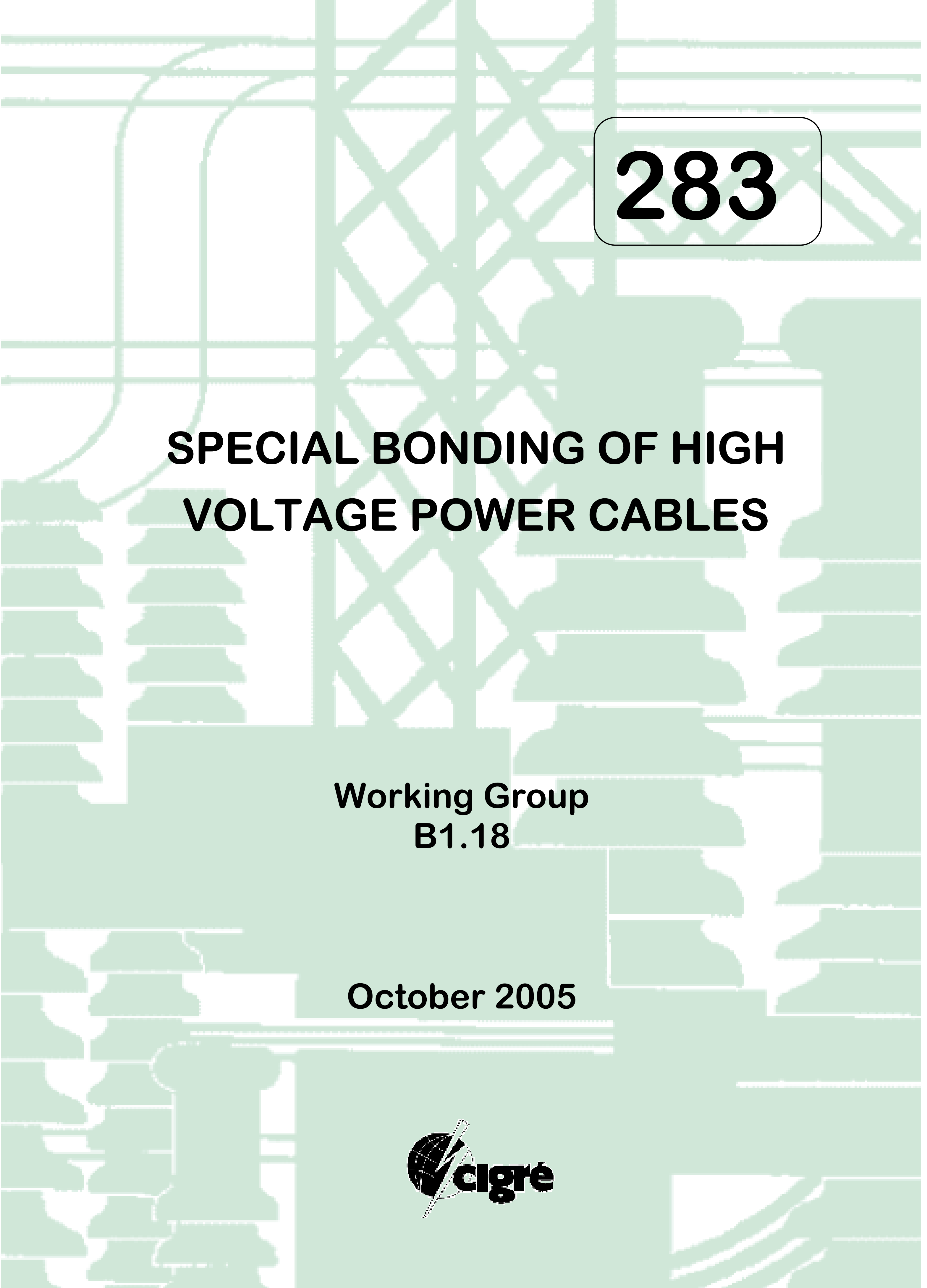

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SPECIAL BONDING OF HIGH VOLTAGE POWER CABLES

Working Group
B1.18

October 2005

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SPECIAL BONDING OF HIGH VOLTAGE POWER CABLES

TECHNICAL BROCHURE

WORKING GROUP B1.18

Stressing the Sheaths and the Sectionalising Joints of a 225kV Siphon

1. INTRODUCTION

GENERAL

TITLE OF THE WORKING GROUP

WG 21(B1)-18 was launched by SC 21 during its Paris meeting in 2000.

The name of the Working Group is **"SPECIAL BONDING OF HIGH VOLTAGE POWER CABLES".**

1.1 Terms of Reference

1.1.1 Background

With the ever rising demand for higher underground bulk power transfer, electricity utilities increasingly rely on properly designed Special Bonding of HV power cables for efficient transmission of electric power. Previous articles in Electra 28, 47 and 128 [1, 2, 3] have addressed the subject of bonding and serve as fundamental basis for many present day designs. With greater use of polymer insulated cables at higher voltages it is considered that certain issues have not been sufficiently covered in the past while others could be updated in order to take advantage of more recent developments in analytical techniques. This project will undertake to address the points outlined below.

1.1.2 Experience with Existing Systems

Utility practices to be surveyed with respect to design, testing, equipment specification and philosophy on allowable induced voltage levels for specially bonded systems under normal and transient operating conditions. As practices vary widely, this survey will summarize experience to date and provide the basis for which equipment requirements and operational guidelines will be formulated.

1.1.3 Identification and Analysis of System Electrical Transients

Computational modeling techniques have significantly progressed over the past years and should enable more accurate prediction of actual system voltages and currents arising from electrical disturbances. In view of this, investigations should be conducted which will more clearly define the electrical parameters of the system under different types of faults and for a variety of installation variables (i.e. multi cable / circuit installations, underground links installed between overhead transmission lines, and installations with high electrical resistivity of the ground). Analysis in this area will provide necessary data to support insulation coordination parameters for various components of the specially bonded cable system.

1.1.4 **Insulation Coordination Criteria**

Several issues need to be effectively addressed in order to provide proper system design guidance for future applications. Different types of cable insulations and corresponding dimensions used on present day HV cables suggest that characteristic impedances and attenuation properties of cables and bond leads should be investigated and coordinated accordingly. The insulation coordination aspect needs to be furthermore tempered by the proper characterization of sheath voltage limiters (SVLs), oversheath voltage withstand capabilities, bond cable length, shield / sheath sectionalizing insulator, and link box designs.

1.1.5 **Additional Key System Design / Application Considerations**

- Requirements of parallel ground conductors for cross bonded as well as single point bonded systems
- Special consideration for bonding protection and grounding of systems with SF_6 terminations
- Identification of cross-bonded system designs and/or operating conditions which could preclude the need for SVL protection
- Treatment of multiple circuits in close proximity, multiple cables per phase and phasing orientation

1.1.6 **Revision**

Due to the large scope of work defined in the terms of reference, it was accepted by SC 21 during its meeting in 08/2003 to issue a preliminary report of the results of work done on power frequency calculations only. The transient calculations were treated in 2004 by TF B1-13.

1.1.7 **Membership**

The membership of the Working Group should largely be made up of representatives from utilities with significant experience in the computation of sheath induced voltages in high voltage cables.

1.1.8 **Time schedule**

The Working Group started its work before the end of 2000 and produced a final report by the end of 2004.

1.1.9 **Scope of work**

The topic of special sheath bonding of high voltage cables has been the subject of extended work by previous Working Groups. Three Working Groups have dealt with the different aspects concerning the design, the selection and the performance of different bonding arrangements.

Reports of these Working Groups were published in Electra [1, 2, 3].

As mentioned above, in 2000, it was believed that the topic of special bonding should be re-examined for the following reasons :

- the rapid growth of high voltage underground cable systems around the world;
- the increased transmission capacity of new cables with large conductors that are operated at higher voltages, reaching 500kV;
- the world-wide adoption of the new polymeric cables; mainly cross-linked polyethylene insulated.

The main objectives of the new Working Group would be to establish the current practices used around the world as well as the emerging trends concerning bonding of high voltage cables.

It was also felt that theoretical calculated values of induced sheath voltages were not systematically verified and compared to actual measured ones.

1.2 Results of the Technical Investigation

1.2.1 Questionnaire

The results of the Technical Investigation are based on the questionnaire which was submitted to Utilities and Manufacturers at the beginning of the WG’s activities, thus being the latest and representative state of the art summary.

1.2.2 Design of high voltage systems

- Many utilities rely on cable suppliers for the design calculations and the selection of bonding systems. However, large utilities with experienced cable engineers have in house programs or utilise specialized firms to assist in this work. Some utilities would use more than one source to validate the results.
- Almost all utilities use a specially bonded sheath arrangement in their underground high voltage systems. One exception was reported. One European utility decided, for practical purposes, to entirely eliminate the sheath protection SVLs on their underground High Voltage Cable systems rated up to 150kV. Instead, it increased the requirements for BIL (transient) withstand voltage on the shield break in the cable joints. It is worth mentioning that the first cable sections in the case of a mixed connection (overhead line – underground cable link) are still protected using SVLs. (More about the justification of this practice is in section 5.2.).
- High voltage cable systems are used to transport up to 900MVA per link at voltage reaching 500kV.
- Maximum copper conductor sizes above 2500mm2 are now being considered.
- Large installations are mainly directly buried with the trefoil arrangement being most favoured. Many urban HV systems are in tunnels with some protection against fire propagation normally applied on tunnel cables.
- Many utilities are using more than one cable per phase in large high voltage cable circuits (links).
- The longest minor section reported is in the order of 900 metres. The longest single point bonding span is 850 metres. However, the WG believes that some minor sections in excess of 1200 metres have been installed in some countries.
- The highest imbalance between cross bonding minor section lengths is 30 %.
- Lead, aluminium and copper are the most common materials used for high voltage cable metallic sheaths.

1.2.3 Sheath bonding and protection

- In the design of large underground cable links, all utilities and cable suppliers take into consideration the induced sheath voltages. Power frequency and transient voltages are considered.
- Most countries have a national standard governing the maximum allowed standing voltages at power frequency. Also, large utilities would follow the recommendations of the wire and

cable manufacturer's association in their respective countries or establish these levels. This is considered an important safety issue particularly for maintenance crews.

- Calculations of induced cable sheath voltages (power frequency and transients), necessary for the design of the protection systems are carried out using EMTP (Electromagnetic transient program), Electra formulae [1, 2, 3] or in-house computer programs.
- Both switching and lightning transients are considered in establishing system models needed during the design stage of the sheath protection. However, lightning surges are considered more stringent.
- For power frequency faults, single phase to earth is considered as the most onerous condition in single point bonded systems, whilst three phase or phase to phase faults are most critical in cross bonded systems.
- A certain residual sheath circulating current related to the imbalance in lengths of minor cable sections is accepted.
- Special bonding is used on all bulk power transmission links. Cross-bonding is used for long links, particularly with higher short-circuit currents, whilst single point bonding is preferred for short HV links and links operated at lower voltages.
- SVLs are almost always used to protect sheath sectionalising insulation, with the exception of solidly bonded systems which are normally grounded at both ends.
- Zinc-Oxide type SVLs are the most commonly used for sheath protection against over voltages.

1.2.4 SVL Installation Arrangement

- SVLs are installed in sealed boxes either underground or above ground depending on the location of the cable joints as well as terminations. In any transition compound from overhead to underground, a physical barrier is usually installed to avoid any contact with the SVLs. Voltages in excess of 400 volts could be present at these locations.
- The main criterion for selecting sheath voltage limiters (SVLs) is the sheath to earth voltage. However a few utilities use the overvoltages across the insulation shield interruption in the joint as their main design value.
- SVLs are connected in a grounded star arrangement with a grounded neutral at most utilities for economic and technical reasons. However ungrounded star and delta arrangements are also reported.
- Under normal load conditions, utilities would tolerate a sheath to earth voltage ranging from 60 Volts to 400 Volts depending on the cable system rated voltage.
- Under transient conditions, the accepted sheath to earth voltage level varies between 20kV and 60kV depending on the cable system rated voltage. The levels for sheath to sheath voltages are naturally higher and would range from 45kV to 110kV.
- Single conductor bonding leads are used on high voltage cables up to 100kV while coaxial cables are used on links rated at 132kV and above.
- Almost all utilities would limit the length of bonding leads to under 10 metres. However, in some cases, bonding leads of excess of 10 metres were used.
- The cross-sectional area of bonding lead conductors is based on short-circuit-current calculations.
- An earth continuity conductor (ecc) is always used in conjunction with single point bonded system.
- Most utilities would not use an additional earth continuity conductor in the case of cross-bonded HV cable systems unless there is a specific local reason.

1.2.5 Maintenance, Safety, Security and Practical Aspects

- All utilities have a maintenance program that would include periodic, mostly an annual visual inspection, as well as electrical testing of SVLs. Test voltages and acceptable leakage current levels depend on the specific SVL used. All utilities would follow manufacturer's instructions in carrying out these tests in order to verify their condition, in to maintain their performance.
- Many utilities would require that SVLs be housed in reinforced boxes (explosion proof) to withstand short-circuit conditions. Some utilities have experienced some damage to their systems due to the failure of SVLs under short circuit conditions.
- Some utilities are undertaking some Research and Development Programs in association with their national cable suppliers and local universities. Work is being done particularly to assess the requirements for refurbishment of existing high voltage cable systems.
- Single point bonding is chosen by some utilities for its lower maintenance as compared to cross bonding systems.
- All newly installed SVLs are of Zinc Oxide type. They are sealed from the environment, particularly to prevent moisture ingress.

2.0 SYMBOLS AND PARAMETERS

SYMBOL	DEFINITION	UNIT
Electrical		
I	Current in phase conductor	Ampere
I_i	Current flowing in the conductor of cable i	Ampere
I_{1E}	Earth fault current in phase conductor 1	Ampere
I_c	Return current flowing in the earth continuity conductor	Ampere
x	Proportion of the short circuit current flowing in the underground link to the overall short circuit current cable (single phase fault)	
ω	Angular frequency of system	
E	Screen/sheath voltage gradient induced by phase currents	Volts/m
E_i	Screen/sheath voltage gradient for cable i	Volts/m
E_1, E_2, E_3	Screen/sheath voltage gradient (phases 1, 2, 3)	Volts/m
E_c	Voltage gradient in the earth continuity conductor induced by phase currents	Volts/m
R_c	a.c. resistance of earth conductor	Ω/m
R_s	a.c. resistance of cable sheath	Ω/m
R'_E	Equivalent a.c. resistance per unit length of earth return path	Ω/m
V	Screen/sheath voltage referenced to local earth	Volts
V_i	Screen/sheath voltage referenced to local earth, for cable i	Volts
V_p	Screen/sheath voltage referenced to local earth in a cable due to three parallel conductors	Volts
V_1	Screen/sheath voltage between sheath 1 and earth reference	Volts
V_2	Screen/sheath voltage between sheath 2 and earth reference	Volts
V_3	Screen/sheath voltage between sheath 3 and earth reference	Volts
V_{12}	Screen/sheath voltage between sheaths 1 and 2	Volts
V_{23}	Screen/sheath voltage between sheaths 2 and 3	Volts
V_{31}	Screen/sheath voltage between sheaths 3 and 1	Volts
μ_o	Permeability of free space	Hm^{-1}

μ	Permeability of materials	Hm^{-1}
ρ_E	Electric resistivity of soil	$\Omega.m$
ε_o	Permittivity of free space	Fm^{-1}
ε_r	Relative permittivity of the dielectric	
Z_{ij}	Mutual impedance (p.u. length) between conductors i and j	Ω
Z_n	Surge impedance of coaxial cable 'n'	Ω
F	Adjustment factor for sheath loss factor (unequal lengths)	

Dimensional

L	Length or span of cable system for induced voltage calculation	m
S	Axial spacing of adjacent cables in a regular three phase flat or trefoil formation	mm
S_{ic}	Axial spacing of screen/sheath of cable i and the earth continuity conductor	mm
S_{if}	Axial spacing of screen/sheath of cable i and faulty cable f	mm
S_{fg}	Axial spacing between two faulty phases (phase to phase fault)	mm
S_{cf}	Axial spacing between the earth continuity conductor and the faulty cable (single phase fault) or one of the faulty cables (phase to phase fault)	mm
S_{cg}	Axial spacing between the earth continuity conductor and the second faulty cable (phase to phase fault)	mm
S_{1P}	Axial spacing of parallel conductor and phase 1 conductor	mm
S_{2P}	Axial spacing of parallel conductor ad phase 2 conductor	mm
S_{3P}	Axial spacing of parallel conductor and phase 3 conductor	mm
S_{1c}	Geometric mean spacing between cable 1 and the earth conductor	mm
S_{2c}	Geometric mean spacing between cable 2 and the earth conductor	mm
S_{3c}	Geometric mean spacing between cable 3 and the earth conductor	mm
S_{12}	Axial spacing of phases 1 and 2	mm
S_{23}	Axial spacing of phases 2 and 3	mm
S_{13}	Axial spacing of phases 1 and 3	mm
d	Geometric mean sheath diameter	mm
D	Distance between the axes of two earth continuity conductors	mm
D_E	Equivalent depth of earth return path	mm
γ_c	Geometric mean radius of earth conductor (for stranded conductors take 0.75 x overall radius	mm

Physical

c	Speed of light in free space (= 300 x 10^6 m/s)	m/s

Abbreviations

SVL	Sheath voltage limiter
ecc	Earth continuity conductor
EPR	Earth potential rise
EMTP	Electromagnetic transient program
ATP	Alternative Transient Program
CIM	Complex Impedance Matrix

Electrical Resistivities and Temperature Coefficients of Metals

Material	Resistivity ohm.m at 20ºC	Temperature coefficient per ºC at 20ºC
a) Conductors		
Copper	1.7241×10^{-8}	3.93×10^{-3}
Aluminium	2.8264×10^{-8}	4.03×10^{-3}
b) Sheaths and armour		
Lead and lead alloy	21.4×10^{-8}	4.0×10^{-3}
Steel	13.8×10^{-8}	4.5×10^{-3}
Bronze reinforcement	3.5×10^{-8}	3.0×10^{-3}
Stainless steel	70×10^{-8}	Negligible
Aluminium	2.84×10^{-8}	4.03×10^{-3}

3.0 POWER FREQUENCY APPLICATIONS

3.1. Calculation methods

3.1.1. Introduction

The calculation of voltages and currents in special bonded high voltage cable systems (either power frequency or transient) is generally based on a model, in which the cable system and its relevant surrounding is represented by distributed impedances. These impedances are either “longitudinal” (resistances of conductors or metallic screens) or “transversal” (capacitance of insulation or non-metallic sheath).

The general model, which includes all impedances, is very complicated and does not allow a fast and easy calculation of voltages and currents. Therefore several simplified models have been derived. Calculations based on these models are usually less complicated but on the other hand several restrictions must be accepted. The following table contains an overview of models and suitable calculation methods:

Model	Description	Calculation methods (examples)
General impedance model	- Elements of cable system and relevant surrounding represented by distributed impedances - Resistances: Conductors, metallic screens, soil - Inductances (self and mutual): Conductors, metallic screens, - Capacitances: Insulation, non-metallic sheath, cable surrounding - Earth return path represented by an equivalent impedance (Carson's / Pollaczek's formula)	- Numeric calculation programs (i.e. EMTP/ATP), suitable for calculation of transient and power frequency parameters

Assumptions when simplifying the analysis to use the power frequency impedance model:

- Influence of capacitances neglected
- Frequency 50 Hz to 60 Hz
- Earth return path may be represented by an equivalent conductor

Model	Description	Calculation methods (examples)
Power frequency impedance model	- Complex impedance matrix representing the cable system, including all additional parallel conductors and the return path through earth - Impedances consist of resistances and reactances (self and mutual impedances included)	- Numeric solution of the equation system built up from the complex impedance matrix and boundary conditions (i.e. CIM method) - Formulas derived from the complex impedance matrix.

Assumptions when further simplifying the analysis to use the "simplified power frequency impedance model" :

- Phase currents are known for all cases
- Symmetric balanced currents in normal operation and during 3 phase faults
- No currents other than currents in phase conductors for normal operation, phase to phase fault and 3 phase fault
- For single phase faults the fault current returns 100 % via the ecc in single point bonded systems or via the cable screens in cross bonded systems
- Cross bonded systems with balanced minor and major sections (sectionalized cross bonding) or with a number of uniform elementary sections exactly divisible by three (continuous cross bonding)

Model	Description	Calculation methods (examples)
Simplified power frequency impedance model	- Simplified formulas derived from the Complex impedance matrix using the above assumptions	- Simplified methods such as shown in sections 3.2, 3.3 and 3.4 of this brochure.

3.1.2. The general impedance model

The general impedance model is the most detailed but also most complicated representation of a special bonded cable system. Due to the complex structure of the model, calculations are only practicable using computer based numeric methods. Several calculation programs like the popular "EMTP/ATP" are available. The calculations can be done either in time domain (transient calculations) or in frequency domain (power frequency calculations).

Several of the impedances used in the model are frequency dependent. This has to be taken into account especially for transient calculations. The available calculation programs usually contain several theoretical models to simulate the frequency dependencies.

In high voltage cable systems, zero sequence current components can flow via the earth. These current components will spread in the earth depending on the conductivity of the soil and the frequency. Theoretical models for the calculation of the equivalent impedance of the earth return path have been developed in the past (Carson's formula for overhead lines, Pollaczek's formula for underground cables, [4]. The abovementioned calculation programs use several implemented approximation methods to solve the infinite integrals which are part of the models for the earth return path.

Although these calculation programs are generally able to produce very exact results much care and experience is required to build up the calculation model and to interpret the results. Furthermore, many parameters must be known or must be assumed in a realistic range.

The use of numeric calculation programs based on the general impedance model is therefore recommended for experienced experts only. For any further details, reference should be made to the manuals of the respective calculation programs.

3.1.3. The power frequency impedance model

If only power frequency voltages and currents shall be calculated, the following simplifications can be made:

- Ignoring the capacitive currents;

  The general impedance model contains capacitances of the insulation and/or non-metallic sheath of power cables and other conductors (i.e. ecc) as well as capacitances of the surrounding (capacitive couplings in air or soil). The capacitive currents at power frequency (50 – 60Hz) are determined by the value of the capacitance and the magnitude of the applied voltage. In high voltage cable systems only the phase conductors have voltages which are high enough to produce significant charge currents, all other conductors like metallic screens, ecc or the surrounding soil remain usually at or close to earth potential, their capacitive currents can therefore be neglected without any problems.

  High voltage power cables are generally designed with single core screening. The maximum capacitive charge currents through the insulation are in the range of about 15A/km for 110kV LPFF cables and 30A/km for 400kV LPFF cables; for XLPE cables these values are approximately 50 % lower. In practical installations the influence of these capacitive currents on the sheath voltages is low. It is therefore acceptable to neglect also these capacitive charge currents between phase conductor and metallic sheath when calculating the induced sheath voltages.

  With this assumption, the impedance matrix of the power frequency impedance model no longer contains capacitances but only resistances and inductances ("longitudinal" impedances).

- Representation of the earth return path by an equivalent conductor

  For power frequency applications the complicated formulas for the impedance of the earth return path can be further simplified. A common approximation uses the infinite series development of Carson's formula, truncated after the first term. The result may be interpreted as the impedance formula for an equivalent conductor. Provided that the soil is uniform and homogeneous, the parameters of the equivalent conductor for a certain power frequency can be determined as follows:

$$R_E^{'} = \frac{\omega \cdot \mu_0}{8} \qquad \text{(A1)}$$

$$D_E = \frac{1.85}{\sqrt{\frac{\omega \cdot \mu_0}{\rho_E}}} \qquad \text{(A2)}$$

with R'_E - Equivalent A.C. resistance per unit length of earth return path
D_E - Equivalent depth of earth return path
ω - Angular frequency ($\omega = 2\,\pi\,f$)
μ_0 - Permeability of soil ($\mu = 4\pi\cdot 10^{-7}$ Vs/Am)
ρ_E - Electric resistivity of soil

The electric resistivity of the soil can vary over a wide range. The following values may be used for calculations [5]

stony ground	5000Ω·m
highly conductive agricultural soil	50Ω·m
(urban area	0.1Ω·m)

The low value for urban areas is not a real value for homogeneous soil but takes into account the influence of metallic installations like pipes, rails, earthed sheaths of other cable installations which are usually existing in such areas. If no information about the type of soil is known, a value of 100Ω·m may be used.

At power frequency (50 – 60Hz) the calculated equivalent depth of the earth return path may reach values up to 1000 m or even more for soil resistivity above 100Ω·m. The representation of the earth return path will only be exact if the length of the system is several times higher than the equivalent depth of the earth return path. Although this is not the case for a number of practical cable installations equations (A1) and (A2) may still be used as an approximation. The deviations usually remain within acceptable limits because in practice only a small portion of the total current will flow through the earth.

Structure of the equation system

The high voltage cable system can be described by the following scheme:

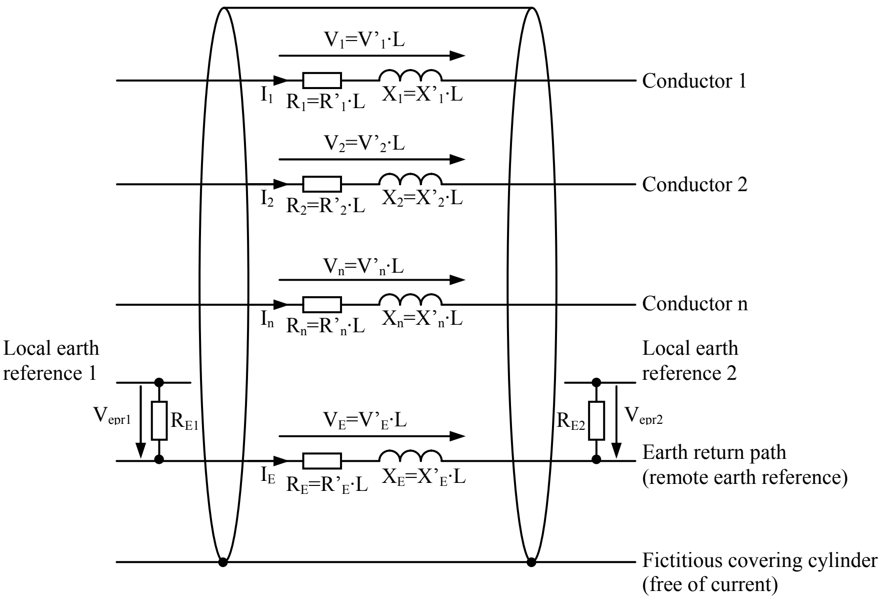


Fig. A1: Equivalent scheme of a high voltage cable system

The term "conductor" in the above scheme refers to the phase conductors as well as to any other parallel metallic structure like metallic screens, ecc, other parallel cables, metallic pipes or similar.

