system in which 6 kV rated voltage arresters are presently used, is admissible, considering the withstand voltage of apparatuses.

Keywords: Insulation co-ordination, underground cable, sheath, surge-arrester, EMTP-RV.

I. Introduction

Because of environmental concerns siphons are more and more widespread in Europe. Siphons are made of an underground cable inserted in an overhead line. In France when the siphon is sufficiently long, sheaths are cross bonded. Cross bonding consists in sectionalizing the sheaths into elementary sections and cross connecting them in order to neutralize the total power frequency induced voltage in three successive sections [1]. Consecutive sections are separated by Screen Interruption Joints (SIJs).

In a siphon configuration the underground cable and its equipment have to be protected against Fast Front Over-voltages [2] (FFO are mainly due to lightning strokes impacting overhead lines).

The primary insulation of the cable is usually protected against FFO by surge arresters installed at both ends of the route (see paragraph 2). The sheaths are usually protected by being grounded at both ends of the route and SIJs are protected by low rated voltage Surge Arresters (SA rated voltage ranging typically from 3 kV to 15 kV) which may be wye-connected or star-connected (grounded or not).

From a design engineer point of view a lightning stroke may be considered as a current source with an impulse-shape, whose crest value may range from a few kA to 200 kA [3]. When a lightning stroke impacts an overhead line this current originates huge Fast-Front Over-voltages which propagate along the conductors and may damage the apparatuses which are connected to the line.

In the case of an overhead line connected to an underground cable (see fig 1) lightning Over-Voltages (OV) arriving at the cable are at the origin of FFO propagating along the sheaths, which are due to two physical phenomena :

- the electromagnetic coupling between sheaths and cores ;
- the injection of current in the sheaths from the grounding electrode of the last tower to which they are bonded.

The goal of this paper is to present some elements related to the efficiency of the protection offered by the surge arresters protecting the SIJs, based on a parameter sensibility analysis conducted on a 225 kV siphon configuration.

It studies particularly the influence of the rated voltage of the arresters on the level of Fast Front Over-Voltages stressing the SIJ. The choice of the rated voltage of arresters is of practical interest because it has an influence on the admissible length of the elementary sections. The SAs need to withstand the 50 / 60 Hz over-voltages due to a fault in a part of the system external to the cable. These over-voltages are approximately proportional to the length of the minor sections [4] (the withstand to over-voltages due to a fault inside cable systems are considered as less important by many utilities, the cable being already damaged). Therefore an increase in the rated voltage of SA will allow an increase in the length of minor sections and then a reduction in cost due to a decrease in the number of sectionalizing chamber.

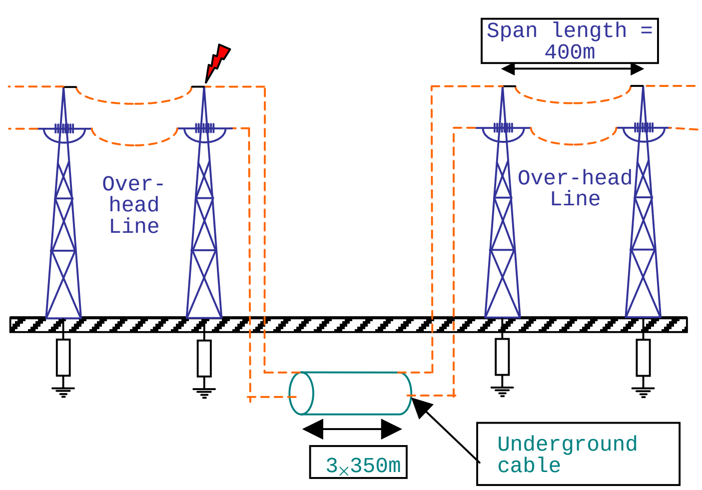

Fig. 1. Description of the 225 kV configuration; the siphon is cross-bonded. It is constituted of 3 minor sections of 350 m length.

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The elements presented in this paper are part of a study conducted at EDF R&D aiming at knowing if an increase of the rated voltage of the arresters protecting the sheaths of a specific 225 kV system in which 6 kV rated voltage arresters are presently used, is admissible considering the withstand voltage of apparatuses.