For power frequency applications complex numbers are used to represent the magnitude and the phase of the voltages, currents and impedances. The relation between voltages and currents in such a system of parallel conductors is described by the following complex matrix equation:

$$(\underline{V}) = (\underline{Z}) \cdot (\underline{I}) \qquad \text{(A3)}$$

with $(\underline{V})$ - Vector of voltages along conductors
$(\underline{I})$ - Vector of currents through conductors
$(\underline{Z})$ - Matrix of self and mutual impedances of conductors

Provided that all conductors including the equivalent earth return path are located inside the fictitious covering cylinder and that the current through the fictitious covering cylinder is equal to zero, all calculated voltages become independent of the radius of the fictitious covering cylinder. Therefore any value may be chosen for that radius.

The complex impedance matrix $(\underline{Z})$ is built up using the following rules:

$$\underline{Z}_{mn} = \underline{Z}'_{mn} \cdot L = \left(R'_{mn} + j\,X'_{mn}\right) \cdot L \qquad \text{(A4)}$$

with $\underline{Z}_{mn}$ - self or mutual impedance between conductors m and n
$\underline{Z}'_{mn}$ - self or mutual impedance per unit length between conductors m and n
R'_{mn} - self or mutual resistance per unit length between conductors m and n
X'_{mn} - self or mutual reactance per unit length between conductors m and n
L - length of the section to be calculated

If a section of a cable system consists of several subsections having different parameters (in particular different geometry) the total impedance matrix is the vectorial sum of the partial impedance matrices per unit length multiplied by the length of every subsection.

The impedances per unit length are calculated using the following formulas:

$$R'_{mn} = R'_{m} \qquad \text{(for m = n)} \qquad \text{(A5a)}$$

$$R'_{mn} = 0 \qquad (\text{for } m \neq n) \tag{A5b}$$

$$X'_{mn} = \frac{\omega \cdot \mu_0}{2\pi} \cdot \ln \frac{r_{\mathrm{cov}}}{g_{mn}} \tag{A6}$$

with R'_m - A.C. resistance per unit length of conductor m
g_{mn} - Mean geometric distance of conductors m and n
r_{cov} - Radius of the fictitious covering cylinder

For cylindrical conductors (the usual conductor form in cable systems) the mean geometric distance is calculated as:

For self impedance of a conductor (m = n)

$$g_{mm} = \alpha \cdot r_m \tag{A7}$$

For mutual impedance between two conductors (m ≠ n)

$$g_{mn} = a_{mn} \qquad (\text{non-coaxial conductors}) \tag{A8a}$$

$$g_{mn} = \max(\bar{r}_m ; \bar{r}_n) \qquad (\text{coaxial conductors}) \tag{A8b}$$

with r_m - Geometric radius of conductor m
α - Coefficient depending on the construction of the conductor
a_{mn} - distance between axis of conductor m and n
$\bar{r}_m ; \bar{r}_n$ - Geometric mean radius of conductors m and n

The coefficient α is taken from table A1:

According to equation (A8a) the mean geometric distance between parallel non-coaxial conductors (i.e. between cable conductors of different phases) is equal to their mutual distance (axis to axis). For conductor configurations where one conductor is located completely inside the (hollow) other the mean geometric distance is equal to the mean radius of the larger conductor not depending on whether the conductor axes are coincident or not (equation A8b). This applies in particular to the mean geometric distance between conductor and metallic sheath of the same phase, which is equal to the mean radius of the sheath.

The self and mutual impedance of the equivalent conductor representing the earth return path is calculated as for a hollow cylinder having a mean radius of D_E (see equation (A2)). The diameters and distances of all real conductors in a cable system in practice are much lower than the equivalent depth of the earth return path D_E. Therefore all mutual impedances between the equivalent earth conductor and any real conductor of the cable system, as well as the self impedance of the equivalent earth conductor itself, are calculated using D_E as the mean geometric distance.

Table A1:

Type of conductor	**Parameters**	**Value of α**
Solid	-	0.779
Stranded compacted	-	0.779
Stranded non-compacted	3 wires	0.678
	7 wires	0.726
	19 wires	0.758
	37 wires	0.768
	61 wires	0.772
	91 wires	0.774
	127 wires	0.776
Hollow	outer radius r_c inner radius r_i $a = \frac{r_i}{r_c}$	$\alpha = e^{-\left[\frac{0.25 - a^2 + a^4(0.75 - \ln a)}{(1-a^2)^2}\right]}$

In real installations all earthed components are connected to a local earthing system. Because the equivalent resistance of the earth return path according to equation (A1) only covers the remote earth path, the earth resistances of the local earthing systems on both sides of the high voltage cable systems have to be considered additionally (see Fig. A1).

Calculation of voltages and currents using the complex impedance matrix (CIM) method

Equation (A3) may be written as

$$(0) = (\underline{Z}) \cdot (\underline{I}) - (\underline{V}) \tag{A9}$$

The variables of this equation system are the vectors ($\underline{V}$) and ($\underline{I}$), the number of unknowns is twice the number of conductors. In order to get a particular solution it is necessary to add equations describing the boundary conditions for every conductor.
These equations are established using the following schematic:

a) Conductors with given current (i.e. phase conductors):

$$\underline{I}_{const\ m} = \underline{I}_m \tag{A10}$$

b) Conductors with open end (i.e. single point bonded sheaths):

$$0 = \underline{I}_m \tag{A11}$$

c) Conductors with both ends connected to earth (i.e. earth continuity conductors)

$$0 = \underline{V}_m - \underline{V}_E - \underline{V}_{epr1} + \underline{V}_{epr2} \tag{A12}$$

In case c) the earth potential rise at both ends has to be taken into account (see fig. A1).

The complete final equation system has the following structure:

$$\left(\begin{array}{c} 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \\ \hline BC_1 \\ \vdots \\ BC_m \\ \vdots \\ 0 \end{array}\right) = \left(\begin{array}{ccccc|ccccc} \underline{Z}_{11} & \cdots & \underline{Z}_{1m} & \cdots & \underline{Z}_{1E} & -1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & & & \vdots & \vdots & \ddots & & & \vdots \\ \underline{Z}_{m1} & & \underline{Z}_{mm} & & \underline{Z}_{mE} & 0 & & -1 & & 0 \\ \vdots & & & \ddots & \vdots & \vdots & & & \ddots & \vdots \\ \underline{Z}_{E1} & \cdots & \underline{Z}_{Em} & \cdots & \underline{Z}_{EE} & 0 & \cdots & 0 & \cdots & -1 \\ \hline BCI_{11} & \cdots & BCI_{1m} & \cdots & BCI_{1E} & BCV_{11} & \cdots & BCV_{1m} & \cdots & BCV_{1E} \\ \vdots & \ddots & & & \vdots & \vdots & \ddots & & & \vdots \\ BCI_{m1} & & BCI_{mm} & & BCI_{mE} & BCV_{m1} & & BCV_{mm} & & BCV_{mE} \\ \vdots & & & \ddots & \vdots & \vdots & & & \ddots & \vdots \\ 1 & \cdots & 1 & \cdots & 1 & 0 & \cdots & 0 & \cdots & 0 \end{array}\right) \cdot \left(\begin{array}{c} \underline{I}_1 \\ \vdots \\ \underline{I}_m \\ \vdots \\ \underline{I}_E \\ \hline \underline{V}_1 \\ \vdots \\ \underline{V}_m \\ \vdots \\ \underline{V}_E \end{array}\right) \tag{A13}$$

with $\underline{I}_m$ - Current in conductor m
$\underline{V}_m$ - Voltage along conductor m
$\underline{Z}_{mn}$ - Self and mutual impedances of conductors m and n
BC_m - Boundary condition for conductor m
BCI_{mn} - Boundary condition term n (current related) for conductor m
BCV_{mn} - Boundary condition term n (voltage related) for conductor m

The BC terms on the left side are set to the appropriate value depending on the type of boundary condition (i.e. equal to injected current, if boundary condition according to equation (A10) or zero, if boundary condition according to equations (A11) or (A12)). The last equation in (A13) contains the boundary condition for the earth return path (sum of all currents in the system is equal to zero).

Several operational cases can be set up adjusting the boundary conditions in the equation system (A13) accordingly. The system is solved using commonly known algorithms (i.e. GAUSS algorithm). The solution vector then contains all relevant currents and voltages. For special cases with defined fixed boundary conditions it is possible to derive calculation formulas from the equation system (A13) for certain values of interest (see [7] as an example).

3.1.4. The simplified power frequency impedance model

The calculation methods described above can give exact results for a wide range of parameters, but they still require the use of computer programs for the numeric solution of the large equation systems. By introducing further assumptions into the power frequency model it is possible to derive simplified equations for induced voltages, which can be handled with simple tools like pocket calculators or universal spreadsheet programs without the need of special numeric computer programs. These assumptions have to be set up in a way that most of the practical cases are covered and the deviations from the exact values will be on the safe side. This results in the simplified power frequency impedance model which is described by the known formulas from former ELECTRA publications [1, 3]. Modifications of these formulas making it possible to calculate some more practical configurations are described later in this document (see clause 3.4.7).

The following assumptions are made:

- Phase currents are known for all cases

  The currents in the phase conductors are assumed to be injected currents. This means that the currents in the phase conductors are known and independent from the parameters of the cable system.

- Symmetric currents flow during normal operation and 3 phase faults

  The currents in the phase conductors are assumed to be pure positive sequence currents (same magnitude, phase differences 120 ° in positive sequence). The phase rotation is described by the complex factor $\underline{\alpha}$:

  $$\underline{\alpha} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \qquad \text{(A14)}$$

  With I being the magnitude of the current the complex currents in the three phase conductors are

  $$\underline{I}_1 = \underline{\alpha} \cdot I \qquad \text{(A15a)}$$
  $$\underline{I}_2 = I \qquad \text{(A15b)}$$
  $$\underline{I}_3 = \underline{\alpha}^2 \cdot I \qquad \text{(A15c)}$$

- No currents flow other than currents in phase conductors for normal operation, phase to phase fault and 3 phase fault

  For normal operation, phase to phase faults and 3 phase faults it will be assumed, that no other currents than the given currents in the phase conductors are present. This means especially, that no induced circulating currents in screens, ecc or any other parallel conductors are considered when calculating the induced voltages. Parallel conductors which are connected to earth at both ends will generally act as screening conductors reducing the induced voltages. So this assumption will give results on the safe side.

- For single phase faults the fault current returns 100 % via the ecc in single point bonded systems or via the cable screens in cross bonded systems

  During single phase faults in real cable systems the returning fault current divides between any parallel conductor which is connected to earth at both ends and the earth itself. For the simplified power frequency impedance model it is assumed that the full fault current returns via the ecc in single point bonded systems and via the three cable screens in cross bonded systems. This assumption will result in slightly higher calculated induced voltages.

- Cross bonded systems have either balanced minor and major sections (sectionalised cross bonding) or a number of uniform elementary sections exactly divisible by three (continuous cross bonding)

  Any unbalance in cross bonded systems will result in circulating currents in the cable screens even when the currents in the phase conductors are symmetric. Unbalances in cross bonded systems may be caused by cable arrangements other than symmetric trefoil (also a regular flat formation without transposition will cause unbalances), by different length of the minor sections in sectionalized cross bonded systems, or by a number of elementary sections which are not divisible by three in continuous cross bonded systems. For the calculations it is assumed that the circulating currents caused by the unbalance are negligible. The induced voltages are calculated for the worst case (i.e. the longest minor section). This will generally give a conservative approximation because the circulating currents in real cable systems will equalise the induced voltages and therefore reduce the maximum values of these induced voltages.

Using the above assumptions a number of general equations for the induced voltages can be derived from the power frequency impedance model (details see clauses 3.2 and 3.4). These formulae give complex numbers for the induced voltages representing the magnitude and the phase of the calculated voltages. For cable systems with varying geometry along the route it is possible to calculate every section separately and superimpose the calculated particular complex voltages.

If the geometric arrangement of the cables is a regular trefoil or flat formation and does not vary along the route it is possible to simplify the formulas still further (see clause 3.2 and 3.4). These simplified formulas give the maximum values for a certain given arrangement. So they can be used for a fast estimation of the expected sheath voltages for a cable system during the planning stage.

3.2 Cross Bonded Systems (No Earth Conductor)

3.2.1 Introduction

The calculation of induced sheath voltage under fault conditions was evaluated using the different methods described in section 3.1 with different worked examples. For most applications the studies support the use of methods previously published in Electra [1, 3] to within good accuracy and with the benefit of being simple to apply.

To aid the User when applying methods in this section a series of worked examples and sample data is provided in section 3.2.8 for a single system model, as studied by the WG. The results shown for this model system also provide an indication of any variation in results from each method, although it must be borne in mind that the differences may vary from study to study.

The following summary shows the recommended methods to be used for each application.

Table B1:

Application	Sheath Voltage Calculation	Recommended Calculation Method
External Single phase to earth fault	Sheath to local earth	EMTP Pi model Complex Impedance Matrix (refer to clauses 3.1, 3.3)
	Sheath to remote earth	EMTP Pi model Complex Impedance Matrix (refer to clauses 3.1, 3.3)
	Sheath to sheath	Refer to clause 3.2.2
Three phase symmetrical fault	Sheath to local earth (1 cable per phase)	Refer to clause 3.2.4
	Sheath to local earth (>1 cable per phase)	
	Sheath to remote earth (1 cable per phase)	EMTP Pi model Complex Impedance Matrix

	Sheath to remote earth (>1 cable per phase)	(Refer to clause 3.1)
Phase to phase fault	Sheath to local earth	Complex Impedance Matrix (refer to clause 3.1) Also refer to clause 3.2.5 for simplified method
	Sheath to remote earth	EMTP Pi model Complex Impedance Matrix (refer to clause 3.1)

It is assumed that an internal cable fault is confined to the phase to earth fault condition and is not applicable to symmetrical or phase to phase faults.

3.2.2 External Single Phase to Earth Fault (solidly earthed neutral)

Under single phase to earth fault conditions the return current divides between the three sheaths in parallel and the earth. The proportion of current returning via the earth depends on the sheath resistance and the earthing resistances at the ends of the circuit. For cables in trefoil arrangement and in flat formation without transposition the return current in the sheaths divides equally between the three sheaths. For flat arrangements with transposition there is an unbalance between the centre and middle sheaths. Voltage between cable sheaths is calculable using simple formulae. The voltages between sheaths are independent of the effects of earth current and can therefore be derived using the simple assumption that sheaths are earthed at one point only and that the whole of the returning current divides between the three sheaths. A simple method is not available for calculating sheath voltage to local or remote earth reference. In these cases more complex methodology is required as summarised in 3.2.1.

The maximum voltages between sheaths at the cross bonding points are given by the following equations. Calculations should be referred to the longest minor section in the case of sectionalised cross bonding or the longest elementary section in the case of continuous cross bonding.

Cables in flat formation (single phase to earth fault in phase 1):-

$$E_{12} = j\omega . I . 2.10^{-7} \ln \frac{2(2)^{1/3} S}{d} \qquad \text{V/m} \qquad \text{(B1)}$$

$$E_{23} = j\omega . I . 2.10^{-7} \ln 2^{2/3} \qquad \text{V/m} \qquad \text{(B2)}$$

$$E_{31} = j\omega . I . 2.10^{-7} \ln \frac{4S}{d} \qquad \text{V/m} \qquad \text{(B3)}$$

Cables in trefoil formation (single phase to earth fault in phase 1):-

$$E_{12} = -E_{31} = j\omega . I . 2.10^{-7} \ln \frac{2S}{d} \qquad \text{V/m} \qquad \text{(B4)}$$

$$E_{23} = 0 \qquad \text{(B5)}$$

$$E_{31} = - E_{12} \qquad \text{V/m} \qquad \text{(B6)}$$

A worked example is shown in section 3.2.8, which gives close agreement between Electra, Complex Impedance Matrix and EMTP (Pi model) methods.

3.2.3 Internal Single Phase to Earth Fault (solidly earthed neutral)

Calculations of voltages between sheaths cannot be accurately made using simple formulae as the analysis requires knowledge of the sheath resistance paths in the faulty phase and the proportion of fault current flowing in each direction.

Calculations of voltages between sheaths and between each sheath and earth require more complex methods such as those described in clause 3.1 (complex impedance matrix and ATP/EMTP).

3.2.4 Three Phase Symmetrical Fault or Balanced Load Condition

The maximum voltages between sheaths and local earth reference at the cross bonding points are given by the formulae shown below. Calculations should be referred to the longest minor section in the case of sectionalised cross bonding or the longest elementary section in the case of continuous cross bonding.

For the general case of cables in any formation:-

$$E_1 = j\omega . I . 2.10^{-7} \left(-\frac{1}{2}\ln\frac{2}{d}\frac{S_{12}{}^2}{S_{13}} + j\frac{\sqrt{3}}{2}\ln\frac{2S_{13}}{d} \right) \quad \text{V/m} \qquad \text{(B7)}$$

$$E_2 = j\omega . I . 2.10^{-7} \left(+\frac{1}{2}\ln\frac{4S_{12}.S_{23}}{d^2} + j\frac{\sqrt{3}}{2}\ln\frac{S_{23}}{S_{12}} \right) \quad \text{V/m} \qquad \text{(B8)}$$

$$E_3 = j\omega . I . 2.10^{-7} \left(-\frac{1}{2}\ln\frac{2}{d}\frac{S_{23}{}^2}{S_{13}} - j\frac{\sqrt{3}}{2}\ln\frac{2S_{13}}{d} \right) \quad \text{V/m} \qquad \text{(B9)}$$

For a flat formation, the highest voltages are in the outer phases and are given by the following expression:-

$$E = j\omega . I . 2.10^{-7} \left(-\frac{1}{2}\ln\frac{S}{d} + j\frac{\sqrt{3}}{2}\ln\frac{4S}{d} \right) \quad \text{V/m} \qquad \text{(B10)}$$

For a trefoil arrangement the sheath voltages are equal and are given by the following expression:-

$$E = j\omega . I . 2.10^{-7} \ln \frac{2S}{d} \quad \text{V/m} \qquad \text{(B11)}$$

A worked example is shown in section 3.2.8, which gives close agreement between Electra, Complex Impedance Matrix and EMTP (Pi model) methods.

For cable groups involving more than one cable per phase, the calculation of sheath to earth voltage described above for one cable group can be supplemented by superposition of voltages from other groups using the general expression for any conductor "P" lying in parallel with a set of three conductors carrying balanced three phase currents:-

$$E_P = j\omega . I . 2.10^{-7} \left(\frac{1}{2} \ln \frac{S_{1P} S_{3P}}{{S_{2P}}^2} + j \frac{\sqrt{3}}{2} \ln \frac{S_{3P}}{S_{1P}} \right) \quad \text{V/m} \qquad \text{(B.12)}$$

It should be noted that formula B12 makes the assumption of equal currents flowing in each phase conductor.

3.2.5 Phase to Phase Fault (External to the cables)

Electra publications [1, 3] have provided conflicting statements for the assessment of phase to phase faults for cross bonded systems. This application has been further studied and recommendations are given below for those applications where a phase to phase fault is specified by the Utility.

Simple formulae for assessing phase to phase faults are provided in clause 3.4.3 for single point bonded arrangements, where a balanced condition is assumed. In considering this for cross bonded systems Electra 128 [3] advised that because of cable transposition, a balanced condition could not be assumed, given that imbalance will lead to sheath currents. In addition, Electra 128 reported that sheath to sheath voltages will be lower under phase to phase fault conditions than under symmetrical three phase fault conditions.

New studies do not support either of these statements, although the results may of course vary from one study to another. In studies of flat spaced cable systems, similar results were obtained with and without transposition. In both cases the results aligned reasonably with the Electra method for a balanced single point bonded system and calculated voltages were higher than for the three phase symmetrical fault condition.

It is therefore considered acceptable to assess phase to phase faults for a cross bonded system using the same approach as for single point bonded systems. In the general case of any cable formation, assuming a fault current I_{12} between phases 1 and 2, the sheath voltage gradients are:-

$$E_1 = j\omega . I_{12} . 2.10^{-7} \ln \frac{2S_{12}}{d} \quad \text{V/m} \qquad \text{(B13)}$$

$$E_2 = -j\omega . I_{12} . 2.10^{-7} \ln \frac{2S_{12}}{d} \quad \text{V/m} \qquad \text{(B14)}$$

$$E_3 = -j\omega . I_{12} . 2.10^{-7} \ln \frac{S_{23}}{S_{13}} \quad \text{V/m} \qquad \text{(B15)}$$

For laid flat arrangements this is a maximum for the outer sheaths, where:-

$$E_1 = j\omega . I_{12} . 2.10^{-7} \ln \frac{4S}{d} \quad \text{V/m} \qquad \text{(B16)}$$

3.2.6 Unequal Section Lengths (Balanced load condition)

The feature of unequal section lengths is more relevant to the calculation of sheath circulating currents than for sheath voltages. In general it would be expected that sheath currents would serve to reduce the level of sheath voltage although the effect would normally be minimal. For sheath voltage assessment therefore, a "worst case" condition may normally be assumed by using the longest section length. For unusual or extreme cases of imbalance, the assessment of sheath voltages would require analysis using methods such as C.I.M or EMTP (refer to clause 3.1).

For calculation of circulating current losses in a cross bonded system with unbalanced minor section lengths, the method below describes how the sheath circulating current loss factor as calculated using IEC 60287 [6] can be modified to provide an appropriate value for λ'.

For a trefoil formation, the currents circulating in the sheaths have the same magnitude. The current in the cable sheaths is:-

$$I_S = -\frac{j(X - X_c)}{R_S + j(X - X_c)} . \frac{p + q.\alpha + r.\alpha^2}{p + q + r} .I \quad \text{A} \qquad \text{(B17)}$$

Assuming that the current $I(A)$ flows in the cable conductor of the first minor section (length p), αI flows in the conductor in the second minor section (length q) and $\alpha^2 I$ in the third section (length r), R_S being the sheath resistance, X the conductor to sheath mutual reactance and X_c the mutual reactance between two cables. Accordingly, the adjustment factor of the solidly bonded system λ' is given by a factor 'F' as follows:--

$$\text{F} = \frac{\frac{1}{4}(2p - q - r)^2 + \frac{3}{4}(q - r)^2}{(p + q + r)^2} \qquad \text{(B18)}$$

which can be reduced to:-

$$F = \frac{p^2 + q^2 + r^2 - pr - pq - qr}{(p + q + r)^2} \qquad \text{(B19)}$$

Additionally, if for the shortest section, r = 1 and p, q are factors related to the shortest length, the adjustment is further simplified to:-

$$F = \frac{p^2 + q^2 + 1 - p - pq - q}{(p + q + 1)^2} \qquad \text{(B20)}$$

The above formulae for trefoil formation are also shown to be suitable for flat formation without incurring significant error.

These formulae are also relevant for deriving values of current flowing in the cable sheaths.

3.2.7 Modelling of the Source

As will be seen in section 3.2.8, calculations of sheath voltage to earth will vary according to how the source and cable sheath earth connections are arranged. It is recommended that the most appropriate arrangement is as shown below in figure B1.

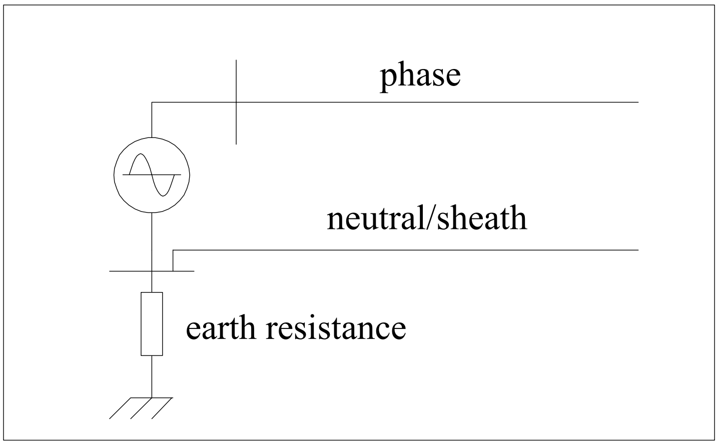


Figure B1: Source referred to substation earthing grid

3.2.8 Sample Data and Comparison of Methods

(a) Introduction

A conventional six cable section cross bonded system with two major cross bonded sections was modeled in order to both provide test data for users and to compare the results from the following different methods:-

- Simple Electra formulae as provided in this paper
- Complex impedance matrix
- EMTP

The EMTP calculations were made with three different models available in Cable Constants. A nominal-PI model and two distributed line models: a constant parameters (CP) model and a frequency dependant (FD) parameters line model. The parameters of the CP model are calculated at 50 Hz. Both CP and FD models include a transformation from the phase domain to the modal domain; the modal transformation matrix introduces approximations that, in general, limit the precision of the distributed line models used for cables.

(b) Cable and System Model:

Table B2:

Item	Value	Unit
Cable Dimensions		
Central duct diameter	12.0	mm
Copper conductor diameter	60.2	mm
Conductor screen diameter	61.4	mm
Insulation diameter (clearance under metallic sheath)	106.0	mm
Corrugated aluminum sheath diameter (mean thickness 2.3mm)	121.0	mm
Polyethylene oversheath diameter	129.3	mm

Conductor resistivity	1.7241E-8	Ω.m @ 20^0C
Sheath resistivity	2.84E-8	Ω.m @ 20^0C
Dielectric constant of insulation ε_r	3.5	
Dielectric constant of oversheath ε_r	2.5	

The influence of bonding leads have been ignored in each of the following 50Hz studies

System Design and Parameters:

Table B3:

Item	Value	Unit
Sheath bonding method	Sectionalised cross bonding with transposition	
Number of cable sections	6 (two major sections)	
Number of circuits	1	
Length per cable section (i.e, one minor section)	500	m
Cables formation	Flat spaced	
Cables axial spacing	300	mm
Depth to top of cables	1000	mm
System frequency	50	Hz
Soil resistivity	20	Ω.m
Earth impedance at terminations	0.1	Ω
Earth impedance at joints	5	Ω
Fault impedance	0.1	Ω
Balanced three phase symmetrical fault	60	kA
External single phase to earth fault	60	kA
External phase to phase fault	60	kA

For the above example, calculations of induced sheath voltage were made at the position of the first joint bay into the circuit, i.e. at *L* = 500m.

(c) Results of Studies

(i) Symmetrical 60kA Fault

Table B4:

Phase	Calculated sheath voltage to local earth (V) at first joint position				
	Electra	CIM	EMTP pi Model	EMTP CP Model	EMTP FD Model
1 (outer phase)	3957	3940	3957	4021	3708
2 (centre phase)	3116	3130	3139	2865	2817
3 (outer phase)	3957	3940	3957	3543	4110

The results show that calculated sheath voltages are within good agreement across all methods. In using EMTP however the pi model is shown to be the most appropriate, which is as would be expected. The results obtained using simple Electra formulae are virtually the same as using the EMTP pi model and therefore support the use of the simpler method.

(ii) Single Phase to Earth 60kA Fault (External) on Phase 1

Source referred to remote earth

Table B5:

Phase	Calculated sheath voltage to local earth (V) at first joint position				
	Electra	**CIM**	**EMTP pi Model**	**EMTP CP Model**	**EMTP FD Model**
1 (outer phase)	NA	-	5367	4746	5453
2 (centre phase)	NA	-	5032	5323	5099
3 (outer phase)	NA	-	5341	5631	5347

A complex impedance matrix model was not developed for this example. Using EMTP, the pi model would be expected to be the most appropriate for 50Hz studies although this is not proven in this limited study.

Source referred to substation earth

Table B6:

Phase	Calculated sheath voltage to local earth (V) at first joint position				
	Electra	**CIM**	**EMTP pi Model**	**EMTP CP Model**	**EMTP FD Model**
1 (outer phase)	NA	2520	2436	2393	2434
2 (centre phase)	NA	1040	1135	949	1024
3 (outer phase)	NA	1910	2006	1890	1916

The results show that calculated sheath voltages are within good agreement across all applicable methods. Differences between the results from different EMTP models are less conclusive than for the previous results.

Source referred to remote earth – Sheath to sheath voltages

Table B7:

Phase	Calculated sheath to sheath voltage (V) at first joint position				
	Electra	**CIM**	**EMTP pi Model**	**EMTP CP Model**	**EMTP FD Model**
1 - 2 (outer phase)	3574	NA	3573	3340	3455
2 - 3 (centre phase)	871	NA	871	964	894
1 - 3 (outer phase)	4445	NA	4444	4280	4349

The results obtained using simple Electra formulae are virtually the same as using the EMTP pi model and therefore support the use of the simpler method. A CIM model was not developed for this example although the method is appropriate for this application.

Source referred to substation earth – Sheath to sheath voltages

Table B8:

Phase	**Calculated sheath to sheath voltage (V) at first joint position**				
	Electra	**CIM**	**EMTP pi Model**	**EMTP CP Model**	**EMTP FD Model**
1 - 2 (outer phase)	3574	3560	3573	3341	3456
2 - 3 (centre phase)	871	870	871	965	895
1 - 3 (outer phase)	4445	4430	4444	4280	4349

The results obtained using simple Electra formulae are virtually the same as using the EMTP pi model and the C.I.M method and therefore support the use of the simpler method.

(iii) External Phase to Phase (Outer phases 1 – 3) 60kA Fault

Table B9:

Phase	**Calculated sheath voltage to local earth (V) at first joint position**				
	Electra	**CIM**	**EMTP pi Model**	**EMTP CP Model**	**EMTP FD Model**
1 (outer phase)	4445	4430	4400	-	-
2 (centre phase)	0	0	0	-	-
3 (outer phase)	4445	4430	4400	-	-

The results obtained using simple Electra formulae are virtually the same as using the EMTP pi model and therefore support the use of the simpler method.

3.3 Cross Bonded Systems – Single Phase to Earth Fault – Sheath to Earth Voltage

3.3.1 Introduction

Single phase to earth faults cause the circulation of current in the earth electrodes of the system. The resulting earth potential rises may contribute to significantly increase the voltage across the SVLs if they are star connected with the neutral earthed. Cable systems fed by overhead lines tend to produce higher earth potential rises. These calculations are complex and detailed calculation methods such as CIM or ATP/EMTP are required. If the SVL's voltage rating is exceeded, the neutral point of the star connected SVLs can be isolated from earth or an ecc can be added.

It is also worth considering earth potential rises for single point bonded systems since they affect the voltages that cable oversheaths have to withstand outside of the zone of influence of electrodes dissipating current.

3.3.2 Sheath to earth voltages during a single phase to earth fault

In this case, the returning fault current flows partly in cable sheaths and partly through earth (see figure C1).

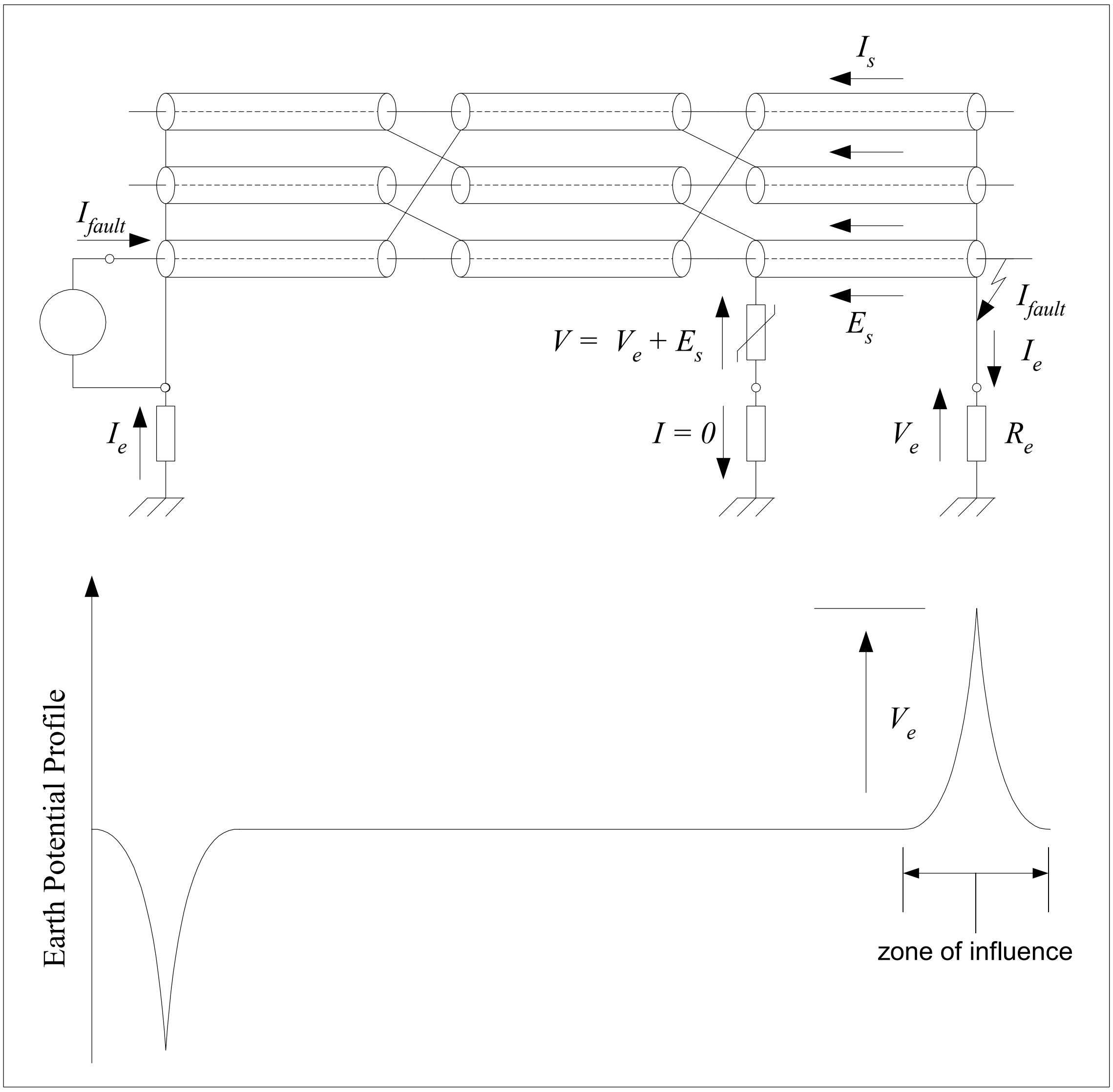


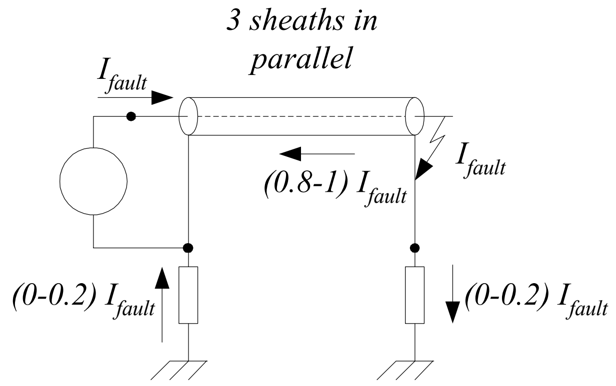
Figure C1 Sheath-to-earth voltages on cross-bonded cable systems in case of phase-to-earth faults

Sheath-to-earth voltages at sectionalising joints result from the vectorial sum of the voltage gradient on sheaths (E_s) and the earth potential rise (V_e) at the cable termination. The earth potential at the sectionalising joint location is assumed to be zero. This assumption is valid if the cable section is long enough (a few hundred metres or more) to be outside the zone of influence of electrodes dissipating earth current and if there is no extraneous metallic connection between earth electrodes along the cable circuit.

3.3.3 Earth potential rise at the cable ends

Calculation of the earth potential rises and the resulting sheath-to-earth voltages is complex because they are sensitive to the current distribution between cable sheaths and earth. Detailed calculation methods such as CIM or ATP/EMTP are required. The precision of the calculation depends on the information available on the impedance of the earthing system. Furthermore, the location of the cable circuit can influence significantly the current distribution between sheaths and earth (see figure C2).

a) Cable system connecting substations in an urban area



b) Cable system inserted in the middle of an overhead line in a rural area

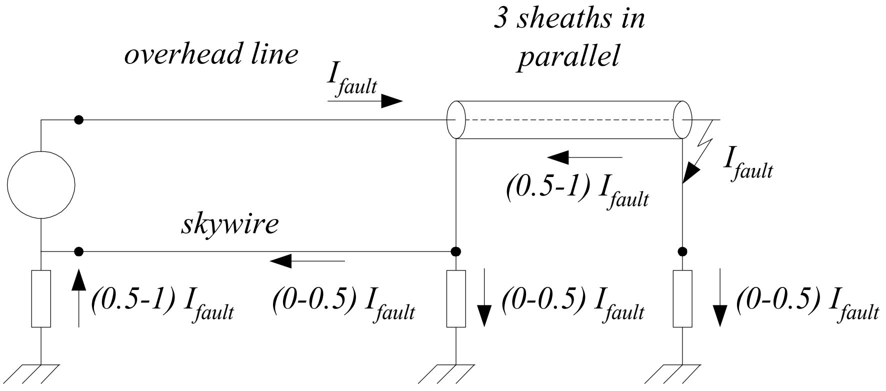


Figure C2 Typical current distribution between earth and cable sheaths during a single-phase-to-earth fault

HV cable systems usually connect substations in urban areas. The low resistance of the three cable sheaths in parallel and the strong magnetic coupling between the faulted phase and sheaths force most of the fault current to return through the sheaths. Furthermore, the earth impedance of substations in urban areas is typically quite low (0.1Ω or less) due to multiple contributions such as buried interconnected metal structures. The earth potential rise (V_e) rarely exceeds 1 or 2kV in such cases.

If the cable system is inserted in the middle of an overhead line, the situation is quite different. If the overhead line does not carry a skywire, the entire fault current is injected in the earth electrodes at the cable system extremities. Very high earth potential rise values (V_e) are to be expected in such cases. For example, a 10kA fault current injected in a 10Ω HV tower earth electrode produces an earth potential rise of 100 kV.

If a skywire is used, it carries a fraction of the fault current. Steel skywires have a high resistance and carry typically 5 to 20% of the fault current. If aluminium is used, this fraction can reach 50%. Furthermore, skywires contribute to reduce the impedance of the earthing system by connecting the tower footings of the overhead line. Earth potential rise values (V_e) typically ranging between 5 and 50 kV are to be expected in such cases.

The SVLs do not have the energy handling capability to limit voltages during power faults. In cases where the voltage exceeds 20 to 30kV, the SVLs should have a voltage rating of at least 15kV$_{rms}$ if they are star connected with the neutral point earthed. Such an arrester would produce voltages in the order of 50kV under transient conditions. The voltage across the sheath interrupt reaches 100kV (two SVLs in series) to which the voltage drop across the bonding leads must be added. These voltages may reach or exceed the BIL of the sheath interrupt.

In such cases, a lower voltage rating for the SVLs can be used if the neutral point connection of the SVLs is isolated from earth or if they are delta connected. Another option is to install an ecc.

3.3.4 Sheath-to-earth voltages with an earth continuity conductor (ecc)

Figure C3 shows a cross bonded system with an ecc. The ecc has to be connected to the local earth electrode at each cross bonding point.

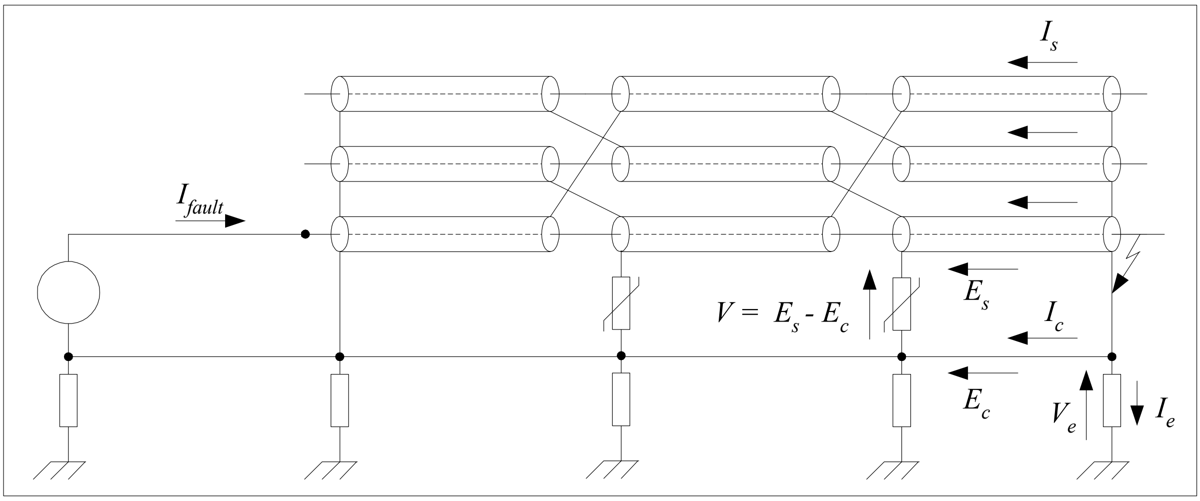


Figure C3 Sheath-to-earth voltages on cross-bonded cable systems in case of phase-to-earth (ecc is added)

The voltage across the SVL is no more dependent on the earth potential rise (V_e) and is therefore significantly reduced. The study case in the following section gives an example.

3.3.5 Study case – worked example

The study case looks at the influence of the earth potential rise on sheath voltages during single-phase faults.

Sheath-to-earth voltages are calculated at power frequency (50 Hz) during faults. Four circuits are considered:

- The first is 1.5km long comprising 3 minor sections of 500 m. The sheaths are cross-bonded (see figure C4).
- The second is 500m long and the sheaths are single-point bonded (see figure C5).
- The third is identical to the first with the exception that the cable circuit is fed by a 10km overhead line (see figure C6).
- The fourth is identical to the third with the exception that an ecc (earth continuity conductor) is added in parallel with the cable sheaths (see figure C7).

In all cases, the 400kV cables are placed in a flat formation. Both three-phase and single-phase faults are considered. They are applied at the end of the cable circuit, on the load side.

Table C1 presents voltages between sheaths and local earth for a cross-bonded cable circuit. Three-phase faults produce the highest voltages.

Tables C2, C3 and C4 present voltages between sheaths and local earth for a single-point bonded cable circuit. Single-phase faults produce the highest voltages. Voltages increase with the resistance of the ecc. The impedance of the earthing system has a mild impact on sheath-to-earth voltages.

Tables C5 and C6 present voltages between sheaths and local earth for a cross-bonded cable circuit fed by an overhead line. Single-phase faults produce the highest voltages. Voltages reach high values and increase with the earth impedance. The impedance of the earthing has a mild impact on sheath-to-earth voltages.

Table C7 presents voltages between sheaths and local earth for a cross-bonded cable circuit fed by an overhead line. An earth continuity conductor (ecc) is added. Voltages produced by single-phase faults are reduced significantly and are lower than those produced by three-phase faults.

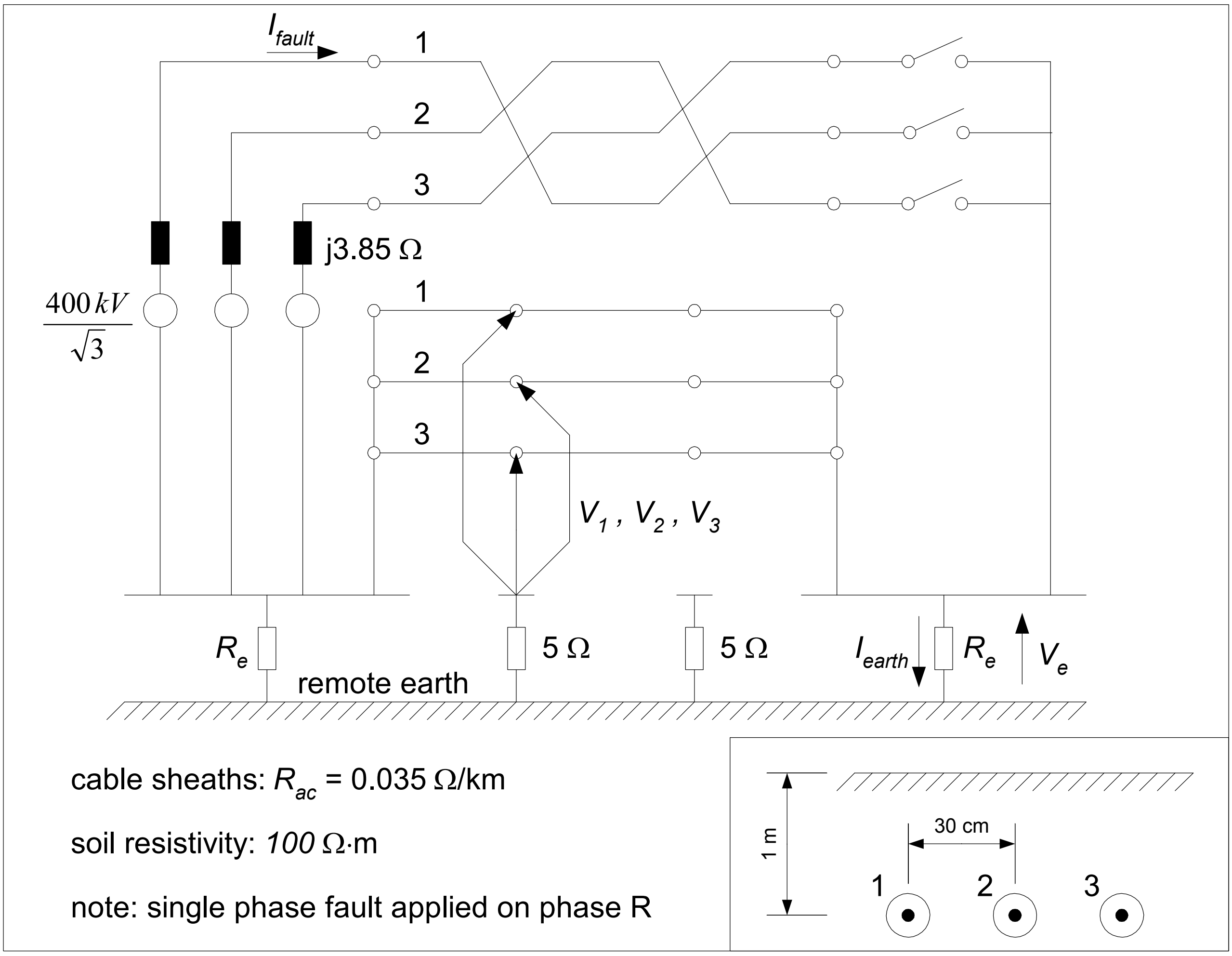
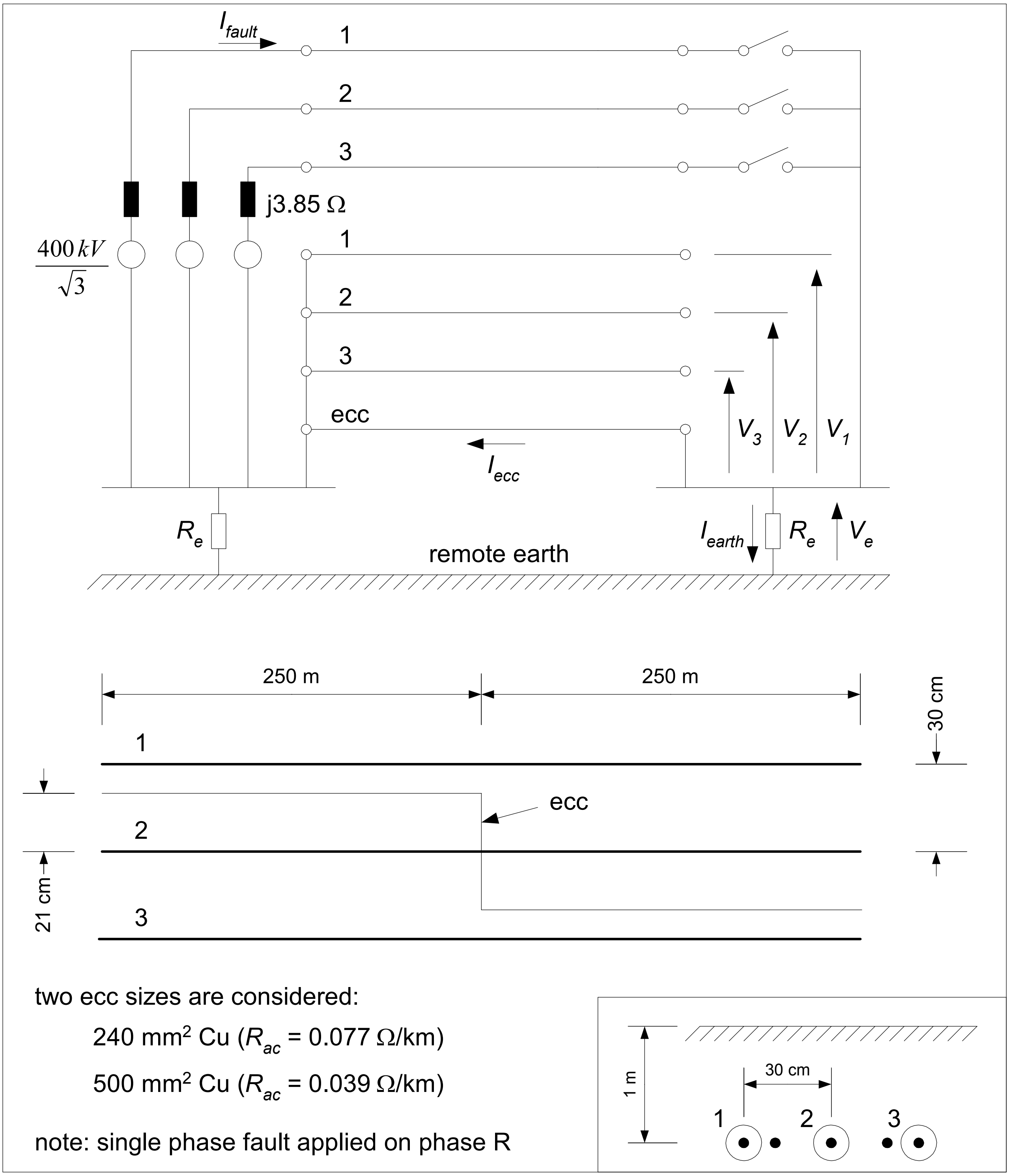


Figure C4 Fault at the end of a 1.5km cross bonded circuit with three 500m minor sections



two ecc sizes are considered:

240 mm^2 Cu (R_{ac} = 0.077 Ω/km)

500 mm^2 Cu (R_{ac} = 0.039 Ω/km)

note: single phase fault applied on phase R

Figure C5 **Voltages between sheaths and local earthing system: 0.5km cable circuit with single point bonded sheaths and an insulated ecc**