The paper gives in paragraph 2 a description of the configuration considered and then details in paragraph 3 the modeling used to perform the calculations. Paragraph 4 presents an analysis of the effect of some parameters on the level of over-voltages stressing the SIJ, based on EMTP-RV simulations [5].

II. Description of the Configuration

The configuration considered in this study is a siphon included in a 225 kV single-circuit line equipped with 2 sky wires (see Fig 1).

A. *Description of the siphon*

The siphon is made of 3 single-core cables. It is constituted of 3 elementary sections of 350 m length. The sheaths are cross-bonded and the phases are transposed. The parameters of the single core cables are given in table 1 below, based on the notations of Fig. 2.

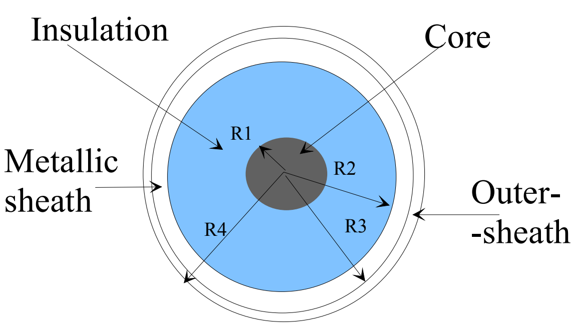

Fig. 2. Notation used for the description of the 225 kV single-core cable.

The value of the loss-factor of the outersheath has been determined, based on field measurements of the attenuation of over-voltages propagating along the sheaths of cables. It accounts for effects which are not taken into account in the EMTP cable model (proximity effect, existence of a vertical field within the soil…).

The single core cables are in a trefoil configuration.

The main insulation of the siphon is protected by surge arresters (rated voltage 225 kV) installed at both ends and connected by a 3 m lead to the grounding electrode (which corresponds to the grounding electrode of the first tower).

TABLE I

Parameters of a single core cable.

Parameter	Value
Radius of the core (R1)	2.45 cm
Internal radius of the metallic sheath (R2)	5 cm
External radius of the metallic sheath (R3)	5.28 cm
External radius of the outersheath (R4)	5.68 cm
Resistivity of the core	$3.68\ 10^{-8}\ \Omega.m$
Main insulation relative permittivity	3.143
Main insulation loss factor	0.0004
Sheath resistivity	$2.1\ 10^{-7}\ \Omega.m$
Outersheath relative permittivity	3.6

The screen interruption joints are protected by star-connected and grounded surge-arresters (see appendix A for the characteristic of the 6 kV SA used in this study). The sheath to local ground and longitudinal lightning withstand voltages of the screen interruption joints are respectively 50 kV and 100 kV.

B. *Description of the overhead line*

The overhead line is a single circuit 225 kV line equipped with 2 sky wires (see table 2). The lightning withstand voltage of the insulator strings is 900 kV. The spans are 400 m long. The connection between the overhead line and the underground cable is 20 m long.

TABLE 2

Position of the conductors of the overhead line

Conductor	Phase 1	Phase 2	Phase 3	Sky Wire 1	Sky wire 2
Horizontal distance of conductors	-5.5m	0	5.5m	-3m	+3m
Vertical height of conductors at tower	20m	20m	20m	25m	25m
Vertical height of conductors at mid span	15m	15m	15m	20m	20m

III. MODELING USED FOR THE STUDY

This paragraph summarizes the modeling used to represent each element of the configuration. The modeling has been made according to the recommendations given in [6].

Overhead line : spans in the close vicinity of the cable are represented using the FD line model [8]. Spans far from the siphon have been modeled as a single long line avoiding unrealistic reflections ;

Underground cable : the sections of the underground cable are represented using the FDQ model [7];

Connections between the overhead line and the underground cable : they have been represented as lumped inductances (1 μH / m);

Towers : they are represented as loss-less lines, with a propagation velocity taken equal to the velocity of light in vacuum, and a surge impedance equal to 150 Ω;

Grounding electrode of towers : they are represented as constant resistances, except for the grounding of the tower just before the siphon, which has been modeled taking into account soil ionization.

Surge arresters : they are modeled as non-linear elements representing the 8 / 20 characteristic of the SAs [6]. Subsequent lightning strokes on phase conductors which may have required a different characteristic are not considered in this paper, electrogeometric application having shown that the shielding failure flashover rate of the overhead line is neglectable.

The leads of the arresters are represented by a lumped inductance calculated using formula 1 below [9] :

$$L=\frac{\mu_0}{2\pi}\left(\ln\left(\frac{1}{r}+\sqrt{1+\left(\frac{1}{r}\right)^2}+\frac{r}{1}-\sqrt{1+\left(\frac{r}{1}\right)^2}\right)\right) \qquad (1)$$

where

L, l and r are respectively the p.u. length inductance, the length of the lead and the external radius of the lead. The modeling of the lead is a crucial issue for over-voltage calculation. However the knowledge in this field is limited. And for the authors it is questionable to expect an improvement of accuracy by using a line propagation model, as line theory application conditions are not paid respect to.

Lightning stroke : the lightning has been represented as a current source, using the CIGRE concave wave shape [3].

50 Hz voltage : it has been represented by voltage sources present at steady state.

IV. SENSITIVITY ANALYSIS

A. Introduction

This paragraph analyzes the effect on the level of FFO stressing the SIJ of several parameters of the configuration such as the grounding resistance of the SAs connected to the sheaths, the length of the leads or the rated voltage of the SA.

B. Effect on FFO of the grounding resistance of the SA connected to the sheaths

In this paragraph the influence of the grounding resistance of the SAs, which are connected to the sheaths on the crest value of the over-voltages to the local ground applied on the sheath at the end of the first elementary section is studied, for two different lightning strokes. Its influence on the longitudinal over-voltage applied to the sectionalizing sleeve in the SIJ is also considered. The SAs have a rated voltage of 6kV. The lightning stroke of 150 kA impacting the first tower before the cable, considered in Fig 3, does not lead to a flash-over, whereas a lightning stroke of 200kA impacting the second tower before the siphon leads to a flash-over.

Fig. 3 shows that an increase in the grounding resistance leads to a slight decrease in the sheath to local ground over-voltage (the local ground voltage is considered to be equal to the voltage at the top of the grounding resistance of the SAs). This is due to the diminishing of the current circulating through the SAs when the grounding resistance increases.

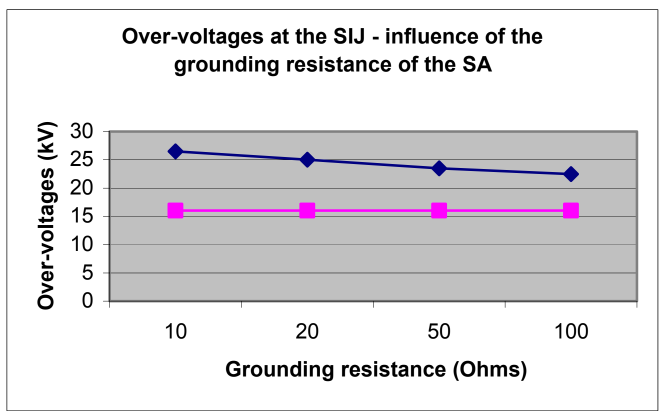

Fig. 3. Crest value of the FFO at the SIJ (first minor section) versus the value of the grounding resistance of the SAs. A lightning stroke of 150 kA impacts the first tower before the cable (_ over-voltage between the sheath and the local ground, _ longitudinal over-voltage).

Fig. 4. below presents the over-voltages at the screen interruption joints situated at the end of the first minor section, versus the value of the grounding resistance, for a lightning stroke of 200 kA impacting the second tower. This lightning stroke leads to a flash-over and creates higher over-voltages than the lightning stroke of 150 kA impacting the first tower.

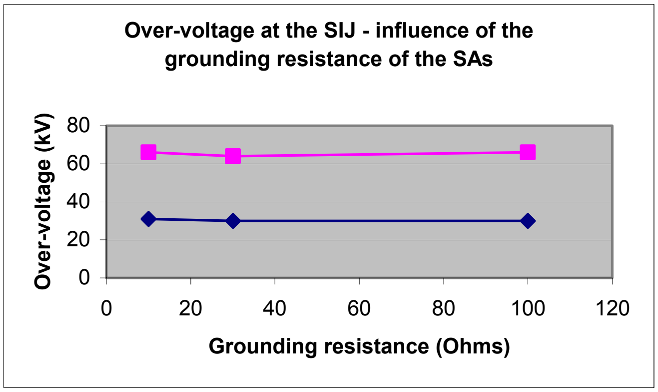

Fig 4. : Crest value of the over-voltage at the SIJ (first section) versus the value of the grounding resistance of the SAs. A lightning stroke of 200 kA impacts the second tower before the siphon (_ over-voltage between the sheath and the local ground , _ longitudinal over-voltage)