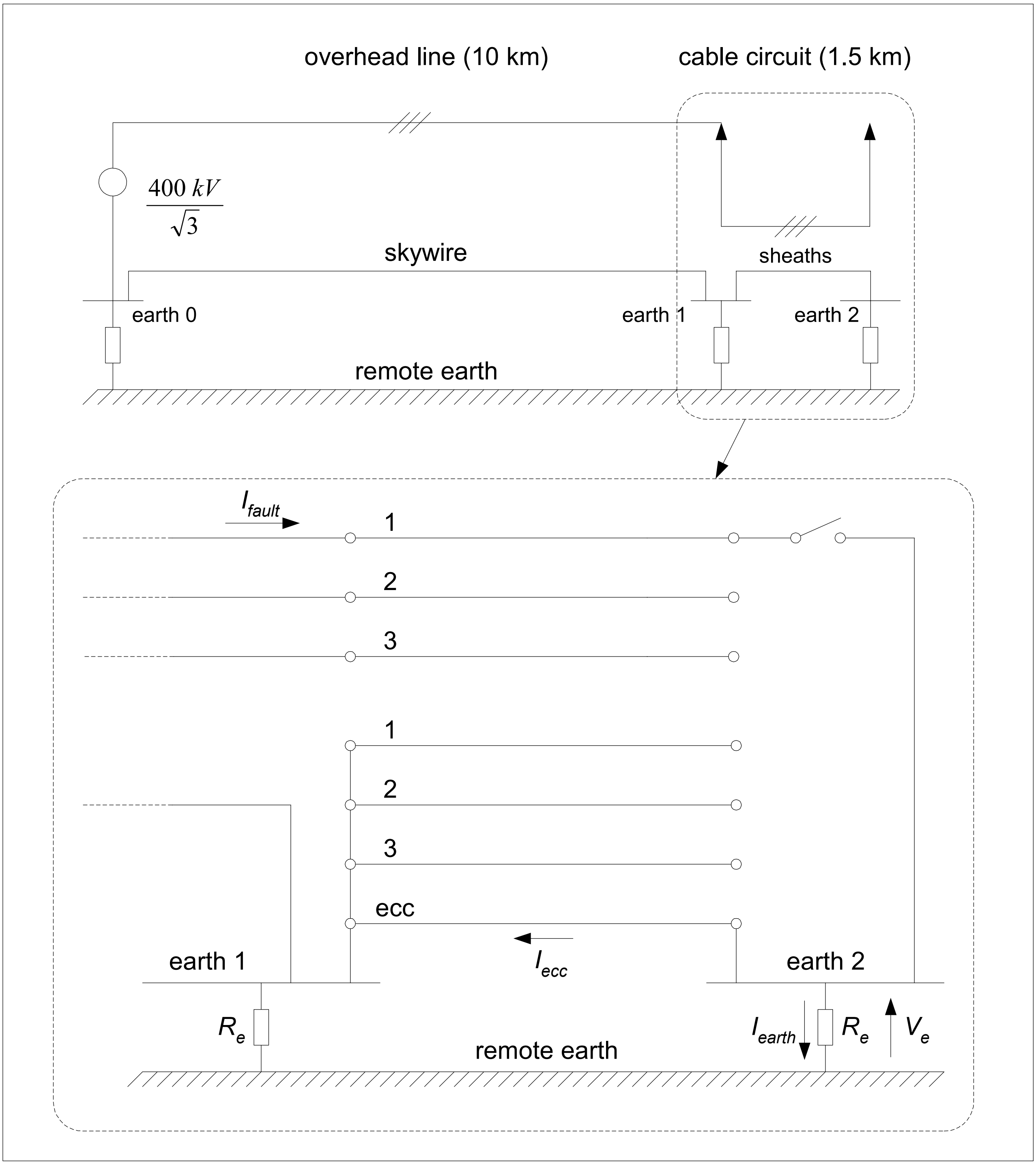


Figure C6 Voltages between sheaths and local earthing system at sectionalizing joints: 1.5km cross-bonded cable circuit (3x500m) fed by a 10km overhead line

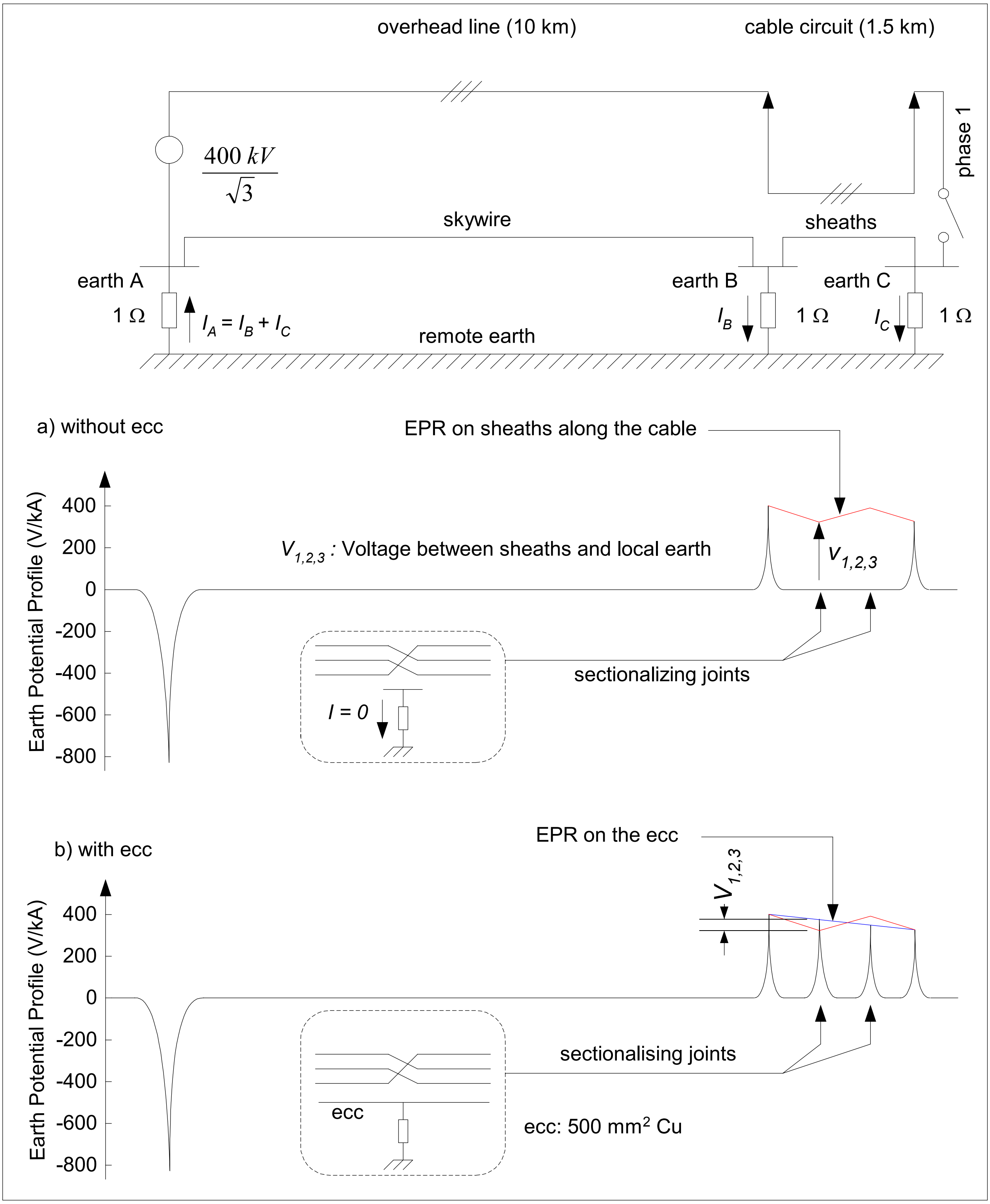


Figure C7 **Influence of an insulated earth continuity conductor (ecc) on voltages between sheaths and local earth at cross bonding points (single phase fault)**

Table C1 **Voltages between sheaths and local earthing system: 1.5km cross-bonded cable circuit with three 500m minor sections (angles are relative to current in phase no.1)**

fault	R_e (Ω)	$\frac{I_{earth}}{I_{fault}}$	V_e (V/kA)	Sheath-to-local earth voltage (V/kA)		
				V_1	V_2	V_3
3 phase	0	0	0	66 ∠-106°	52 ∠150°	66 ∠46°
single phase	0	0.022 ∠-84°	0	42 ∠-90°	17 ∠90°	32 ∠90°
	100	≈0	8.6 ∠-1°	42 ∠-94°	17 ∠99°	32 ∠95°

Table C2 **Voltages between sheaths and local earthing system for a three phase fault: 0.5km cable circuit with single point bonded sheaths and an insulated ecc ($240mm^2$)**

R_e (Ω)	$\frac{I_{ecc}}{I_{fault}}$	$\frac{I_{earth}}{I_{fault}}$	V_e (V/kA)	Sheath-to-local earth voltage (V/kA)		
				V_1	V_2	V_3
0	0.002 ∠-60°	0.003 ∠62°	0	66 ∠-106°	52 ∠150°	66 ∠46°

Table C3 **Voltages between sheaths and local earthing system for a single-phase fault: 0.5km cable circuit with single point bonded sheaths and an insulated ecc ($240mm^2$)**

R_e (Ω)	$\frac{I_{ecc}}{I_{fault}}$	$\frac{I_{earth}}{I_{fault}}$	V_e (V/kA)	Sheath-to-local earth voltage (V/kA)		
				V_1	V_2	V_3
0	0.70 ∠4°	0.30 ∠-10°	0	121 ∠-100°	70 ∠-108°	50 ∠-115°
0.1	0.76 ∠-5°	0.25 ∠16°	25 ∠16°	126 ∠-106°	77 ∠-117°	59 ∠-115°
1	0.97 ∠-3°	0.05 ∠60°	54 ∠60°	151 ∠-106°	102 ∠-115°	83 ∠-121°
10	0.998 ∠0°	0.006 ∠70°	57 ∠70°	155 ∠-105°	104 ∠-112°	85 ∠-117°
100	1 ∠0°	0.0006 ∠73°	57 ∠70°	155 ∠-105°	104 ∠-112°	85 ∠-117°

Table C4 **Voltages between sheaths and local earthing system for a single-phase fault: 0.5km cable circuit with single point bonded sheaths and an insulated ecc ($500mm^2$)**

R_e (Ω)	$\frac{I_{ecc}}{I_{fault}}$	$\frac{I_{earth}}{I_{fault}}$	V_e (V/kA)	Sheath-to-local earth voltage (V/kA)		
				V_1	V_2	V_3
0	0.73 ∠2°	0.27 ∠-4°	0	113 ∠-96°	61 ∠-101°	40 ∠-107°
0.1	0.80 ∠-6°	0.23 ∠13°	23 ∠13°	119 ∠-101°	68 ∠-110°	49 ∠-119°
1	0.98 ∠-3°	0.05 ∠69°	47 ∠69°	138 ∠-100°	86 ∠-105°	66 ∠-110°
10	0.999 ∠0°	0.005 ∠70°	49 ∠78°	140 ∠-98°	88 ∠-103°	67 ∠-107°
100	1 ∠0°	0.0005 ∠73°	49 ∠81°	140 ∠-98°	88 ∠-103°	67 ∠-107°

Table C5 Voltages between sheaths and local earthing system for a three-phase fault: 1.5km cross-bonded cable circuit fed by an overhead line

R_e (Ω)	V_e (V/kA)			Sheath-to-local earth voltage (V/kA)		
	subst. 0	subst. 1	subst. 2	V_1	V_2	V_3
0	0	0	0	65 ∠-108°	55 ∠148°	65 ∠43°

Table C6 Voltages between sheaths and local earthing system for a single-phase fault: 1.5km cross-bonded cable circuit fed by an overhead line

R_e (Ω)	V_e (V/kA)			Sheath-to-local earth voltage (V/kA)		
	subst. 0	subst. 1	subst. 2	V_1	V_2	V_3
0.1	92 ∠170°	88 ∠-2°	13 ∠-78°	76 ∠-39°	60 ∠11°	65 ∠24°
1	825 ∠171°	491 ∠7°	377 ∠-29°	439 ∠-8°	435 ∠0°	435 ∠2°

Table C7 Voltages between sheaths and local earth for a single-phase fault: 1.5km cross-bonded cable circuit (with an ecc) fed by an overhead line

R_e (Ω)	V_e (V/kA)			Sheath-to-local earth voltage (V/kA)		
	subst. 0	subst. 1	subst. 2	V_1	V_2	V_3
0.1	92 ∠170°	87 ∠-2°	13 ∠-81°	58 ∠-90°	73 ∠-90°	14 ∠-90°
1	830 ∠172°	428 ∠10°	316 ∠-29°	54 ∠-89°	69 ∠-89°	11 ∠-82°

Summary of the results

Table C8 summarises the results.

Table C8 Voltages between sheaths and local earthing system: summary of the results of the study case (angles are relative to fault current)

Type of cable circuit		Type of fault		
		Three phase	Single phase	
			R_e=0,1 Ω	R_e=1 Ω
cross-bonded connecting substations (3 minor sections of 500m)		66	42	42
cross-bonded fed by an overhead line (10km)	without ecc	65	76	439
	ecc: 500 mm^2	66	58	54
single point bonded (1x500m section)	ecc: 240 mm^2	66	126	151
	ecc: 500 mm^2	66	119	138

The main conclusions are the following:

- For cross-bonded cable circuits connecting substations in urban areas, sheath-to-earth voltages are higher for three-phase faults and the value of earth impedances has no significant impact.

- For cross-bonded cable circuits fed by an overhead line, sheath-to-earth voltages are higher for single-phase faults and the value of earth impedances has a determining impact. If an ecc is added, voltages are reduced to the level of urban systems.

- For single-point bonded cable circuits, single-phase faults produce higher voltages but they show a weak dependence on earth impedance values.

For cross-bonded cable circuits located in urban areas (as it is the case for the majority of HV cable systems), highest sheath-to-earth voltages are caused by two-and three-phase faults. If the cross-bonded cable circuit is inserted in the middle of an overhead line, single-phase faults produce the highest sheath-to-earth voltages that increase with earth impedances. The SVLs do not have the energy handling capability to limit voltages during power faults. In cases where the voltage exceeds 20 to 30 kV, SVLs can be delta connected or star connected with the neutral point isolated from earth. Another option is to install an ecc.

3.4 SINGLE-POINT BONDED SYSTEMS

3.4.1 General

As already mentioned in section 3.1, Electra formulae are derived with the 2 main following assumptions :

- The voltage gradient and the current flowing in the earth continuity conductor are negligible, when considering balanced phase currents.
  This condition is fulfilled if either the cables or the earth continuity conductor(s) are transposed. If not, special attention has to be paid to this point.

- The single-phase short-circuit return current flows entirely in the earth continuity conductor. This assumption is normally very nearly true, except for siphon systems, when the underground link is connected to an overhead line without ground wire. In that case, calculated sheath overvoltages may be largely overestimated.

Electra formulae may be applied when two earth continuity conductors are installed, with slight alterations detailed hereafter. They may be applied too when several circuits run parallel, using a superposition method.

When dealing with the design of surge voltage limiters, only screen to local ground voltages have to be taken into account.

For single-phase faults, the electrical stress applied to oversheaths at some distance from the ends, out of the areas involved in earth potential rises is the screen to remote ground voltage. The difference lies in the voltage drop in the end ground rod due to return current flowing to ground. It is worth calculating this voltage drop only for siphon systems with overhead lines without a sky wire. For, in this configuration, a significant proportion of the return current flows to ground through end ground rods.

Calculations based on Electra formulae are in quite close agreement in most cases with results from the Complex Impedance Matrix method or software such as EMTP/ATP. For particular cases such as a siphon system (or a substation entrance with a very low earth impedance at the overhead to underground compound), they result in an overestimation of the screen overvoltages.

3.4.2 Three Phase Symmetrical Fault or Balanced Load Condition

3.4.2.1 General

As it is assumed that the voltage gradient and the current in the earth continuity conductor are negligible, the type and the location of the earth continuity conductor(s) have no influence.

These assumptions hold if the voltage gradient induced in the earth continuity conductor by the phase currents is negligible and if there is no current coming from the earth grid, to which the earth continuity conductor is connected.

The induced voltage gradient is nil when cables are fully transposed, if the earth continuity conductor is laid at the trefoil centre, or for non touching cables in a flat formation with transposition of the earth continuity conductor laid at 0.7 times the cable spacing from the middle cable. For other configurations, the induced voltage gradient is not nil but is sufficiently small to be neglected, providing that the earth continuity conductor is transposed half way the cable route, as illustrated in example 1 in clause 3.4.8..

The current in the earth continuity conductor results from voltages induced by the phase currents :

- directly in the ecc when its position is asymmetric with respect to phase currents
- in the ground wire of an overhead line, to which the ecc may be connected

The current is limited by the self impedance of the earth continuity conductor (and ground rods resistance) and is negligible in every practical situation.

If the installation is designed with transposition of the cables or the ecc, screen overvoltages may be derived from the formulae given in clause 3.2.4 for both a trefoil arrangement and for a flat formation with transposition of the ecc. For sake of completeness in the case of a flat formation with cable transposition, the following formula may be derived :

$$V = j\frac{\omega\mu}{2\pi}.I.Ln\left(\frac{\sqrt[3]{2}.S}{d}\right).L \qquad \text{(D1)}$$

3.4.2.2 Several circuits.

For cable groups involving more than one cable per phase, the calculation of sheath to earth voltages described above for one cable group can be supplemented by superposition of voltages from other groups using the general expression for any conductor "P" lying in parallel with a set of three conductors carrying balanced three phase currents :

$$V_p = j.\frac{\omega\mu}{2\pi}.I.\left(+\frac{1}{2}\ln\frac{S_{1p}.S_{3p}}{S_{2p}^2} + j\frac{\sqrt{3}}{2}\ln\frac{2S_{3p}}{S_{1p}}\right).L \qquad \text{(D2)}$$

A worked example is shown hereafter, which gives close agreement between Electra, Complex Impedance Matrix and EMTP (Pi model) methods.

3.4.3 Phase to Phase Fault (External to the cables)

The maximum voltage gradient due to the fault current flowing in the cores occurs in the screen of the faulty cables :

$$E = \pm j \frac{\omega\mu}{2\pi}.I.\ln\frac{2.S_{fg}}{d} \qquad \text{(D3)}$$

I is the fault current
S_{fg} is the spacing between the 2 faulty phases.

The induced voltage gradient in the ecc is :

$$E_c = \pm j \frac{\omega\mu}{2\pi}.I.\ln\frac{S_{cf}}{S_{cg}} \qquad \text{(D4)}$$

S_{cf} and S_{cg} are the distances of the ecc to faulty cables (taking into account the possible transposition of either the cables or the ecc).

If either the cables are fully transposed or the ecc is transposed, this voltage gradient is nil. In such cases, the current flowing in the ecc is expected to be small.

Then the maximum is for the outer sheaths in a flat arrangement, as stated in Electra 128 [3]

$$V = \frac{\omega\mu}{2\pi}.I.\ln\frac{4.S}{d}.L \qquad \text{(D5)}$$

If not, the voltage gradient in the ecc has to be taken into account in order to derive the voltage from sheath to local earth. The current flowing in the ecc may be considered negligible in most cases as for normal operation.

3.4.4 External Single Phase to Earth Fault (solidly earthed neutral)

The screen to local earth voltage may be expressed for cable i as :

$$V_i = \left\{ j\frac{\omega\mu}{2\pi}.\ln\frac{S_{cf}}{S_{if}}.I - \left[R_c + j\frac{\omega\mu}{2\pi}.\ln\frac{S_{ic}}{\gamma_c} \right].I_c \right\}.L \qquad \text{(D6)}$$

where :

Ic is the return current, flowing in the ecc
S_{cf} is the spacing between the ecc and the faulty cable
S_{if} is the spacing between screen of cable i and the faulty cable.
S_{ic} is the spacing between screen of cable i and the ecc.

The screen to local earth voltage of the faulty cable is :

$$V = \left[R_c + j\frac{\omega\mu}{2\pi}.\ln\frac{2.S_{cf}^2}{d.\gamma_c} \right].I.L \qquad \text{(D7)}$$

if the ecc carries the whole of the return current

For a flat formation with non touching cables and transposition of the ecc (located 0.7 times the spacing of cables to the middle cable), this is equivalent to Electra formula Clause 3.3 when the resistance of the ecc is not disregarded.:

$$V = \left[R_c + j\frac{\omega\mu}{2\pi}.\ln\frac{S^2}{d.\gamma_c} \right].I.L \qquad \text{(D8)}$$

According to Electra 128 [3] this assumption is normally very nearly true and leads to sheath overvoltages which are slightly higher than those observed in practice.

In the particular case of a siphon system, indeed, sheath overvoltages may be largely overestimated (see 3.4.5).

Precise calculations are not straightforward since the proportion of the return current which is carried by the ecc and the proportion which flows in the earth grid to which it is connected and the earth itself, depends on a number of factors which are not usually accurately known. Indications are given in reference [7] to work out an estimate.

3.4.5 Siphon systems

In practical situations, underground links are generally connected to a substation at one end. This is the first configuration illustrated below (Fig. D1). The UG link is connected directly to a substation, at the left hand end. The earth resistance at the left end is expected to be low, as it is the substation earth resistance. If the earth impedance at the right hand end (UG to OH compound) is much higher than the earth resistance of the substation, then, in the case of a single-phase fault, the short-circuit current returns mainly through the ecc and the Electra formula is applicable. In the unlikely case where the earth impedance at the UG to OH compound is very low, the return short-circuit current flows mainly in the ground and the Electra hypothesis is no longer fulfilled. Using it results in overestimating stresses.

When considering siphon systems, the situation is quite different.
In the second situation illustrated below, (Fig. D1), the UG link is a siphon, inserted in a OH line without a skywire.

Assuming that the earth resistances at both ends have the same magnitude, then the short-circuit return current divides roughly equally between the ecc and the earth rod at the fault position. So the Electra hypothesis that the whole return current flows in the ecc is not fulfilled.

If the overhead line involves a skywire, the situation is not different, except that the path for the short circuit return current is no more the earth resistance at the ends, but these resistances in parallel with the skywire. These turn into lower earth impedances.

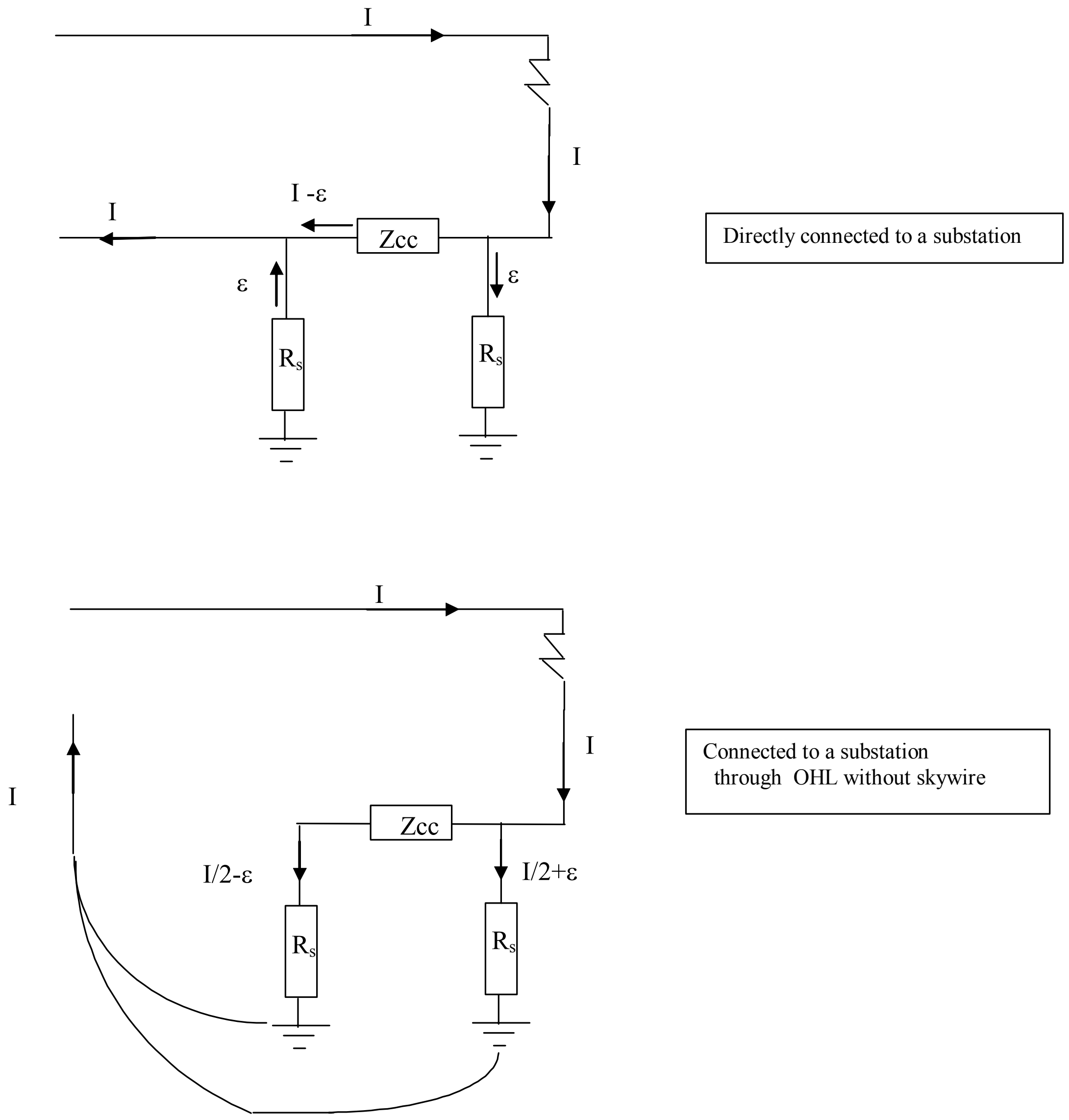


Figure D1

3.4.6 Two earth continuity conductors.

Introduction

Factors influencing the induced sheath voltage in single point bonded systems include the earth continuity conductor dimensions and its spacing from the three phase cables. One option for reducing the level of induced sheath voltage is to include more than one ecc within the cable group.

Calculation of Induced Sheath Voltage

Where two ecc's are used, the term 'γ_C' (geometric mean radius of ecc) in the equations shown above may be replaced by the following expression:

$$\sqrt{\gamma_C \times D} \qquad \text{(D9)}$$

Where:
γ_c = geometric mean radius of ecc (mm)
D = distance between axes of the two ecc's (mm)

The distance of the faulty cable to the ecc has to be replaced by the geometric mean distance to the 2 ecc's :

$$\sqrt{S_{c1f}.S_{c2f}} \qquad \text{(D10)}$$

If the resistance of the ecc is considered, the effective resistance is half the resistance of the ecc.

Comments

Where two ecc's are used it is still important to emphasise the need for transposition of each ecc at the mid-point of the section, to avoid or to minimise the generation of circulating currents in the ecc during normal load conditions. For trefoil groups it is not possible to locate the ecc in a balanced position unless it is placed at the middle of the trefoil group – which is seldom feasible except in special ducted configurations. Therefore the ecc (or two ecc's) should be located as close as possible alongside the power cable trefoil group and be transposed at the mid point of the route.

3.4.7 Internal Cable Fault

As stated in Electra 128 [3] clause 3.4, the highest sheath to earth voltage arises from an internal fault adjacent to a termination at the end where the screens are not directly grounded, assuming that the system is fed from the opposite side.

The fault current passes down the screen of the faulty cable to the bond at the far end of the circuit and returns partly via the earth conductor and partly through the ground rod.