These 2 examples show that the stress on the SIJ is fairly limited even for very strong lightning strokes. Regarding over-voltages to local ground it is due to the protection offered by the potential rise of the grounding electrode of the SAs. The over-voltages between sheath and remote ground are more significant. For instance the lightning stroke of 150 kA impacting the first tower before the siphon leads to FFO between sheath and remote ground having a crest value of 250 kV.

C. Effect on FFO of the length of the leads connecting the SAs to the sheaths

In this sub-paragraph the FFO at the end of the first minor section are calculated for different values of the inductance of the leads connecting the SAs to the sheaths. The SAs have a rated voltage of 6 kV, they are connected to a grounding resistance of 10 Ω.

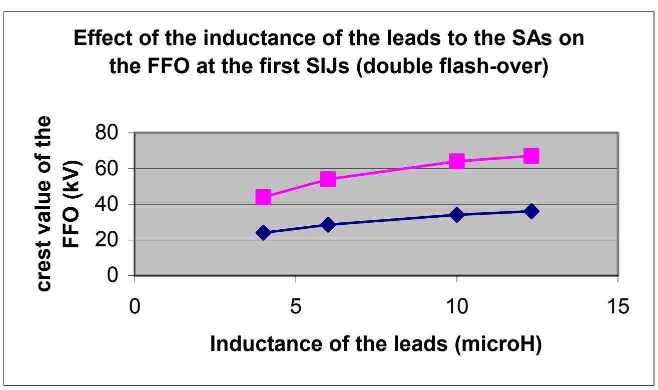

Fig. 5. : Crest value of the FFO at the SIJs (first minor section) versus the inductance of the leads to the SAs, for a lightning stroke of 200 kA impacting the second tower before the siphon (double flash-over) (_ over-voltage between the sheath and the local ground, _ longitudinal overvoltage).

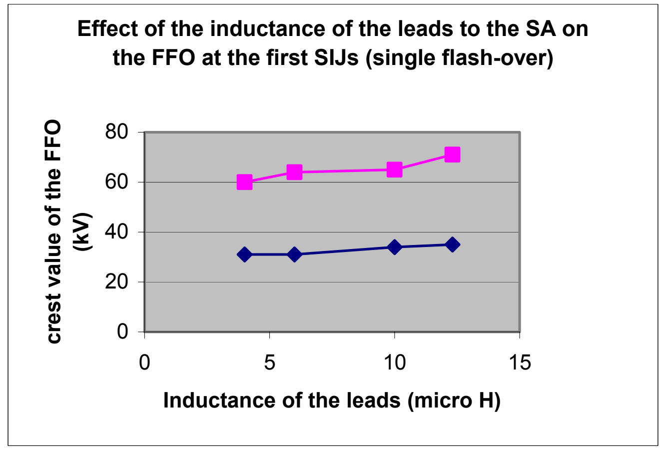

Fig. 6. : Crest value of the FFO at the SIJs (first minor section) versus the inductance of the leads to the SAs, for a lightning stroke of 200 kA impacting the second tower before the siphon (single flash-over) (_ over-voltage between the sheath and the local ground, _ longitudinal overvoltage).

Fig. 5 and Fig. 6 show the influence of the inductance of the connections to the SA on the crest value of the OV respectively in a case of double and single flash-over. The increase in the crest value of the OV versus the inductance of the leads can be seen. The effect is limited because the lightning electromagnetic wave presents a front fairly un-steep at the end of the first minor section due to its attenuation along the sheath. However it should be pointed out that some uncertainty remains on the way leads should be modeled.

D. Effect on FFO of the rated voltage of the SAs connected to the sheaths

The FFOs at the SIJ situated at the end of the first minor section are evaluated for several values of the rated voltage of the arresters protecting the SIJs. These SAs are connected to a grounding resistance of 10 Ω. The leads connecting the sheaths to the SAs is 10 m long (represented by lumped inductances of 12.32 μH).