The maximum voltage related to the local earth as given by Electra is derived assuming that the ecc carries the whole of the return current :

$$V = \left[R_s + R_c + j\frac{\omega\mu}{2\pi}.\ln\frac{2.S_{cf}^2}{d.\gamma_c} \right].I.L \qquad \text{(D11)}$$

where R_s is the screen resistance per unit length.

As for single phase external faults, in the particular case of a siphon system, screen overvoltages may be largely overestimated. Moreover, if the system is fed from both sides, a better estimate of screen overvoltage may be derived from the following formula :

$$V=\left\{\left[R_s+jx.\frac{\omega\mu}{2\pi}.\ln\frac{2.S_{cf}}{d}\right].I-\left[R_c+j\frac{\omega\mu}{2\pi}.\ln\frac{S_{cf}}{\gamma_c}\right].I_c\right\}.L \tag{D12}$$

where x is the proportion of the short-circuit current flowing in the underground link relative to the overall short-circuit current I.

And I_c is the return current which is carried by the ecc, depending on a number of factors which are not usually accurately known, as indicated in paragraph 3.4.4.
The preceding formula corresponds to the worst case.

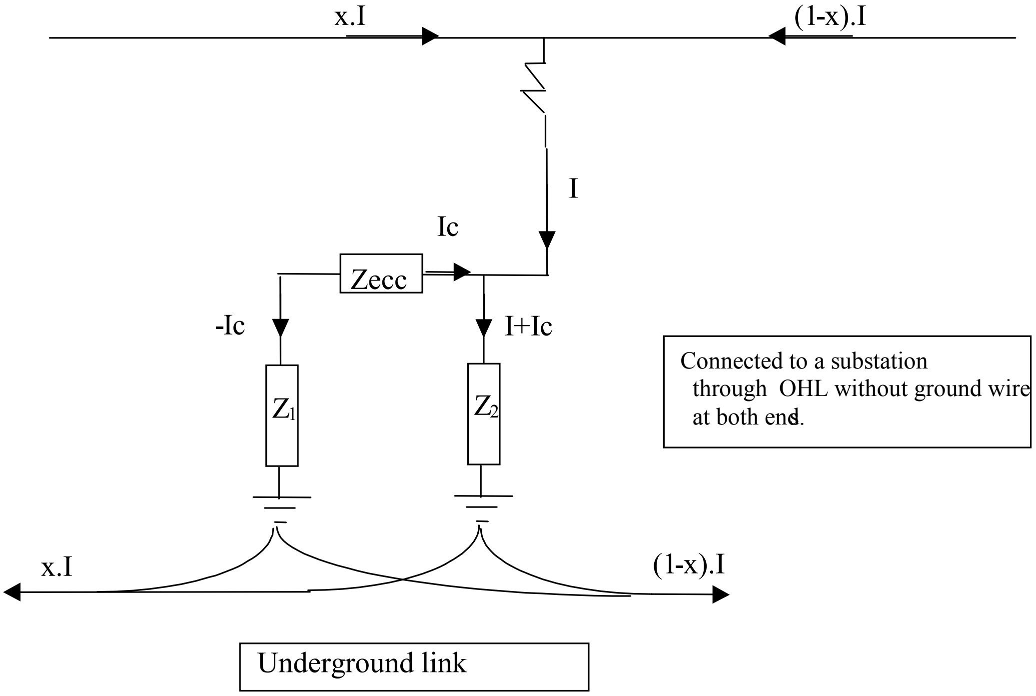


Figure D2

3.4.8 Worked Examples and comparison of methods

Example 1 : Balanced load conditions.
400kV system – touching cables laid in flat formation.

Table D1:

Layer	**Diameter (mm)**
Copper conductor	49.0
Insulation	113.5
Aluminium sheath	129.3
Polyethylene oversheath	150.0
ε_r (insulation)	3.5
ε_r (oversheath)	2.5
Sheath a.c. resistance (μΩ/m @20^{0}C)	35.50

Current : 1000 A - Elementary section length : 733m

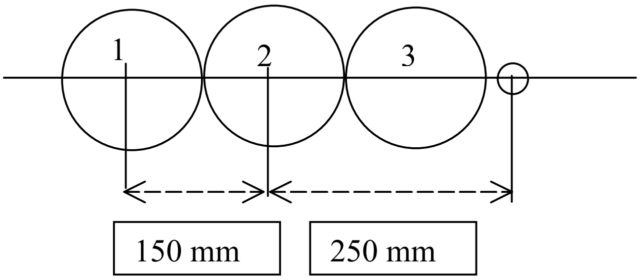


Figure D3

Table D2:

Calculations using CIM	ecc transposed	ecc not transposed
Voltage gradient in the screen of cable R (V/m)	$\pm 8.69\ 10^{-2}-j6.65\ 10^{-3}$	$\pm 8.69\ 10^{-2}-j6.65\ 10^{-3}$
Voltage gradient in the ecc (V/m)	$-j1.4\ 10^{-2}$	$7.54\ 10^{-2}-j1.4\ 10^{-2}$
Voltage screen to earth for cable R (V)	63.96	119.14
Voltage screen to earth for cable R (V) neglecting the voltage gradient in the ecc, as in Electra	63.88	63.88

Example 2 : Two circuits

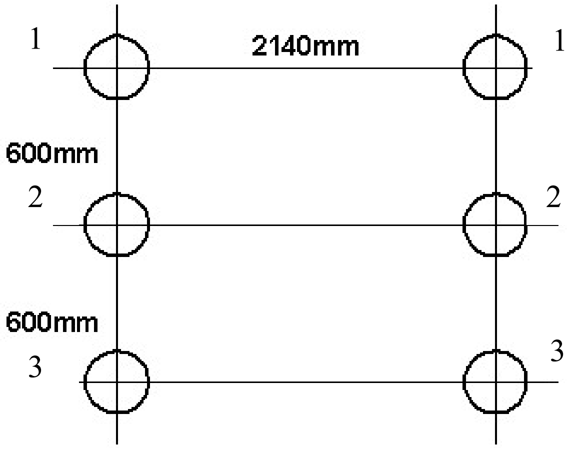


Figure D4

Electra calculated sheath voltage (to local ground) for balanced cable loading:

Group 1 only loaded: E (outer cable) = $-0.1624 - j0.0502$V/m,
Groups 1 & 2 loaded: E^{+} (outer cable) = $-0.00744 + j0.001917$V/m
Groups 1 & 2 loaded: E (outer cable) = $-0.1698 - j0.0483$V/m

Voltage gradient in the ecc
Group 1 only loaded: $E_c = 0$V/m

Groups 1 & 2 loaded: $E_c = j\ 0.0021$V/m
Comparison

Table D3:

Groups Loads (A)		**Phase**	**Sheath voltage (V) to local ground**			**Difference (%)**
Group 1	Group 2		**Electra**	**CIM**	**ATP (PI)**	
1000	0	Outer	124.6	124.6	124.1	0.0 - 0.4
1000	0	Middle	105.5	105.5	105.1	0.0 - 0.04
1000	1000	Outer	129.3	129.8	128.4	0.4 - 0.7
1000	1000	Middle	107.3	105.7	106.4	1.5 - 0.8

Example 3 : Single-phase fault in a system with 1 earth continuity conductor
(System as illustrated in figure C5)

2000mm^2 copper, 400kV fluid filled cable

Table D4:

Layer	**Diameter (mm)**
Duct	12.0
Conductor (copper)	60.2
Screen (aluminium)	61.4
Insulation (clearance under metal sheath)	106.0
Corrugated aluminium sheath (mean thickness 2.3mm)	121.0
Polyethylene oversheath	129.3

ε_r (insulation)	3.5
ε_r (oversheath)	2.5
Conductor a.c. resistance (μΩ/m @20^{0}C)	10.33
Sheath a.c. resistance (μΩ/m @20^{0}C)	35.50

Flat formation - Cable axial spacing = 300mm - Section length = 500m

Earth Continuity Conductor (ecc) Cable Details

Table D5:

Cross section	**240mm^2**	**500mm^2**
Layer	**Diameter (mm)**	**Diameter (mm)**
Conductor (copper)	17.5	25.2
Insulation	20.0	28.0

ε_r (insulation)	2.5	2.5
Conductor a.c. resistance (μΩ/m @20^{0}C)	76.5	38.82

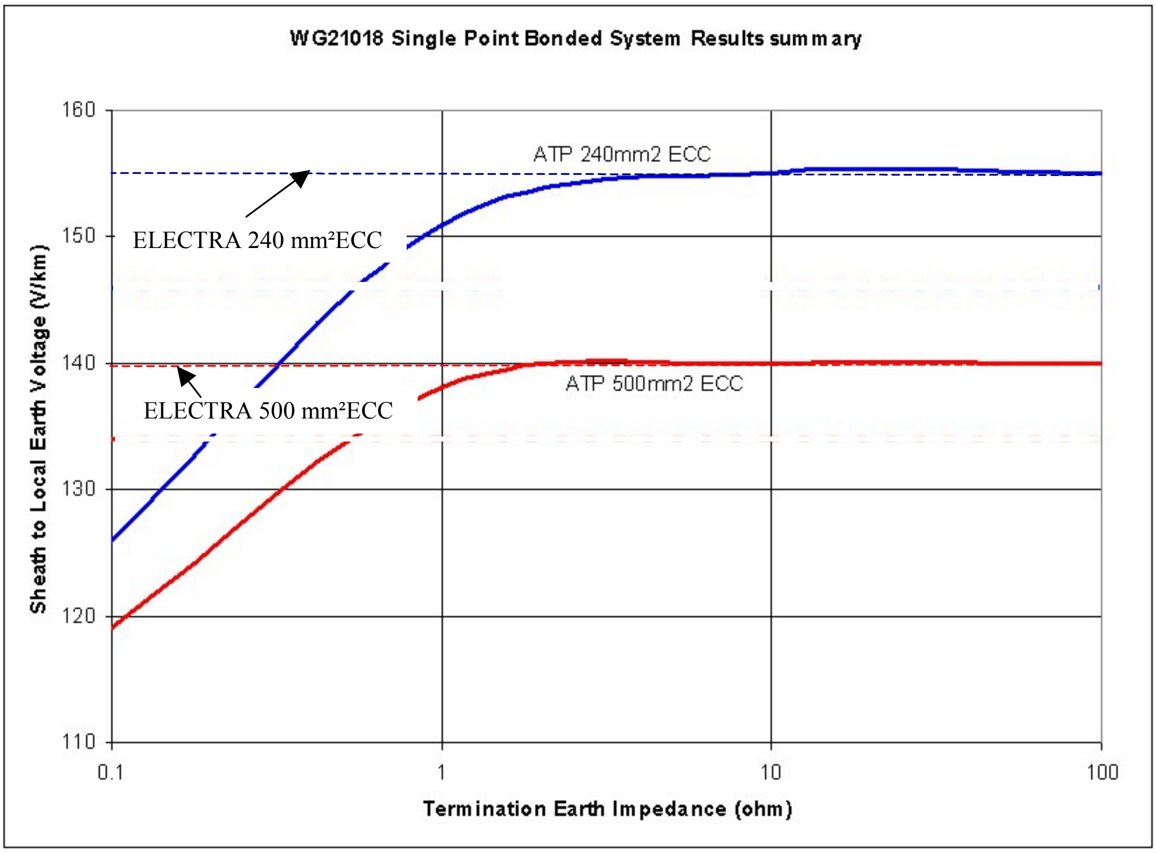


Figure D5

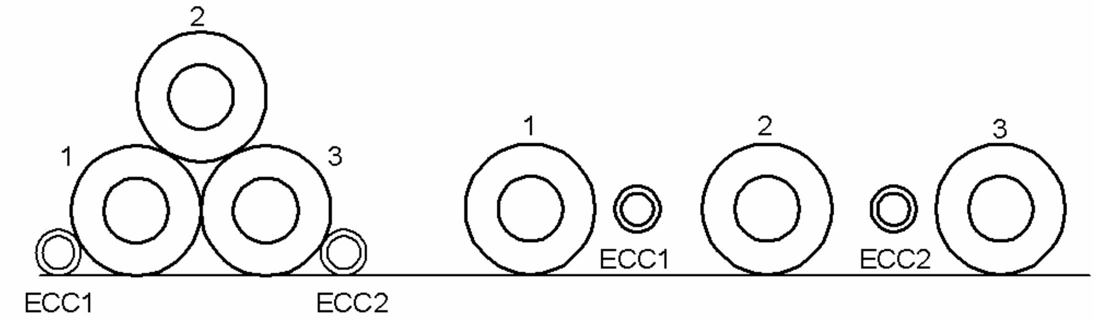
Comment

Calculations using CIM are in full accordance with ATP calculations. Detailed results are shown in tables C3 and C4.

The Electra formula is quite good for larger earth resistances (typically larger than 4Ω); for smaller earth resistances, they result in an overestimation of stresses (the condition that the whole of the return current flows in the ecc being no longer fulfilled). If the Electra formula is used in its “short expression”, neglecting the resistance of the ecc, an underestimate of 3 % or 1 % is introduced respectively for the 240mm² ecc and for the 500mm² ecc, and for larger resistances.

Example 4: Single phase fault in systems with two earth continuity conductors.

2000mm^2 copper, 400kV fluid filled cable, as per earlier example.



Trefoil group with 2 eccs Flat spaced group with 2 eccs

Figure D6

Each ecc is assumed to be transposed about the group at the x = 250m position.

Table D6:

Cross section	**240mm^2**	**500mm^2**
Conductor (copper) diameter (mm)	20.1	29.8
Conductor a.c. resistance (μΩ/m @20^{0}C)	76.5	38.82

Fault current : 63 kA.

Table D7:

Configuration	ecc Size (mm^2)	Faulty Phase	E (kV) Sheath Voltage with 1 ecc	E (kV) Sheath Voltage with 2 eccs
Trefoil	240	1/2/3	7.1 / 9.1 / 7.1	3.7 / 5.6 / 3.7
	500	1/2/3	6.5 / 8.3 / 6.5	3.4 / 5.2 / 3.4
Flat Spaced	240	1/2/3	9.2 / 9.2 / 9.2	5.3 / 5.2 / 5.3
	500	1/2/3	8.8 / 8.8 / 8.8	4.9 / 4.8 / 4.9

4.0 TRANSIENT OVERVOLTAGE APPLICATIONS

4.1 General Considerations

Historically, specially bonded sheath cable systems have been mostly designed to include SVLs at cross bond positions (for cross bonded systems) and at the unearthed ends of single point bonded systems. The inclusion of SVLs in general reduces the degree of specialist transient overvoltage study necessary by the cable System Designer and analysis of power frequency applications is more relevant, in order to correctly select the SVLs. The level of transient overvoltage study where SVLs are included, is generally limited to the following issues:-

- Permissible lengths of bonding leads
- Sheath interrupt withstand voltage for cross bonding with SVLs
- Design of protective gaps (arcing horns) at terminations to limit incoming transients

For transient overvoltage analysis, complex design study has not therefore historically been a typical activity and relatively simple system analysis based on cable and bonding leads surge impedances has generally been considered as suitable. However, two relatively recent developments have acted to necessitate more complex analysis:-

- The use of EMTP and ATP software to model cable systems
- The expressed objective by some Utilities to eliminate or to reduce the use of SVLs in specially bonded systems; usually for reasons of reduced cost and/or maintenance.

General guidelines are given in clause 4.9 regarding the application of EMTP/ATP to cable system transient studies and clauses 4.3.2 and 5.1.2 consider the application or removal of SVLs in specially bonded systems. In addition, the following clauses consider important issues of bonding leads, SVL characteristics and performance and worked examples which study transient behaviour in 225kV and 400kV cable systems.

4.2 The Characteristics of Lightning

4.2.1 Typical Lightning Flash

Figure E1 illustrates a typical lightning flash. A first stroke is followed by subsequent strokes. A residual current circulates between strokes. According to CIGRÉ [8], the typical flash duration is 200ms. It includes 2 to 3 strokes with an interval of typically 45ms between the first two and 35ms between the subsequent strokes.

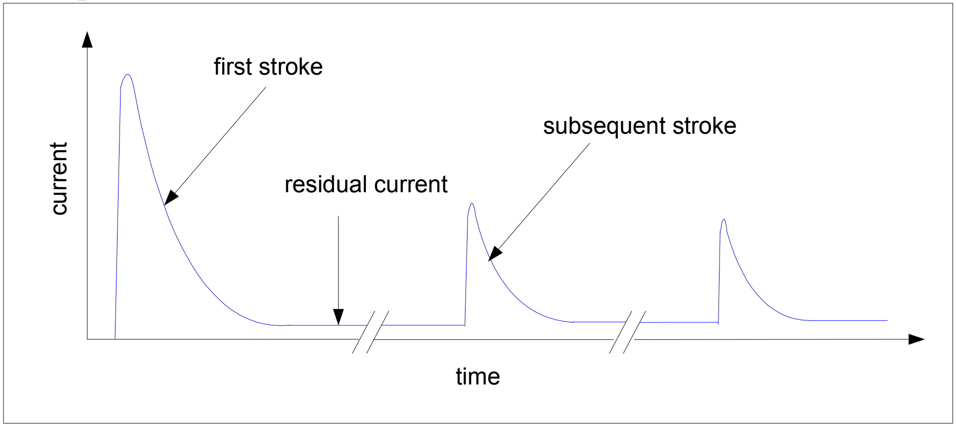


Figure E1 Typical lightning flash

Table E1 presents the characteristics of 20 and 50% probability lightning flashes. Although subsequent strokes have lower amplitudes, they have shorter rise times associated with higher d*i*/d*t*.

Table E1: Characteristics of lightning flashes

Stroke	Probability of exceeding	Peak value (kA)	Rise time (µs)	max. d*i*/d*t* (kA/µs)	Stroke duration (µs)
First	50%	30	4.5	24	80
	20%	60	1.8	40	110
Subsequent	50%	12	0.6	40	30
	20%	20	0.25	80	70

Since the voltage drop on bonding leads is proportional to the d*i*/d*t* of the current in the SVLs, subsequent strokes are likely to produce higher voltages.

4.2.2 Shielding Failure vs Backflashover

Low amplitude lightning strikes can bypass the overhead sky wire and strike directly on phase conductors (shielding failure). Higher amplitude flashes strike the shield wire and may cause a backflashover. It has been estimated in [9] that, on the 400kV system considered, a 20kA shielding failure (1 in 40 years) is more probable than a 100kA strike on the sky wire (1 in 150 years). Similarly, a 35kA shielding failure (1 in 300 years) is more probable than a 150kA strike on the sky wire (1 in 600 years).

A strike to the shield wire excites mainly the sheath-to-earth mode that is characterized by high attenuation [section 4.8]. Results show significant attenuation for distances exceeding a few hundred metres. Since high frequencies are significantly attenuated, the d*i*/d*t* of the current in the bonding leads is low as is the voltage drop (see worked example of section 4.8). Back flashovers and shielding failures excite coaxial modes of propagation in the cable that are much less attenuated (see worked example in section 4.7).

4.3 Bonding Leads and SVLs

4.3.1 Introduction

Bonding leads are important items in sheath bonding and earthing circuits and whilst for power frequency applications their influence on induced sheath voltage is negligible, for transient overvoltage applications bonding leads can have a significant effect on sheath voltages.

The worked examples shown in clauses 4.7 and 4.8 illustrate the influence of bonding lead type and length on sheath interrupt voltage for two different cross bonded systems. Furthermore these examples assess systems with and without SVLs and using SVLs of different voltage ratings. The examples consider specific system models, whilst a more general consideration of bonding lead and SVL issues is given below in 4.3.2 to 4.3.5.

4.3.2 The Application or Omission of SVLs

a) Cross Bonded Systems

Clause 5.1 details the approach taken in Belgian 70kV and 150kV cross bonded systems to remove SVLs in long cable systems. The method is often referred to as “Direct Cross Bonding” and in general can be characterised by the following design features.

- Detailed system assessment using EMTP
- Use of line surge arrestors to limit incoming transients
- Design of sheath sectionalising insulation at cross bonding joint to withstand predicted barrier voltages under transient conditions.
- In the case of a mixed connection (overhead line – underground link), SVLs are retained for the cross bonding joints in the first major section close to the overhead lines, because these sections are considered vulnerable to transient overvoltages above the withstand level of the sheath sectionalising insulation at joints.

For the worked examples shown in clauses 4.7 and 4.8, the inclusion of SVLs is shown to have a significant influence on sheath voltages at cross bond joints. It must of course be remembered that the purpose of the SVL is to protect the sheath sectionalising insulation at the cross bond joint and is not expected to provide a more general protection along the cable sheath. An illustration of this is provided in the second worked example, in clause 4.8.

b) Single Point Bonded Systems

For single point bonded systems it is recognised that in most cases the unearthed sheath location is at a cable terminal and therefore vulnerable to incoming transient overvoltages, whether switching or lightning in nature. For single point bonded systems where the unearthed location is remote from terminals (e.g, mid-point bonding) the distance between the unearthed position and the terminals is unlikely to be considerable and again, is therefore vulnerable to incoming transients. For single point bonded systems therefore, it is recommended that SVLs should be used at the unearthed positions.

4.3.3 Earthing of SVL Star Point

For cross bonded connections where SVLs are connected in star formation it is not considered that sheath voltages under transient conditions would differ significantly whether the star point is earthed or not as very little current would flow to earth via this connection. For other reasons it may be considered preferable to earth the star point (e.g. safety, maintenance) or not (to limit power frequency voltages).

4.3.4 SVL Response to very fast front transients

In the particular case of an internal cable fault the phase voltage collapse can have a front time in the order of 10ns. Switching transients in GIS also produce very high frequencies. Laboratory measurements have shown that the response time of ZnO is smaller than 1ns [10], [11]. Therefore, SVLs should not introduce any significant time delay in the protection of sheath interrupts against fast front transients. However, the bonding leads introduce a delay proportional to their length. As an example, assuming a speed of propagation of 150m/μs, 5m bonding concentric leads introduce a delay of 67ns. Given that attenuation is greater at higher frequencies, remote joints with sheath interrupts are less vulnerable to these high frequency transients.

Where cables are terminated into GIS having no transformer between termination and circuit breaker the sheath sectionalising insulation (if present) should be protected against voltage flashover during switching operations. Short circuiting links or SVLs, as appropriate, should be connected directly across the sectionalising insulation and where practical, at least two such connections should be made at 180 degrees around the sealing end circumference. These connections, including SVLs if fitted, should be as short as possible and as a guide, should not exceed 500mm.

4.3.5 Bonding Lead Type - Concentric and Single Core

The present practice reflected in clause 1.2.3 is that both single core and concentric bonding leads are widely used for cross bonded systems at all voltages, with concentric leads used more than single core at 132kV and above. Concentric leads have the benefit of both low surge impedance and inductance. Single core leads have higher surge impedance and inductance. For typical lengths of bonding lead inductance is considered the more relevant parameter. The study reported in section 4.7 shows that for single core bonding leads spaced at 300mm apart, the overshoot of transient voltage across the barrier is in the order of 250% when compared with concentric leads. The current rise time in the SVL is also increased due to the higher inductance between bonding leads (figure H6).

However, when using single core leads, the voltage overshoot can be greatly reduced by tie-wrapping the go/return leads together to minimise inductance or by restricting bonding lead length. Tests carried out in the Netherlands to compare barrier voltages when using concentric and tie-wrapped single core leads, indicate that for the single core case the voltage is typically higher by 5% (for 3m leads), 8% (for 10m leads) and 22% (for 20m leads). These results relate to an applied transient voltage having a rise time of 1.3 - 2.1μsec and a time to half peak of 31 - 34μsec and should be considered as indicative only.

In conclusion, whilst concentric leads have a superior transient performance, single core leads can also be used and may offer other advantages such as needing simpler joint protection systems. It is however recommended that in single core lead applications, go/return leads are tie-wrapped. In those conditions where the link boxes are very close to the joints, bundling the leads may not be practical, but is not needed due to the low inductance.

4.3.6 Bonding Lead Length

When SVLs operate under transient conditions, the premise can be taken that the barrier must be able to withstand the residual voltage across the SVL(s) plus the voltage dropped across the bonding leads.

It can also be assumed that this voltage drop is linked to the surge impedance of the bonding leads and to the travelling time within the leads [12], or it can be linked mainly to the lead inductance [13]. Of these parameters, lead inductance is likely to be the most representative.

The two approaches are compared in section 4.5.

With both methods, the voltage drop across the bonding leads is roughly proportional to the lead length.

The main problem with both methods is the modelling of the bonding leads, i.e. the determination of the surge impedance or the inductance.
Large scatterings are found in the literature (e.g. inductances p.u. length ranging from about 0.1 to 1.2μH/m) leading to significant discrepancies on the voltage drop.

4.4 The Influence of Earth Resistance at Terminations and Joint Bays on Sheath Voltages

EMTP calculations carried out on a typical 225kV XLPE cable siphon show that the sheath to earth voltages increase slightly with the ground resistance at the transition.

The influence of the earth resistance at joint bays (for systems with grounded star connection of the SVL) is not very significant in the range from 10 to 100Ω (an increase of the resistance probably turns into a reduction of the current flowing to earth).

4.5 Simplified Calculation Methods

4.5.1 Introduction

Electra 47 [2], table II sets out recommended withstand voltage (impulse) levels for sheath sectionalising insulation where SVLs are used.

As the method for deriving these levels is not reported and some assumptions are questionable, the WG considered the only known published “simple” method for determining barrier voltage when using SVLs [12], and, more generally, investigated on the stresses applied on underground links under transient conditions, as they may be estimated using EMTP software.

4.5.2 Electrical Data

Electra 47 is based on calculations (method not reported) using the following data:

- Residual voltage of SVL = 20kV (assumed 2 x SVLs, each with 10kV residual voltage)
- PE bonding lead surge impedance = 30Ω (assuming a coaxial cable)
- Cable main insulation surge impedance (Z_1) = 20Ω
- Cable sheath surge impedance (Z_2) = 10Ω
- 3 m and 10 m length bonding leads

- 1.2/50µs. wave – modified to 1µs. Front with 15% BIL adjustment (stated that the “pulse” is typically only 1µs.).
- adding 25% to calculated barrier voltage and rounding up to next IEC standard level

4.5.3 IEEE Method

Electra 47 provides no details on the calculation method for barrier voltage with SVLs.
The only known published “simple” method for determining barrier voltage when using SVLs is that shown in the 1965 IEEE paper [12]. This method, which does not work for the Electra 47 data, was used with typical cable constructions.

By following the adjustments suggested in Electra 47 for both incoming transient and for rounding the calculated barrier voltage, different levels are achieved than those shown in table II of Electra 47. Table F1 below shows the comparison, with values in brackets being the existing Electra 47 levels.

Table F1 : Calculated barrier voltage using IEEE method

BIL (kVp)	Barrier Voltage (kVp)	
	3m	10m
325	40 (40)	60 (40)
650	45 (40)	75 (75)
1050	45 (40)	75 (95)
1425	45 (40)	75 (125)

These results assume that 45kVp is an acceptable standard.

4.5.4 Simplified Formula (Cigre WG)

Recently, a simple formula was presented [2] for determining barrier voltages in the case of lightning strikes on the phase conductor. This formula was deduced from numerous calculations carried out with EMTP, where the bonding leads were modelled as inductances, with an assumed value of 0.24µH/m.

The barrier voltage (for 2 SVLs star connected) is :

$$E_{1b} = 2.\left[U_R + 0.45.L_b.L.\frac{I}{\tau}\right] \qquad \text{(F1)}$$

where :
U_R is the SVL residual voltage (kV)
I is the incoming current (kA)
τ is the duration of the wave front (µs)
L is the length of bonding leads (m)
L_b is the inductance per unit length of the bonding lead (µH/m)

This simple formula leads to barrier voltages which are not very different from the Electra levels, for an incoming current :

$$I = \frac{BIL}{Z_1} \qquad \text{(F2)}$$

If the inductance of the bonding leads is linked to the surge impedance by the following relationship:

$$L_b \approx \frac{Z_{1b}}{v} \qquad \text{(F3)}$$

where v is the wave velocity (value used in table F2 is 200m/µs).

4.5.5 Data and results for the present study

Cables: Fluid filled and XLPE 'typical' middle of the size range constructions and dimensions
PE oversheath
Designs for BIL = 325kVp. 650kVp, 1050kVp, 1425kVp

Bonding Lead: PE concentric leads (assuming UK standard EATS C55/4)
Conductor sizes: 120mm^2, 240mm^2, 300mm^2, 500mm^2

The surge impedances of cables and bonding leads and the bonding lead inductances are reported in table F2, together with calculated barrier voltages for 3m and 10m bonding lead lengths. It should be noted that the bonding lead impedances are different from those obtained from Electra 47 : i.e. $Z_{1b} = Z_{2b} = 30\Omega$.). The following results are before adding 25% or rounding up to IEC levels.

Table F2 : Data and calculation results

Cable	**BIL (kVp)**	**Z_1 (Ohm)**	**Z_2 (Ohm)**	**Z_1/Z_2**	**Z_{1b} (Ohm)**	**L_{1b} (µH/m)**	**Z_{2b} (Ohm)**	**Z_2/Z_{2b}**	**Barrier voltage (kV)**		
									IEEE (3 m)	**IEEE (10 m)**	**Cigre WG (10 m)**
SCFF	325	11.09	4.97	2.23	22.30	0.113	7.81	0.64	30	48	50
SCFF	650	13.99	4.12	3.40	17.35	0.088	6.34	0.65	33	59	57
SCFF	1050	22.23	3.55	6.26	15.57	0.079	6.90	0.51	33	58	54
SCFF	1425	27.42	3.05	8.99	16.84	0.085	4.25	0.72	33	58	60
XLPE	325	21.55	3.84	5.61	22.30	0.113	7.81	0.49	25	34	35
XLPE	650	26.69	3.68	7.25	17.35	0.088	6.34	0.58	27	41	39
XLPE	1050	34.71	3.03	11.46	15.57	0.079	6.90	0.44	28	43	41
XLPE	1425	33.59	2.59	12.97	16.84	0.085	4.25	0.61	30	48	53

4.5.6 EMTP Calculations

In addition, the WG carried out calculations on a typical 225kV siphon (as reported in section 4.8), modelling bonding leads as inductances (12.3µH for 10m). The study focussed on the effect of lightning strikes impacting the overhead line close to the transition compound, since the present design of overhead lines, including optimisation of the sky wire(s) location, results in a very low probability of shielding failures, with relatively low currents.

When dealing with strikes on a sky wire, without back flash-over, the voltages applied are more or less the same on the three screens of the cables, and, so, the voltages on the screen interruptions are quite moderate.

Back flash-over may occur but the stresses applied on the underground links are reduced due to the low surge impedance of underground links compared to overhead lines, and the presence of surge voltage limiters at the transition compound.

Screen voltages (referring to remote earth :

- depend on the location of the lightning strike (the closer, the higher);
- are roughly proportional to the lightning strike current;
- may reach high values at the transition compound, but decrease with the distance to the transition (e.g. from 100kVp to 40kVp , 350 m to the transition for a 20kA current)
- are only slightly influenced by the earth resistance at the transition.

The voltage applied to the screen interruptions at the first cross-bonding position does not depend on the earth resistance at the transition compound. When a back flash-over occurs, the voltage is higher, compared with the situation without back flash-over, and is about two times the screen to ground voltage, which depends on the SVL rated voltage. However the effect of bonding lead length is only slight. Even in the case of a 200kA lightning strike impacting the second tower to the transition, resulting in a back flashover, the overvoltage is less than 80kVp (for 10m bonding leads and 10kV rated SVLs).

4.6 Insulation Coordination

Voltages that may be applied to an underground link connected to an overhead line seem to be overestimated in Electra 47 table II, with the exception of systems for 345kV BIL having 10m bonding leads.

This is clear for the situation where lightning strikes impacting the overhead line phase conductors, as sky wires prevent high current injection. Conversely, if lightning strikes occur on the sky wires, high stresses may occur if the impact location is close to the transition compound, and if the current level is high enough to produce back flashovers. However, even in this particular case, and assuming that the bonding leads may be modelled as 1μH/m inductances, the stress is below the recommended withstand level (assuming a typical 225kV system and 10kV rated SVLs).

Considering the satisfactory outcome of experience with present designs, the WG recommends the withstand voltage (impulse) levels for sheath sectionalising insulation recommended in Electra 47, table II be kept, except in the case of “long” bonding leads for a system with 325kV BIL.
The WG consider that this level should be increased to 60kVp. Recommended levels are therefore as shown in table G1 below:-

Table G1 : Recommended Barrier Lightning Withstand Voltages for 3m and 10m Bonding Leads

	Barrier Voltage (kVp)	
BIL	**3m**	**10m**
325	40	60
650	40	75
1050	40	95
1425	40	125

For VHV systems, where the design of the sectionalising joint is made for 10m bonding leads, SVLs with higher ratings may be used. The limit of SVL rating for 225kV systems is 20kV (instead of 10kV quoted in Electra 47). This can result in longer minor sections, thereby reducing the number of cross bonded sections. The design needs also to be compared against the withstand levels of the sectionalising insulation, the joint protection and the cable oversheath.

Once the SVLs have been selected, the maximum length of the minor sections is deduced by considering induced voltage levels under power frequency conditions, taking account of any safety limits under normal service conditions.

4.7 Worked Example 1: Influence of the Bonding Leads on the Voltage Across Sectionalising Joints During Fast Front Transients

4.7.1 Lightning conditions considered

With a view to complement the worked example given in 4.8, the shielding failure is considered. The current is injected on the phase conductor at the cable sealing end. This injection excites a coaxial mode in the cable system that is significantly less attenuated than the sheath-to-earth mode. Furthermore, subsequent strikes are considered because of their higher d*i*/d*t* on the front of the wave. Amplitudes of 12 and 20kA are considered. The characteristics of the current pulses are given in Table E1.

4.7.2 System considered

A 400kV cable system as previously defined in tables B2 and B3 of clause 3.2.8 for a power frequency worked example has been studied under transient conditions in the following sections. The system is a 3km long cross-bonded circuit comprising two major sections. Cable spans (minor sections) are 500m long. Calculations are performed with EMTP and a distributed line model with frequency dependent parameters (FDQ cable model) is used for the cable.

4.7.3 Bonding leads and SVLs

SVLs have a 6kV nominal rating; they are star connected with the neutral point earthed. Both single conductors and concentric bonding leads are considered (see figure H1). A PI circuit is used to model the bonding leads. Single core leads are 30cm apart. A length of 5m is considered.

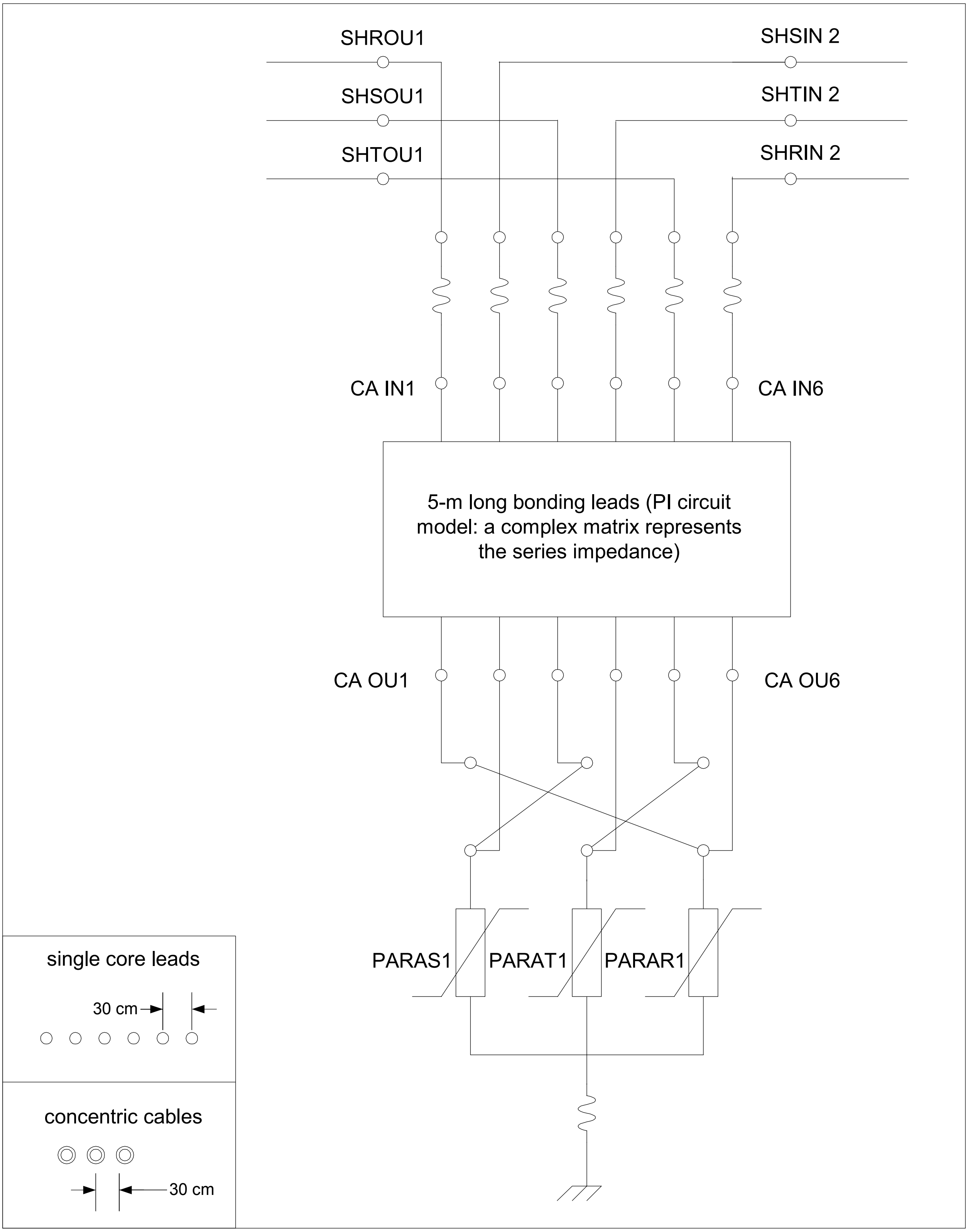


Figure H1: Configuration of the bonding leads

4.7.4 Results

Figure H2 presents the 20kA current pulse injected on phase R and the resulting voltage on phase R at the injection point. The overvoltage is significantly lower than the protection level of the arrester protecting the main insulation of the cable.

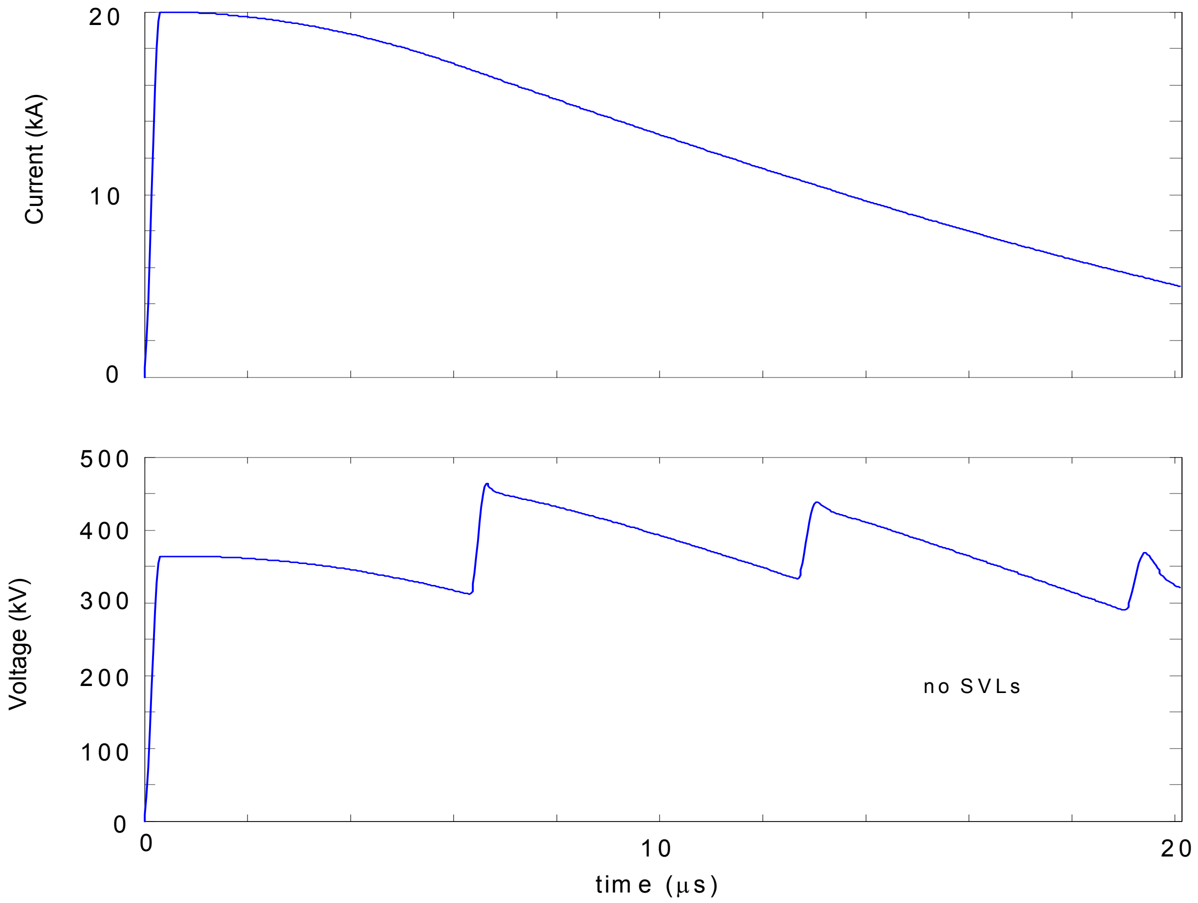


Figure H2 Injected current on phase R and phase-to-neutral voltage on phase R

If there are no SVLs protecting the sheaths, the voltage across the interrupt at the first and the fifth joints reaches 200kV and 180kV respectively (see Figure H3). The voltage is reduced by only 10% over the 2km between the two joints. For the 12kA pulse, the overvoltage is reduced to 120 and 110kV respectively. Since the arrester protecting the main insulation does not operate, the overvoltages are proportional to the impulse current amplitude.

With SVLs, the voltage across the interrupt is limited to approximately 50kV except for a very short period that coincides with the wave front (see Figure H4). Figure H5 presents a zoom of the first microseconds of Figure H4. The overvoltage reaches close to 250kV and 100kV for single core and concentric leads respectively. The duration of the overvoltage is less than 1µs. For the 12kA pulse, the overvoltage reaches 135kV and 60kV for single core concentric leads respectively. Reducing the length of the bonding leads would reduce the overvoltage accordingly.

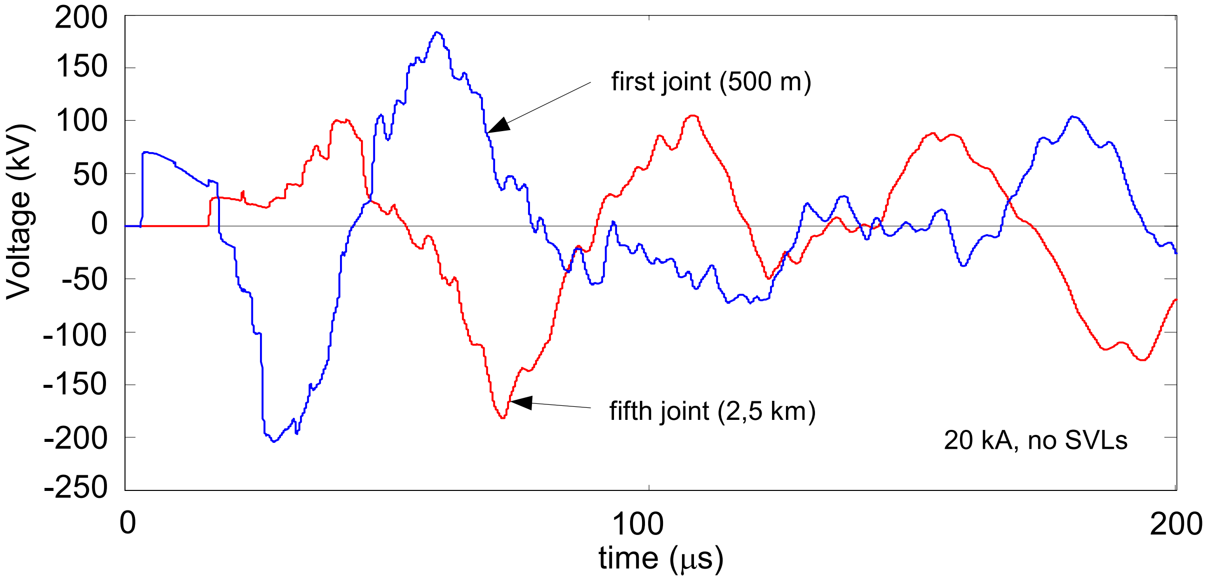


Figure H3: Voltage across the sheath interrupt (20kA, no SVLs)

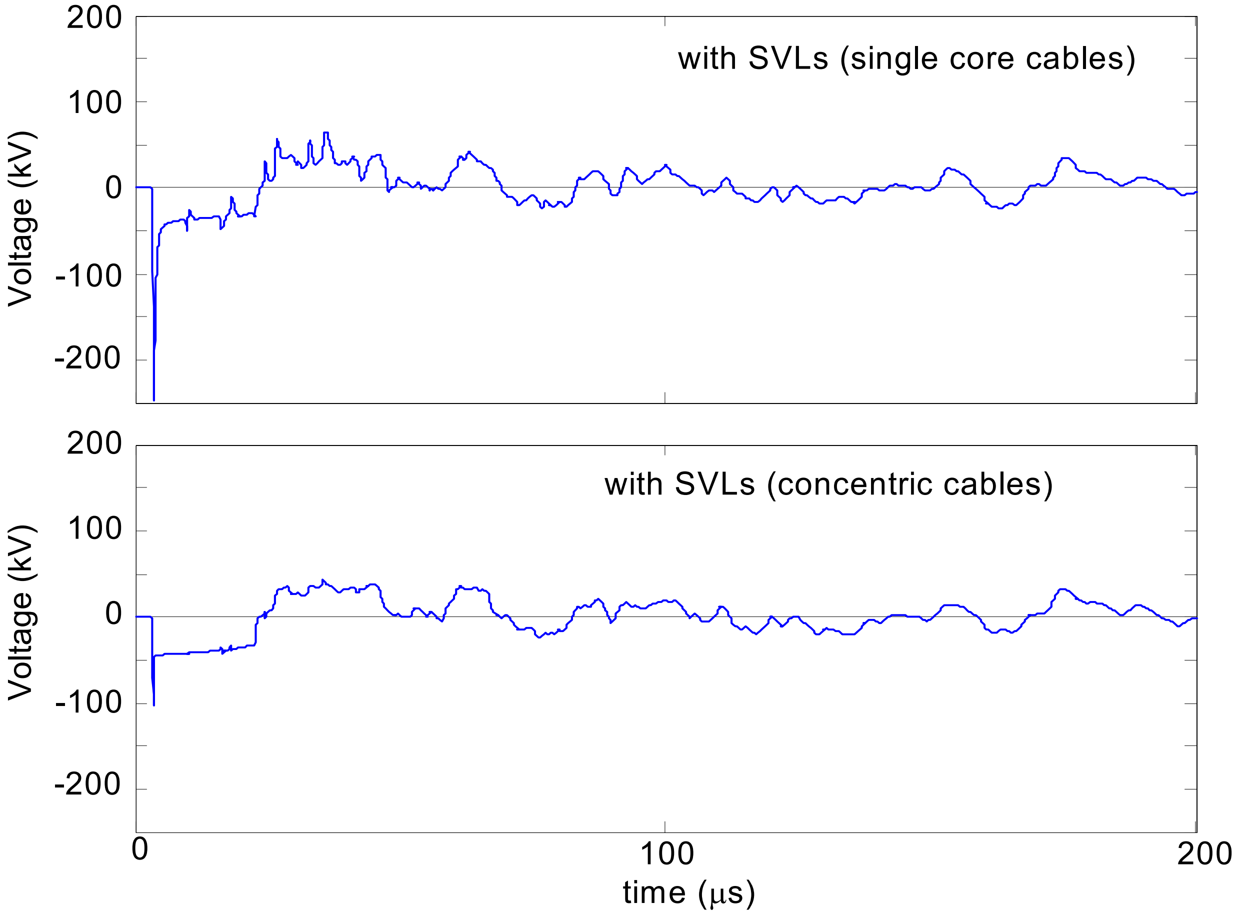


Figure H4: Voltage across the first sheath interrupt (20kA, with SVLs)

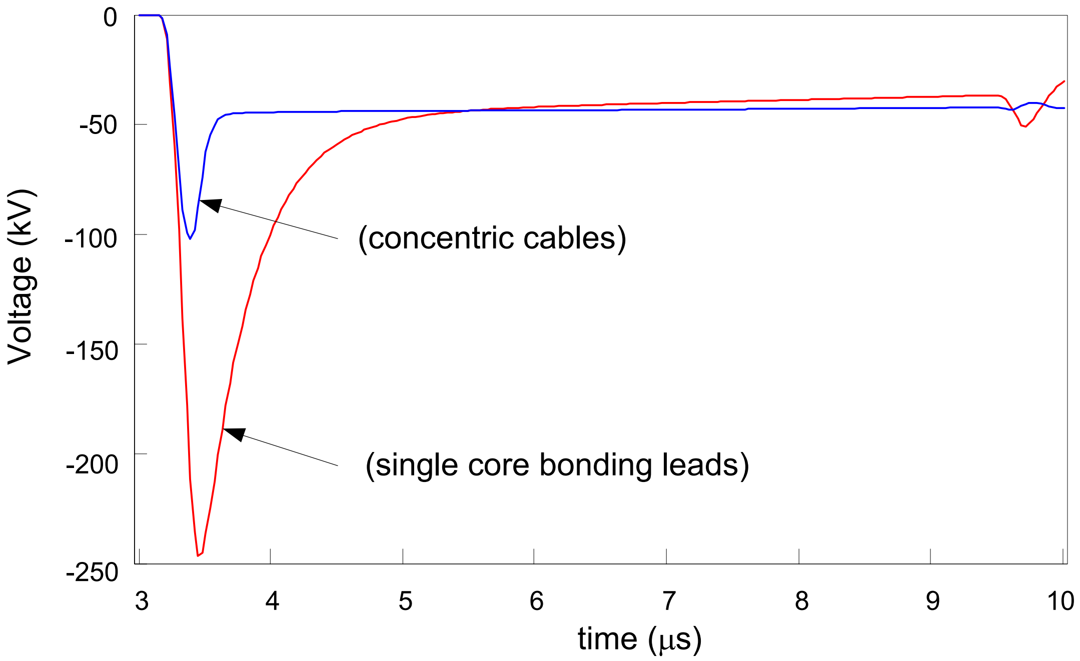


Figure H5: Voltage across the sheath interrupt (20kA, with SVLs, first joint)

Figure H6 shows the current in the SVLs for concentric and single core cables. The higher inductance of the single core leads contributes to reduce the d*i*/d*t* of the current in the SVLs and the overvoltage accordingly.