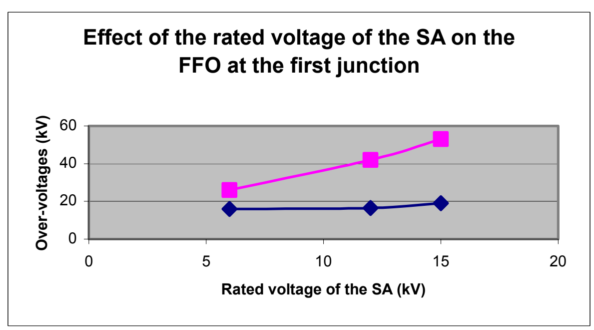

Fig. 7. : crest value of the FFO at the SIJs located at the end of the first minor section versus the rated voltage of the SAs, for a lightning stroke of 150 kA impacting the first tower (_ max sheath to local ground, _ max longitudinal over-voltage stressing the SIJs).

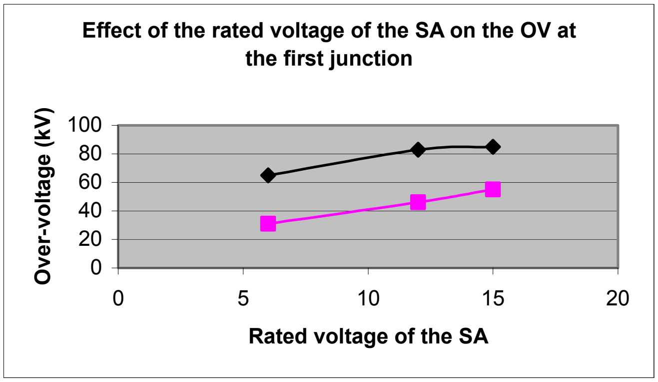

Fig. 8. : crest value of the FFO at the SIJs located at the end of the first section versus the rated voltage of the SAs, for a lightning stroke of 200 kA impacting the second tower (_ max sheath to local ground, _ max longitudinal over-voltage stressing the SIJs)

Fig. 7. corresponds to a case without flash-over and Fig. 8. to a case with flash-over. It can be noted from both figures that the crest value of the sheath to local ground over-voltages is slightly proportional to the rated value of the SAs and that, even in presence of a back-flashover, sheath to local ground over-voltages are relatively limited.

That is not the case for longitudinal over-voltages. The presence of a flash-over has strongly increased the crest value of the FFO. Regarding the variation of the longitudinal over-voltages versus the rated voltage of the SAs figures 7 and 8 show a slight increase. This increase is limited to 20 kV for a variation of the rated voltage from 6 kV to 15 kV for the most stressing case (case with flash-over).

However the crest value of the longitudinal over-voltage remains fairly low compared to the withstand voltage which may be specified for SIJ.

E. Effect on the energy absorbed by the SAs of the rated voltage of the SAs

The energy absorbed by the SAs is evaluated for several values of the rated voltage of the SAs (6kV, 12 kV and 15 kV). The arresters are star-connected to a grounding resistance of 10 Ω. The length of the leads connecting the sheaths to the SAs is taken equal to 10 m (corresponding to 12.32 μH).

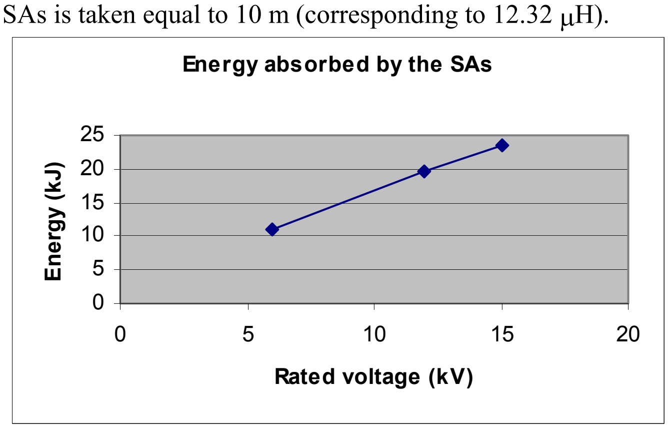

Fig. 9. : Energy absorbed by the SAs (higher level of energy absorbed among the arresters) protecting the SIJs when a lightning stroke of 150 kA impacts the first tower before the siphon.

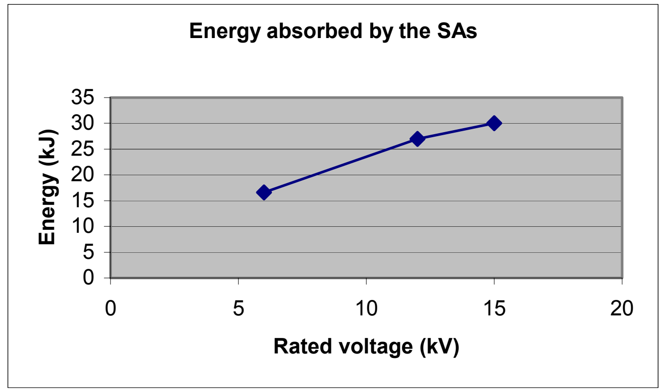

Fig. 10. : Energy absorbed by the SAs (higher energy absorbed among the arresters) protecting the SIJs when a lightning stroke of 200 kA impacts the first tower.

Fig. 9 and 10. above show a slight linear increase in the energy absorbed by the SA with the rated voltage of the arrester. Comparison of Fig. 9 and Fig. 10 shows that for a SA of rating voltage 15 kV an increase in lightning current from 150 kA to 200 kA leads to an increase in the energy stress by 20 %.

In the case of a family of arrester withstanding 3.6 k Joule / kV of rated voltage, The SAs 6, 12 and 15 kV considered in this paragraph will be able to absorb respectively 21 kJ, 43 k J and 54 kJ. It can be deduced from the figures above that these arresters are able to withstand the energy stress due to the very high lightning strokes considered here.

F. General analysis of the results

The over-voltages calculated are in most of the cases well below the withstand voltages of the SIJs, even for very strong lightning strokes of very low probability (According to [3] the probability of having a lightning current higher than 100 kA is lower than 5 %).

Because of the high withstand voltage of the insulator strings and of the low value of the footing resistance of towers, flashovers of insulator strings are very scarce and most of the stresses at SIJs are due to the over-voltages which are injected from the grounding resistance of the last tower before the siphon and which propagate along the sheaths with a strong attenuation. These over-voltages do not present a front sufficiently steep to have the efficiency of the arresters reduced because of the length of their leads.

V. CONCLUSION

This paper has presented a study of the FFO stressing the screen interruption joints of a 225 kV cross-bonded cable. A siphon configuration was considered. A sensitivity study has been conducted and the influence on the level of over-voltages of major parameters like the length of the leads connecting the arresters to the sheaths and the rated voltage of arresters has been analyzed.

In most of the cases the crest value of over-voltages has been found lower than the withstand voltage of the SIJ, even for strong lightning strokes impacting the overhead line in the vicinity of the siphon. The results of the study seem to indicate that an increase in the rated voltage of the surge arresters from 6kV to 12 or 15 kV could be acceptable, which would permit an increase in the length of cable minor sections and then a decrease in the cost of the cable.

However the limitations of the modeling should be kept in mind. Some aspects of modeling like the representation of the leads connecting the surge arresters protecting SIJ or the representation of the attenuation of the over-voltages propagating along the sheaths have a significant impact on the level of over-voltages but still deserve some research.

VI. Appendix

A. *Characteristic of the 6 kV SA installed to protect the SIJ*

TABLE 3
CHARACTERISTIC OF THE 6 kV SA USED IN THE STUDY

Current	Voltage
.001	10000
.01	11000
.1	12000
1	12500
10	12700
100	13000
1000	14500
10000	18500
100000	27500

VII. References

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VIII. Biography

Alain Xémard was born in France on December 20, 1961. He graduated from the National Institute of Applied Sciences (INSA Lyon) in Lyon, France, with an engineering degree in electrical engineering in 1985. His research interests include insulation coordination, and development of tools for electromagnetic transient calculation. He has been working at the Research Division of EDF since 1992. He is convener of the CIGRE group C4 3 01.

Eric Dorison was born in France on January 23, 1955. He graduated from Electricity High School in 1977. Since 1978, he has been with Electricité de France as Design Engineer within the Research Division, dealing with underground systems. His main fields of interest are VHV synthetic cables and both thermal and electrical modeling. He is a member of several IEC and CIGRE working group.