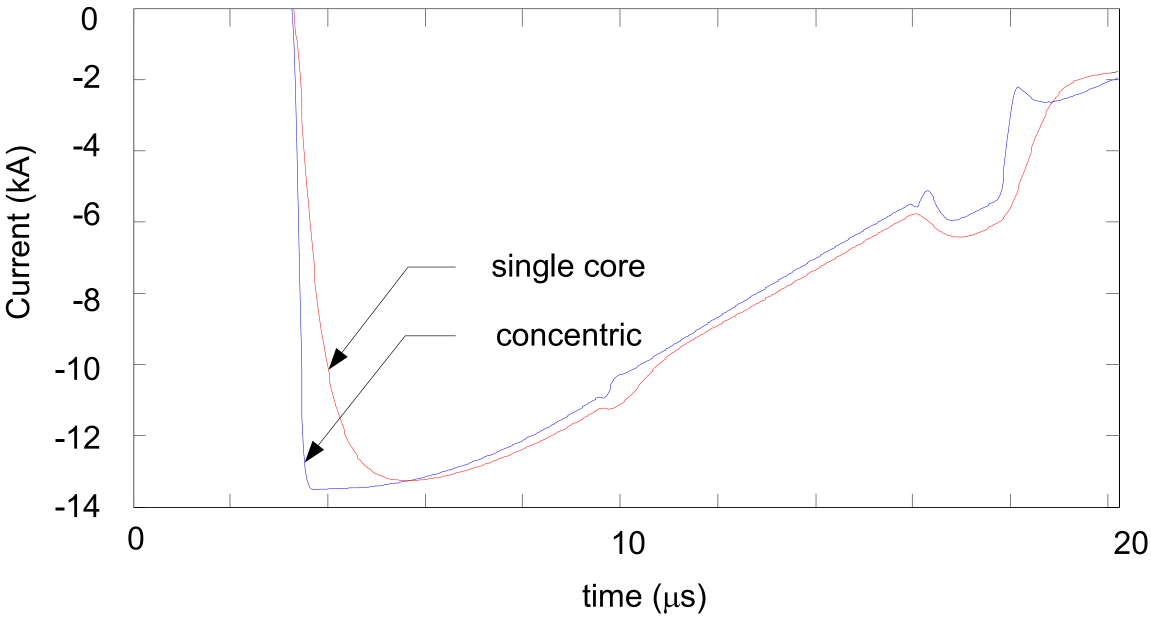


Figure H6: Current in the SVLs (20kA, first joint)

As shown in Figure H7, SVLs installed only in the first main section contribute to the reduction of the overvoltages in the second main section. The voltage across the fifth interrupt is reduced from 180 to 130kV if SVLs are installed at the first two joints.

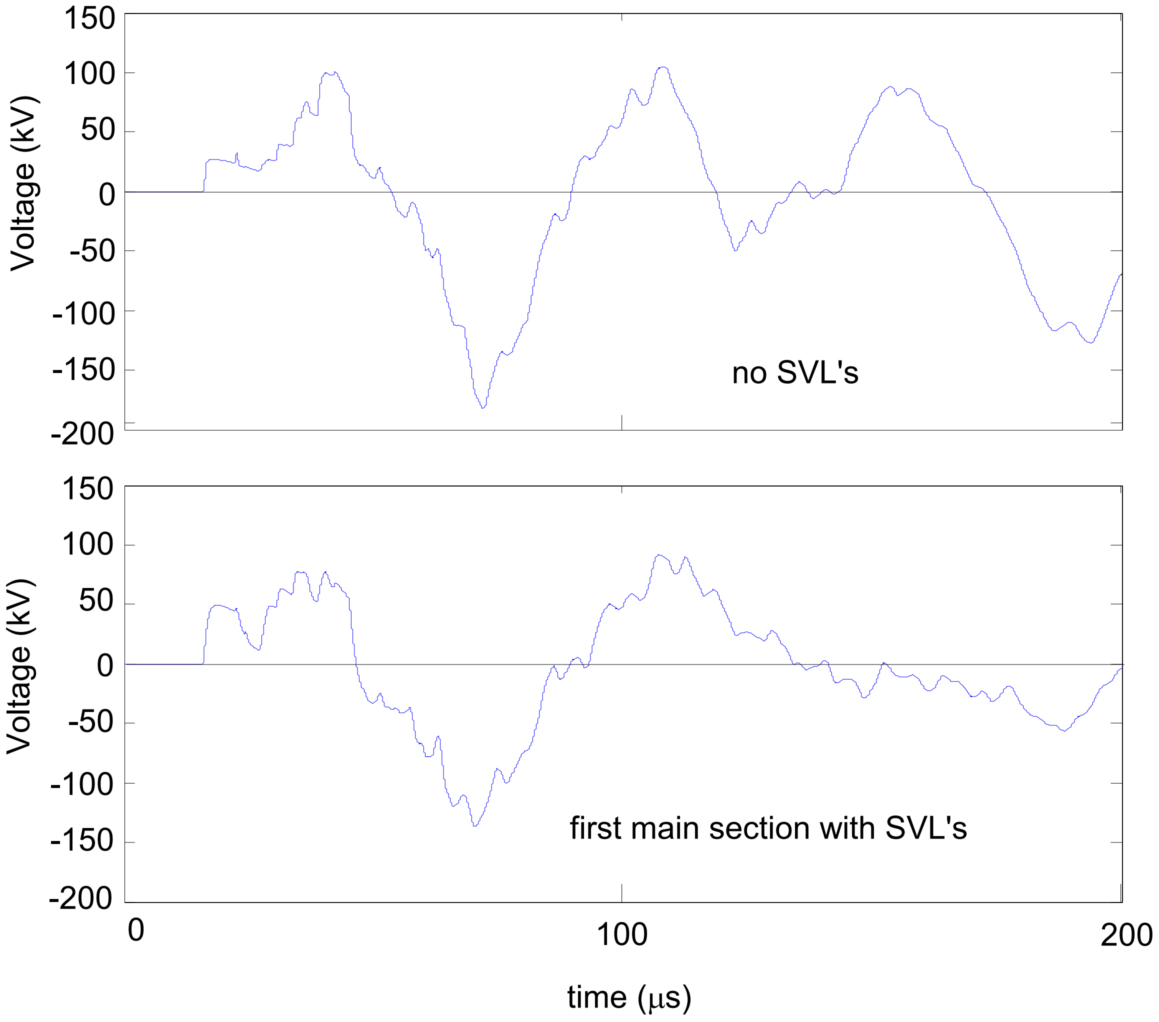


Figure H7: Voltage across the interrupt (20kA, fifth joint)

4.7.5 Summary of the Results

Lightning transients resulting from back flashover or a shielding failure excite coaxial modes of propagation in the cable system that are characterised by low attenuation. The overvoltages associated with these transients can therefore affect sheath interrupts located up to a few kilometres.

For the analysis of lightning transients, bonding leads can be modelled with their inductance only. The model should include both self and mutual inductances. Bonding leads can produce significant overvoltages across the interrupt but their duration is typically less than 1µs.

Coaxial (or concentric) bonding leads produce lower voltages due to their lower inductance. The inductance (and associated overvoltages) of single core leads can be reduced by bundling the go/return leads together.

4.8 Worked Example 2: Parameter Study of the Fast Front Over-Voltages Stressing the Sheaths and the Sectionalising Joints of a 225kV Siphon

4.8.1 Introduction

This example presents a study of the fast front over-voltages stressing the sheaths and the sectionalising joints of a 225kV cross-bonded siphon equipped of sheath voltage limiters at each junction.

The detailed description of the configuration under study is given in section 4.8.2 and is followed by a summary of the modelling used to perform the calculations (sections 4.8.3 – 4.8.4 – 4.8.5). The report then presents some calculation of over-voltages along the sheath of the first elementary section in order to determine the spot where the stress is a maximum in order to study afterwards the influence of several parameters on the level of over-voltage obtained at this spot. The subsequent sections are devoted to the study of over-voltages stressing the sheath and the sectionalising joint at the first junction.

The software EMTP-RV has been used to perform the calculations (www.emtp.com).

4.8.2 Description of the configuration

This study considers the case of a 225kV single-circuit siphon included in a single circuit overhead line protected by 2 sky wires

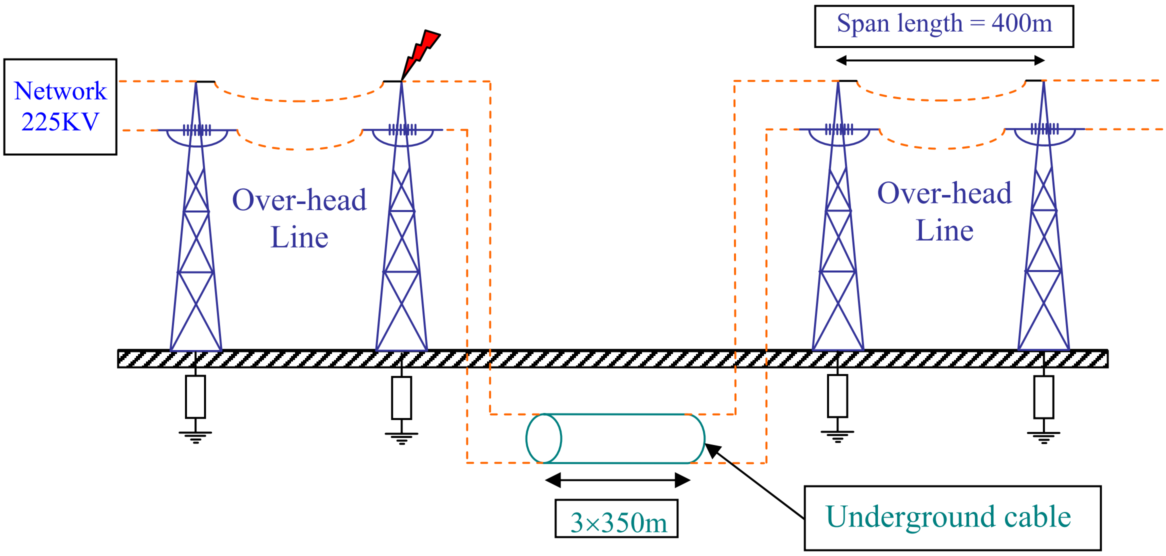


Figure J1: Representation of the configuration

4.8.3 Description of the underground cable

The underground part is made of 3 single-core cables whose sheaths are cross-bonded and whose phases are transposed. It is constituted of 3 elementary sections of length 350m.
The description of the each single core cable is given in table J1.

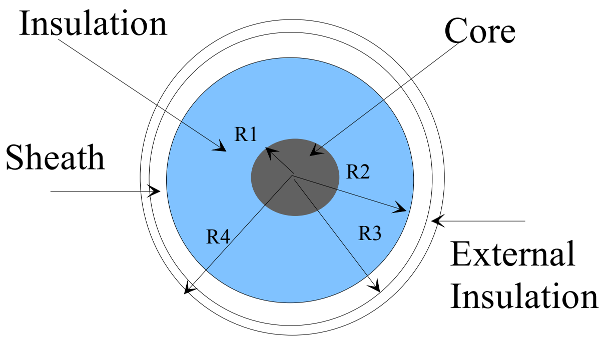


Figure J2: Notations used to describe the single-core cable

R1 (cm)	2.45
R2 (cm)	5
R3 (cm)	5.28
R4 (cm)	5.68
Resistivity of the core (Ω.m)	3.68e-8
Main insulation relative permittivity	3.143
Main insulation loss factor	0.0004
Sheath resistivity (Ω.m)	2.1 e-7
Sheath insulation relative permittivity	3.6
Loss-factor	0.3
Length of a minor section (m)	350 m

Table J1 : Parameters of the single core cable.

The loss-factor of the sheath has been increased to account for losses which are not represented in EMTP (proximity effect, presence of semiconductor layers and the existence of a vertical electrical field in the soil)

The position of the single core cables in the ground is given in table J2.

Cable number	Abscissa (m)	Ordinate (depth in the soil (m))
1	0	1
2	0.1	1.194
3	0.2	1

Table J2 : Position of the single-core cables in the soil.

4.8.4 Description of the overhead line

The 225kV overhead line is equipped with 2 sky wires. Its description is given in Table J3.

Conductor	Phase 1	Phase 2	Phase 3	Sky wire 1	Sky wire 2
DC resistance (Ohm / km)	0.057	0.057	0.057	0.237	0.237
Outside diameter (cm)	3.15	3.15	3.15	1.96	1.96
Horizontal distance of conductors from a vertical axe (m)	-5.5	0	5.5	-3	+3
Vertical height of conductors at tower (m)	20	20	20	25	25
Vertical height of conductors at mid span (m)	15	15	15	20	20
Length of a span (m)	400				
Resistivity of the soil (Ω.m)	100				

Table J3 : Description of a span. The line is a 225kV single circuit line equipped with 2 sky wires.

The protection of the main insulation
The main insulation of the cable is protected by surge arresters (rated voltage 225kV) installed at both terminals. Data used to represent the surge arrester has been obtained from a 96kV surge arrester whose characteristic has been given in section 4.8.17. They are connected by a 3 m long lead to the grounding electrode (corresponding to the grounding electrode of the first tower).

The protection of the junctions
The sheaths and the sectionalising joints at the junction are protected by star-connected and grounded sheath voltage limiters. Several rated voltages are considered. Data corresponding to a rated voltage of 6kV is given in table J13. The data for other rated voltages will be obtained based on this one.

The connection between the overhead line and the underground cable
It is 20 m long.

The towers
Their height is 20m. Except when specified otherwise their grounding impedance is 10Ω. The withstand voltage of their insulator strings is 900kV.

4.8.5 Modelling used

Representation of the sections of the underground cable
The sections of the underground cable have been represented using the FDQ model [10][11].

Representation of the overhead line
Spans in the vicinity of the siphon have been represented using the FDLINE model. Corona effect has not been taken into account. Spans far from the siphon have been represented by single long line avoiding unrealistic reflections.

Towers
Towers have been represented as loss-less lines. The wave velocity has been taken equal to the velocity of light in vacuum.

Air gap
They are represented as an ideal switch closing when the voltage between its terminals reaches the withstand voltage of the air gap.

Grounding electrode of towers
They have been represented as a constant resistance, except for the grounding electrode of the tower just before the underground cable, which has been represented taking into account soil ionisation [15].

Connections between the overhead line and the underground cable
They have been represented as a lumped inductance (1µH/m).

Sheath Voltage Limiters
Sheath voltage limiters (SVLs) have been modelled as a non-linear element representing the U(I) 8 / 20µs characteristic of the SVLs. An inductance added to the connection of the SVL accounts for the change of characteristic when steeper fronts are considered.

SVL leads
Lumped inductances are used to represent them.

Lightning strike
The CIGRE Concave model is used (see section 4.8.16)

4.8.6 Study of the voltage along the sheath of the first section of the underground cable

The goal of this chapter is to study the distribution of the over-voltages along the sheath of the first section when a lightning strike impacts the overhead line in the vicinity of the siphon.

Several aspects are considered:

- The determination of the location where the stress is maximum
- The level of over-voltage obtained
- The protection offered by the surge arresters installed at the junction (end of the first section)

Numerous numerical simulations have been performed but only a few of them are presented in the body of the document.

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10Ω
Surge arresters connected to the sheaths	6kV / 5 kA
Length of the connections to the SA	10m (12.32µH)

Table J4 : main parameters of the configuration

Table J4 above gives the main parameters used in the following calculations, unless otherwise specified.

4.8.7 Maximum value of the over-voltages along the sheath of the first elementary section

For several values of the lightning current and several points of impact, EMTP-RV has been used to evaluate the distribution of the maximum value of the lightning current along the sheath of the first elementary section. In order to do that the first section of the cable has been modelled as a succession of 25m long underground cables.

The sheaths are supposed to be grounded at both ends of the cable by a 10Ω resistance. At junctions the sheaths are protected by 6kV / 5kA SVLs, which are star-connected and grounded using a 10Ω resistance. The connections of the sheaths to the SVL correspond to an inductance of 12.32µH.

An example of results obtained with a lightning strike of 20kA impacting the first tower is given in figure J3, which shows that the crest value of the over-voltage is a maximum at the beginning of the junction and decreases uniformly versus the distance.

Figure J4 presents the results for a lightning strike of 50kA impacting a sky wire 100m from the last tower before the siphon.

At both ends of the cable, the voltage increase of the earth electrode reduces significantly the stress on the sheath. However the effect is very local and does not exist any more a tenths metres from the ends of the cable (it is not taken into account in the graphs presented in this chapter).

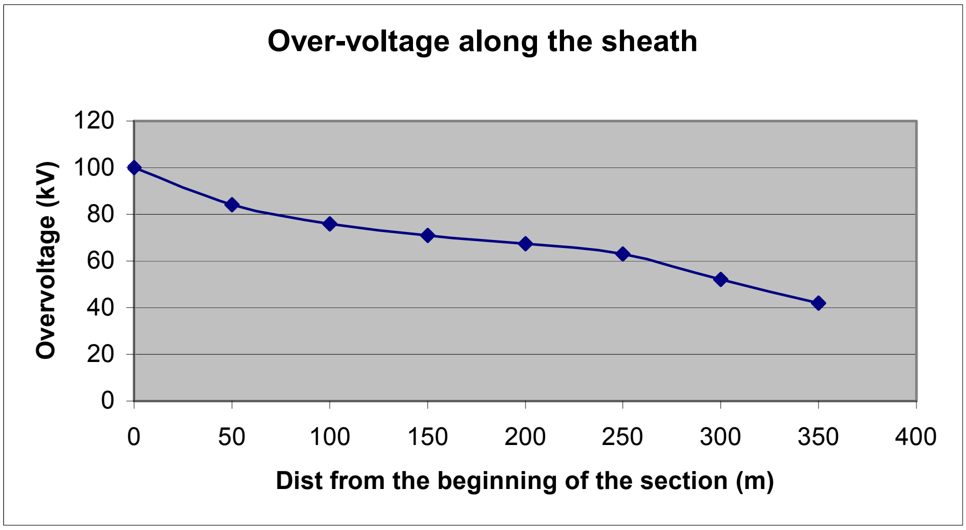


Figure J3 : crest value of the over-voltage (taken from far ground) along the sheath of the first section; the case corresponds to a lightning strike of 20kA impacting the first tower

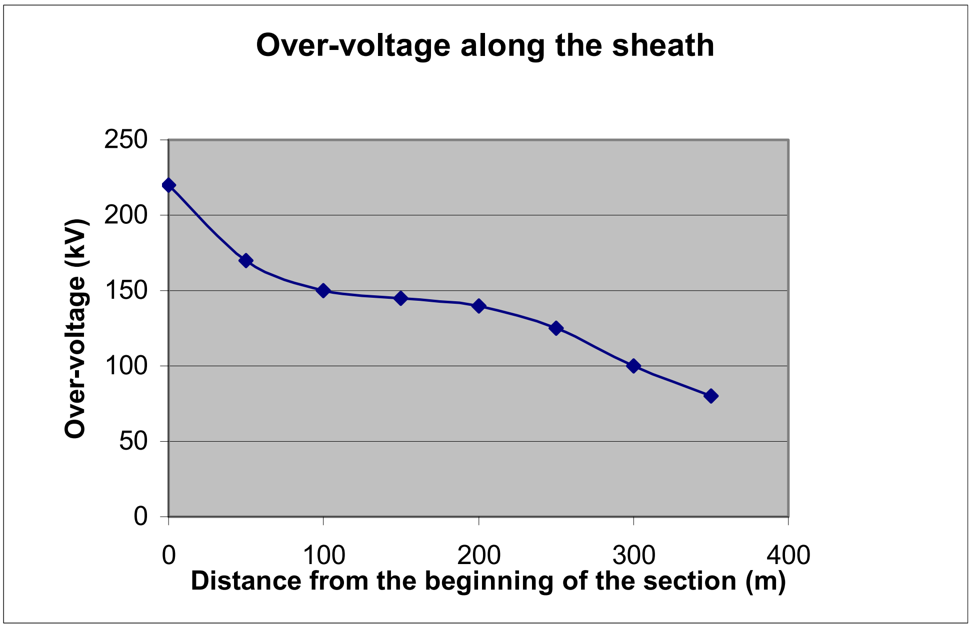


Figure J4 : Crest value of the over-voltage (taken from far ground) along the sheath of the first section; this case corresponds to a lightning strike of 50kA impacting one of the sky wires 100m from the last tower before the siphon

According to the results presented in figure J3 and figure J4 and according to the comment above regarding the effect of protection of the grounding electrodes at both ends of the cable location of the maximum stress along the sheath may be approximated as being 50m from the end of the cable. Figure J5 gives at this location the crest value of over-voltages versus the crest value of the lightning current for several points of impact.

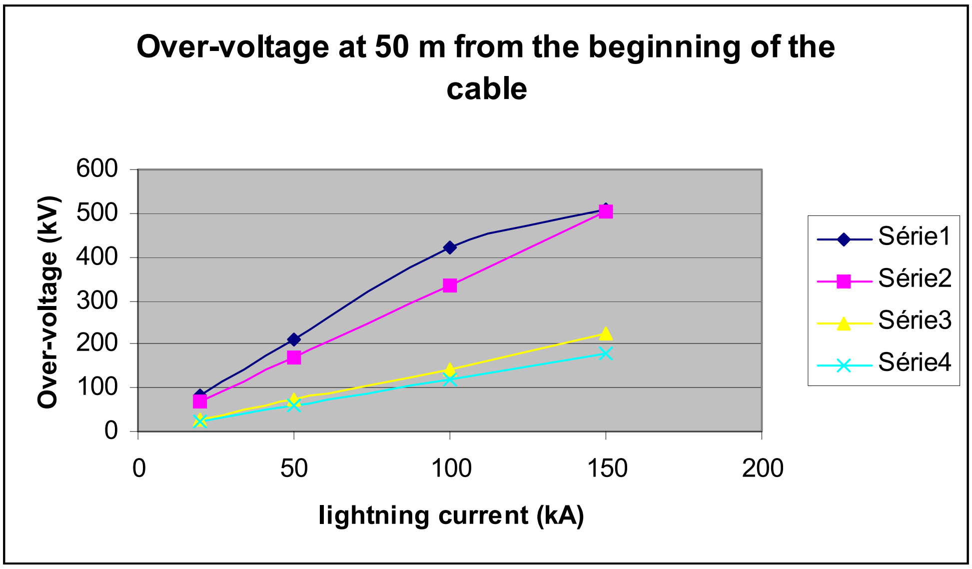


Figure J5: Crest value of the over-voltage at 50m from the beginning of the cable.

- *series 1 = lightning strike impacting the first tower*
- *series 2 = lightning strike impacting the first span 100 m from the last tower*
- *series 3 = lightning strike impacting the second tower*
- *series 4 = lightning strike impacting the second span, 100 m from the second tower*

Comment 1 : because of the negative reflection at the entrance of the cable and because of the relatively high withstand voltage of the insulator strings (900kV), no flashover occurs when a lightning strike impacts the first tower before the siphon.

Comment 2 : When interpreting these results we have to keep in mind that the number of lightning strikes impacting the first tower or the first span is very limited and that according to reference [14] only 5 % of the lightning strikes have a crest value higher than 100 kA.

4.8.8 Effect of the SVL installed at the first junction on the maximum value of the over-voltages along the sheath

(a) The influence of the SVL grounding resistance on sheath overvoltage

The star connected SVLs installed at the first junction are connected to a grounding impedance which is increased from 10Ω to 30Ω. The goal of this paragraph is to evaluate the impact of this change on the maximum crest value of the over-voltage along the first elementary section.

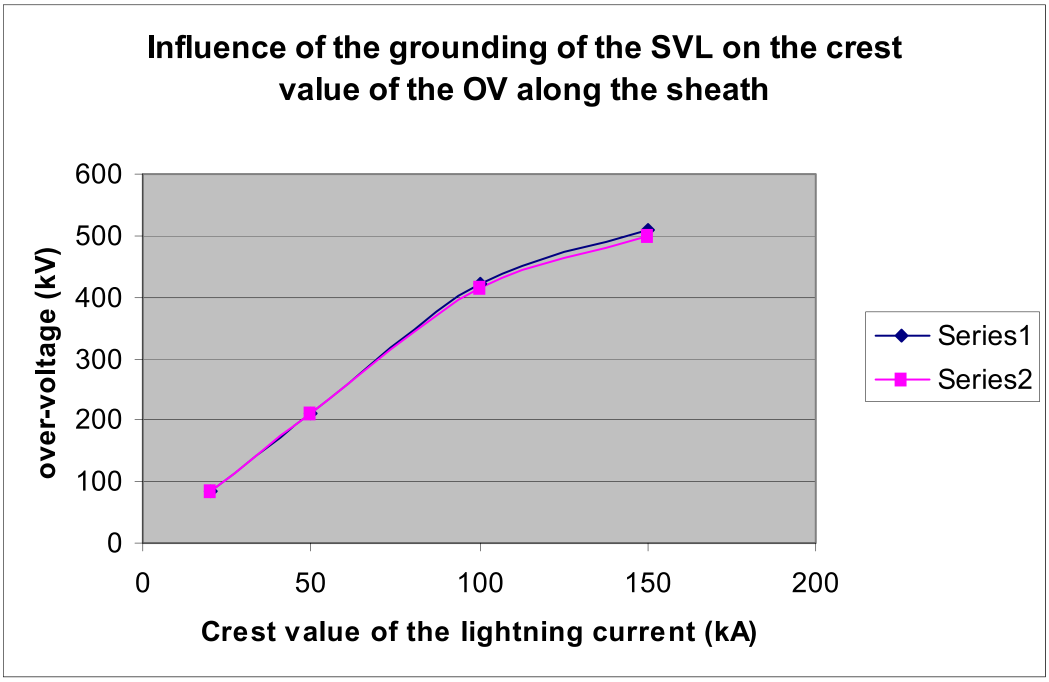


Figure J6: Crest value of the over-voltage at 50 m from the beginning of the cable for a point of impact at the first tower

- *series 1 – grounding resistance of the SA protecting the sheath = 30Ω,*
- *series 2 – grounding resistance of the SA protecting the sheath = 10Ω.*

(b) The effect of removing the SVLs

In that case the SVL protecting the sheath have been removed.

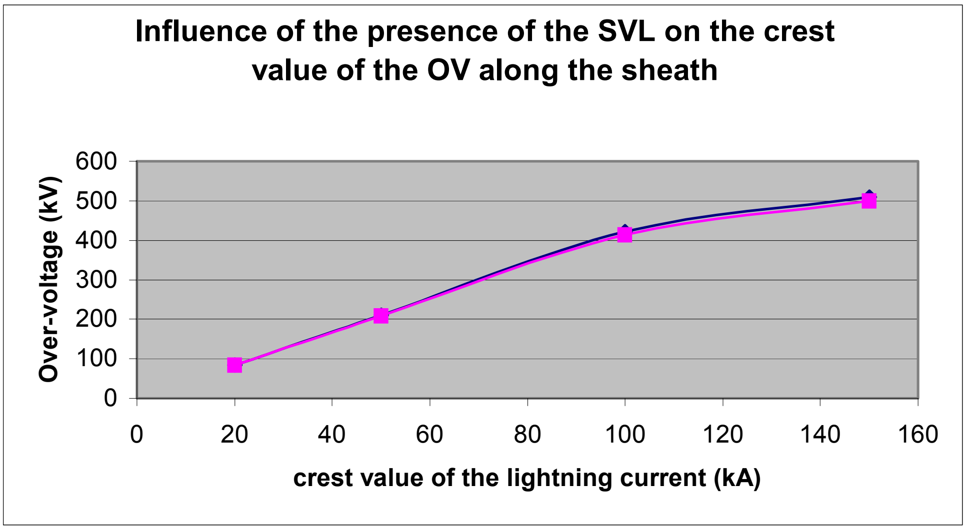


Figure J7: Crest value of the over-voltage at 50m from the beginning of the cable for a point of impact at the first tower

- *Black curve : presence of SVL to protect the sheath ;*
- *Pink curve : absence of SVL to protect the sheath.*
-

(c) Conclusion on the influence of SVLs.

It has been shown in section 4.8.7 that in the configuration considered in this study, the stress due to Fast Front Over-voltages (FFOV) reaches a maximum at the beginning of the first section and decreases versus the distance from the beginning of section 7. Section 4.8.8 confirms that the SVL installed at the end of the first section have only a local effect and are not able to decrease the stress due to FFOV at the other end of section, where it is a maximum.

4.8.9 Effect on FFOV of the grounding resistance connected to the sheaths at both ends of the cable

The grounding resistance at both ends of the cable is increased from 10Ω to 30Ω. The surge arresters protecting the sheaths are connected to a 10Ω resistance.
The maximum value of the over-voltages stressing the sheath is given versus the lightning current at a position 50m from the beginning of the cable for different points of impact.

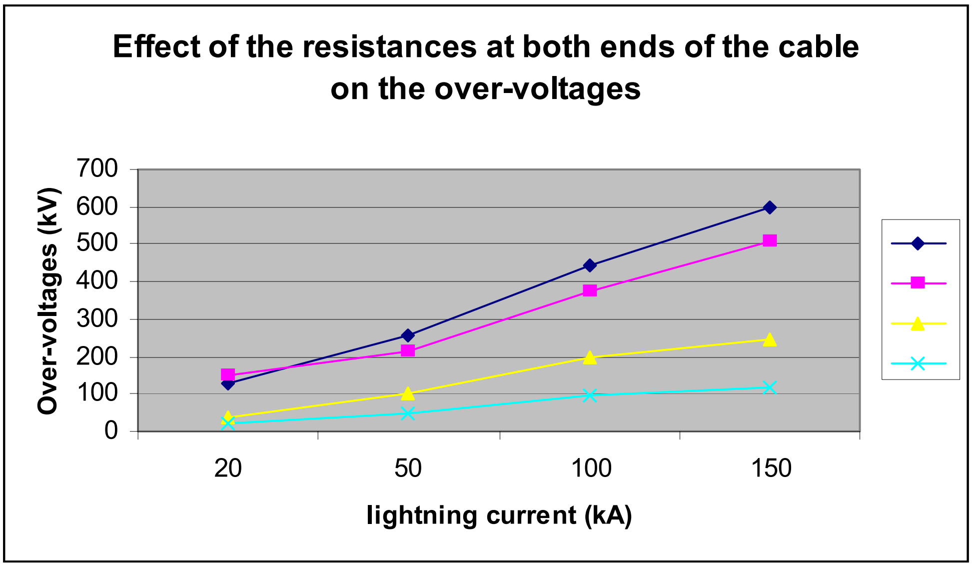


Figure J8: Crest value of the over-voltage at 50m from the beginning of the cable versus the lightning current for several values of the lightning current

- *Black curve - impact on the first tower ;*
- *Pink curve – impact on the sky wire, 100 m from the first tower,*
- *Yellow curve – impact on the second tower ;*
- *Blue curve – impact on the third tower.*

A comparison of Figures J5 and J8 shows a slight increase of the over-voltages due to the increase of the grounding resistance.

4.8.10 Study of the over-voltages at the sectionalising joint of the first junction Study of the effect of the grounding resistance of the star connected SVL.

The main parameters of the configuration are given in the table below

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10Ω
Sheath voltage limiters to the sheaths	6kV / 5kA
Length of the connections to the SVL	10m (12.32 µH)

Table J5: Main parameters of the configuration

The crest value of the lightning over-voltages on the sheath at the end of the first section and between the terminals of the sectionalising joints are calculated for several values of the grounding resistance of the SVL.

The results are given in figure J9. It can be seen that the over-voltage between the sheath and the local ground diminishes versus lightning current due to the decrease of the current circulating through the SVL.

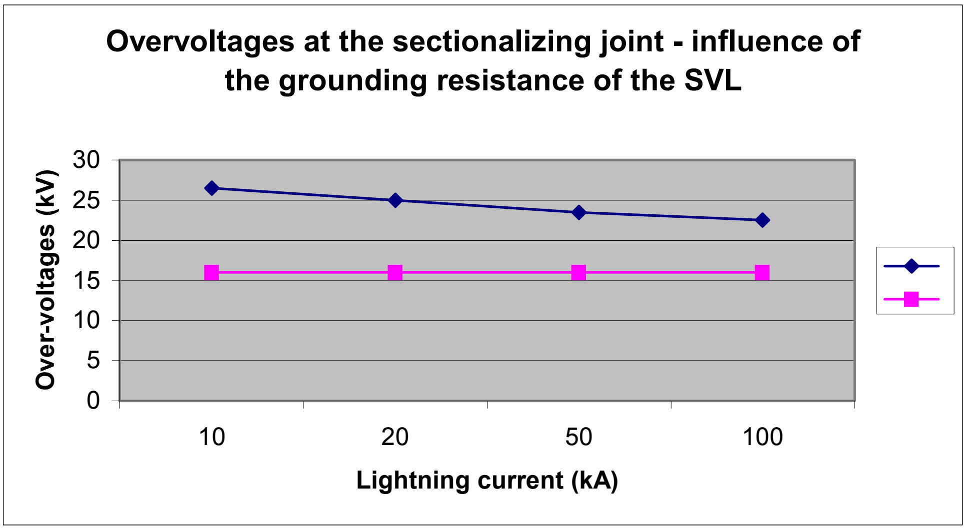


Figure J9: Crest value of the over-voltage at the sectionalising joint versus the value of the grounding resistance of the SVL. A lightning strike of 150kA impacts the first tower before the cable

- *Pink curve : longitudinal over-voltage applied to the sectionalising joint ;*
- *Black curve : over-voltage between the sheath and the local ground at the junction.*

It should be pointed out that the lightning strike of 150kA considered in Figure J9 does not lead to a back-flash-over due to the high withstand voltage of the insulator string.
In order to evaluate the effect of a back-flash-over on the level of over-voltages a lightning strike of 200kA impacting the second tower before the siphon is considered below. Table J6 presents the results. It can be seen that a flash-over leads to over-voltages significantly stronger.

Grounding resistance of the SVL protecting the sheath (Ω)	10	30	100.
Most critical OV / local ground At the end of the sheath (among the 3 sheaths) (kV)	31	30.	30.
Most critical longitudinal OV at the sectionalising joints (kV)	66.	64	66.

Table J6: Maximum value of the over-voltages at the sectionalising joints of the first junction, when a lightning strike of 200kA impacts the second tower before the siphon.

4.8.11 Study of the effect of the length of the connections to the SVL protecting the sheaths

In this paragraph the effect of the length of the connections to the SVL protecting the sheath is studied. The main parameters of the configuration are given below.

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10 Ω
Surge arresters connected to the sheaths	6kV / 5kA
Grounding resistance of the SVL	10Ω

Table J7: Main parameters of the configuration

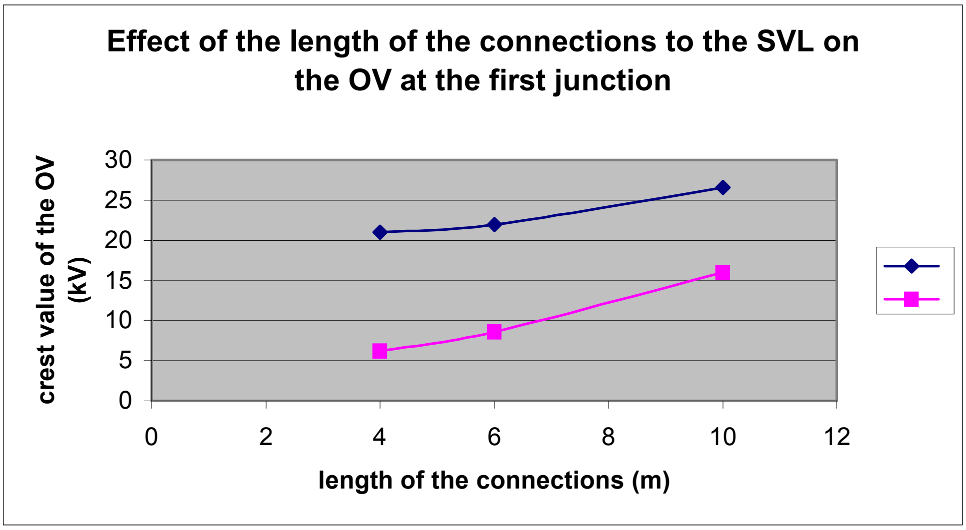


Figure J10: Crest value of the over-voltages at the first junction versus the length of the connections, for a lightning strike of 150kA impacting the first tower (no flashover)

- *Black curve – OV between the sheath and the local ground*
- *Pink curve – longitudinal OV between the terminal of the sectionalising joints.*

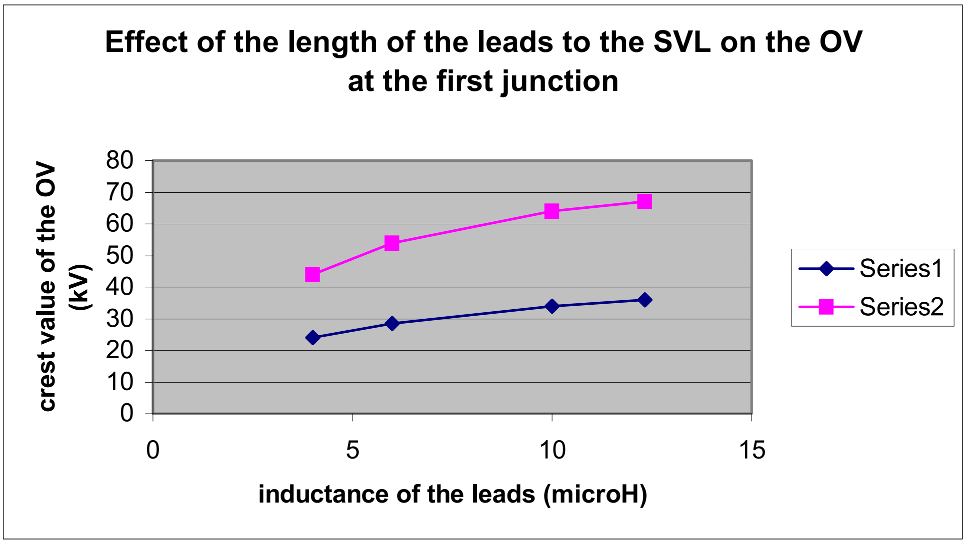


Figure J11: Crest value of the over-voltages at the first junction versus the length of the connections, for a lightning strike of 200kA impacting the second tower (double flash-over) – the grounding resistance of the second tower is equal to 10.2Ω.

- *Black curve – OV between the sheath and the local ground ;*
- *Pink curve – longitudinal OV between the terminals of the interruption joints.*

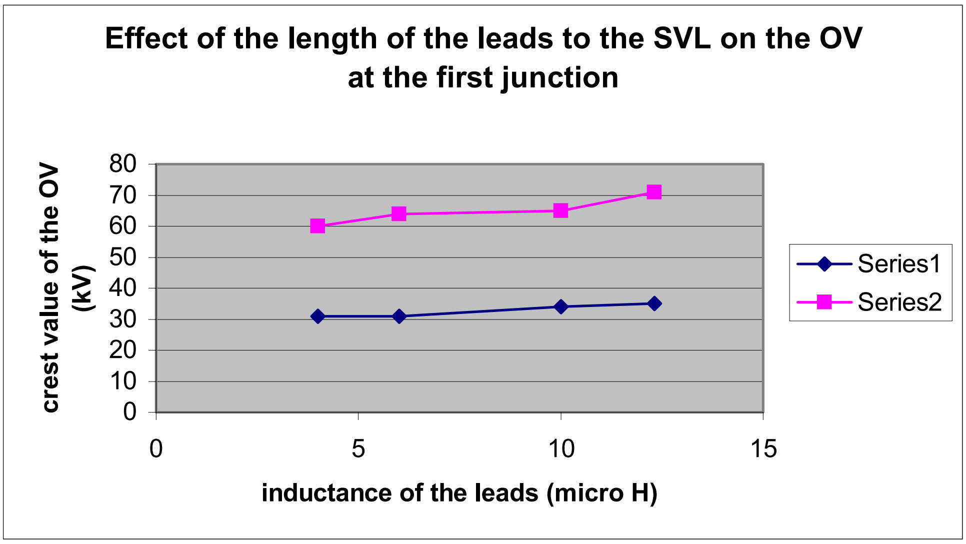


Figure J12: Crest value of the over-voltages at the first junction versus the length of the connections, for a lightning strike of 200kA impacting the second tower (single flash-over) – the grounding resistance of the second tower is equal to 9.9Ω.

- *Black curve – OV between the sheath and the local ground ;*
- *Pink curve – longitudinal OV between the terminals of the interruption joints.*

In figure J9 the level of overvoltage is very limited due to the absence of flash-over. Figures J11 and J12 correspond to a lightning strike of 200kA impacting the second tower before the siphon. The level of over-voltages is higher than previously because of the presence of flash-overs.

4.8.12 Study of the effect of the rated voltage of the SVL protecting the sheaths

The over-voltages are calculated for several values of the rated voltage (6, 12 and 15 kV) protect the sheath. The main elements of the configuration are given in the table below.

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10Ω
Sheath voltage limiters connected to the sheaths	6kV / 5kA, 12kV and 15kV calculated from the 6kV / 5kA.
Grounding resistance of the SVL	10Ω
Length of the connections to the SVL on the sheaths	10m (12.32µH)

Table J8: Main parameters of the configuration

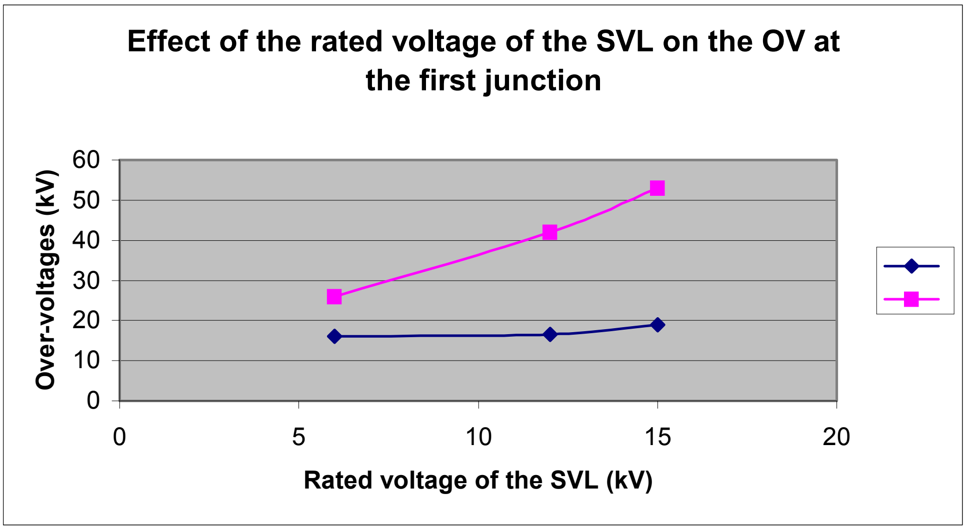


Figure J13: Crest value of the over-voltages at the sectionalising joints of the first junction, versus the rated voltage of the SVL of the sheath, for a lightning strike of 150kA impacting the first tower

- *Pink curve : max sheath / local ground over-voltage at the first junction,*
- *Black curve : max longitudinal over-voltage stressing the sectionalising joint.*

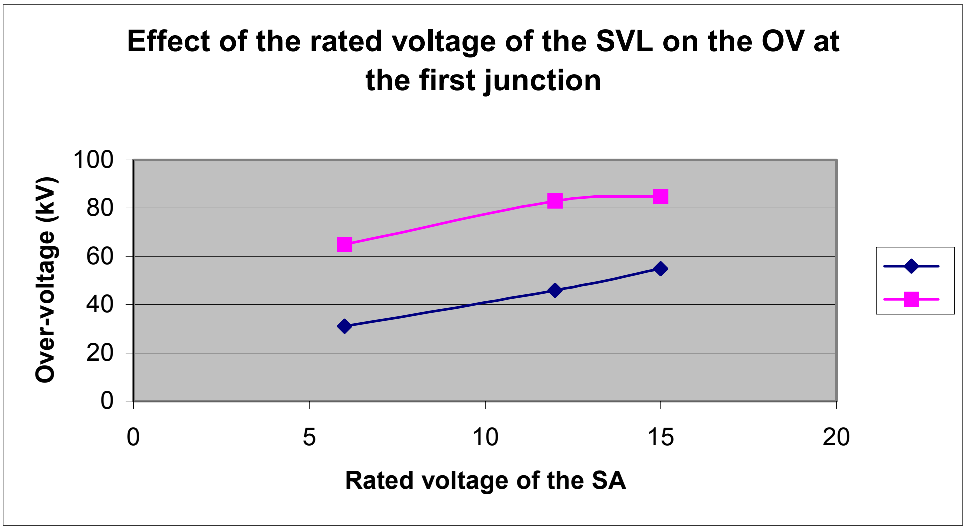


Figure J14: Crest value of the over-voltages at the sectionalising joints of the first junction, versus the rated voltage of the SVL of the sheath, for a lightning strike of 200kA impacting second tower

- *Black curve: max sheath / local ground over-voltage at the first junction,*
- *Pink curve : max longitudinal over-voltage stressing the sectionalising joint.*

4.8.13. Energy absorbed by SVLs

The energy absorbed by the surge arresters is calculated for several values of the rated voltage (6, 12 and 15kV) of the SVLs which protect the sheath. The main elements of the configuration are given in the table below.

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10Ω
Surge arresters connected to the sheaths	6kV / 5kA , 12kV and 15kV calculated from the 6kV / 5kA .
Grounding resistance of the SVL	10Ω
Length of the connections to the SA on the sheaths	10m (12.32μH)

Table J9: Main parameters of the configuration

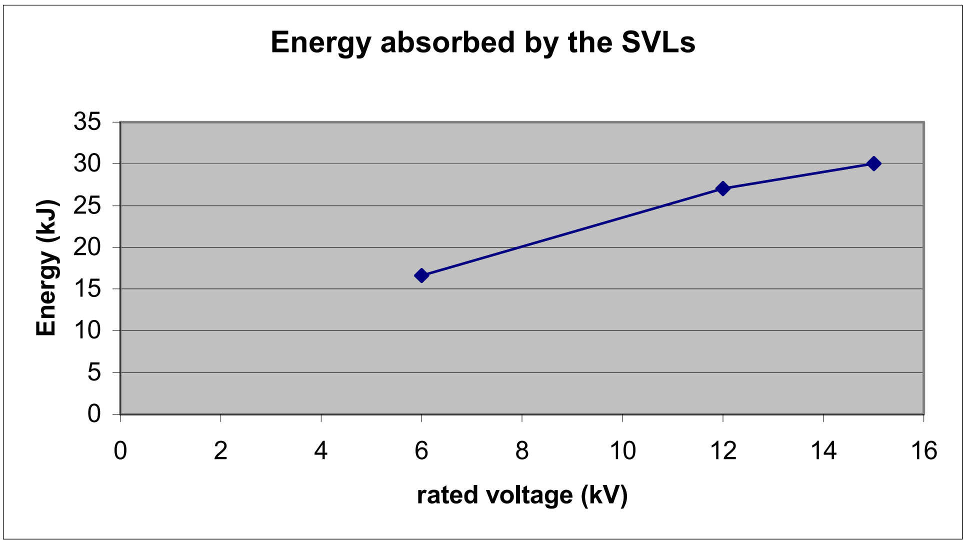


Figure J15: Energy absorbed by the SVLs (higher level of energy absorbed among the arresters) protecting the sheath when a lightning strike of 200kA impacts the second tower before the siphon

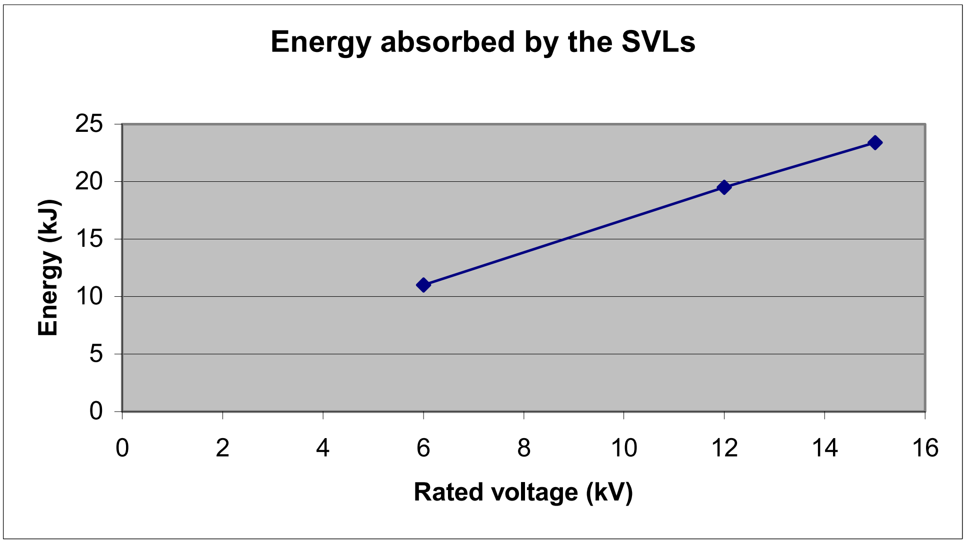


Figure J16: Energy absorbed by the SVLs (higher level of energy absorbed among the SVLs) protecting the sheath when a lightning strike of 150kA impacts the first tower before the siphon

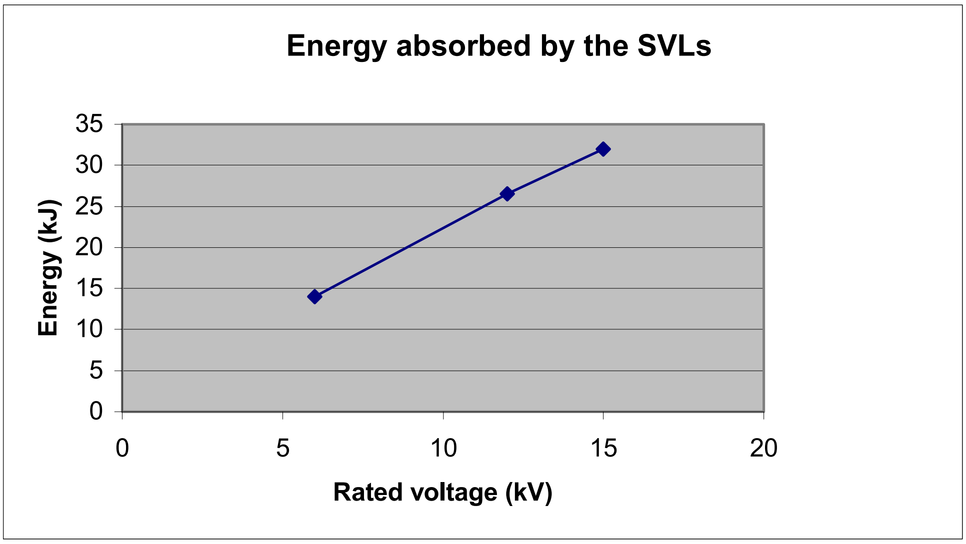


Figure J17: Energy absorbed by the SVLs (higher level of energy absorbed among the SVLs) protecting the sheath when a lightning strike of 200kA impacts the first tower

4.8.14 Study of a case of shielding failure

In this paragraph a lightning strike of 7kA is supposed to impact phase A in the first span before the siphon. This lightning strike leads to a flash-over at the second tower before the siphon (and not at the first one because of the negative reflection at the entrance of the cable).
The parameters of the configuration are given in the table below.

Length of an elementary section	350m
Grounding impedance at both ends of the cable	10Ω
SVLs connected to the sheaths	6kV / 5kA
Grounding resistance of the SVL	10Ω
Length of the connections to the SVL on the sheaths	10m (12.32µH)

Table J10: Main parameters of the configuration

At the first junction the crest value of the phase to local ground over-voltage stressing the sheath is equal to 37kV. The crest value of the longitudinal over-voltage stressing the interruption joints is equal to 44kV. The energy stress of the surge arresters installed at the end of the first section is not significant.
The crest value of the phase to ground over-voltages stressing the sheaths at a distance of 50m from the beginning of the siphon is equal to 31kV.
The results found for 15kV / 5kA arresters are very similar to the results presented above.

4.8.15 Slow –Front Overvoltage Calculations – Re-energisation of a 225kV Line Including a Siphon

(a) Presentation of the case study :

An 80km long 225kV single circuit line is re-energized[1]. A siphon constituted of 3 minor sections crossbonded is located at a distance of 20km from the end of the line.

(b) Description of the configuration :

The 80km long overhead line is a single circuit line equipped with 2 sky wires, whose detailed description is given in section 4.8.2. The siphon is constituted of 3 x 350m minor sections with sheaths cross-bonded. The cable is described in 4.8.3. The joints are protected by SVLs having a rated voltage of 15kV, star connected to a grounding impedance of 10Ω.

The main insulation of the siphon is protected by arresters installed at both ends (rated voltage 225kV).

Neither arrester nor air-gap has been installed at the terminals of the line in order to maximise the transient over-voltages.

The substation from which the line is re-energized is represented by a Thevenin's equivalent
Its equivalent impedance has been calculated in order to have a three-phase short-circuit current around 30kA and a single-phase short-circuit current around 15kA (see 7.4.1 of [15] for calculation). The corresponding values of Lp (self inductance) and Lm (mutual inductance) are respectively 26mH and 13mH.

(c) Calculations and results :

The overvoltages on the sheaths have been calculated for several values of the residual voltages and several values of the closing time of the breaker.
The phase to remote earth overvoltages obtained at the ends of the minor sections are lower than 3kV.

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[1] According to [1] opening and fast closing of the line circuit-breaker as the consequence of a fault or a relay maloperation. With respect to line energization, trapped charges are taken into account

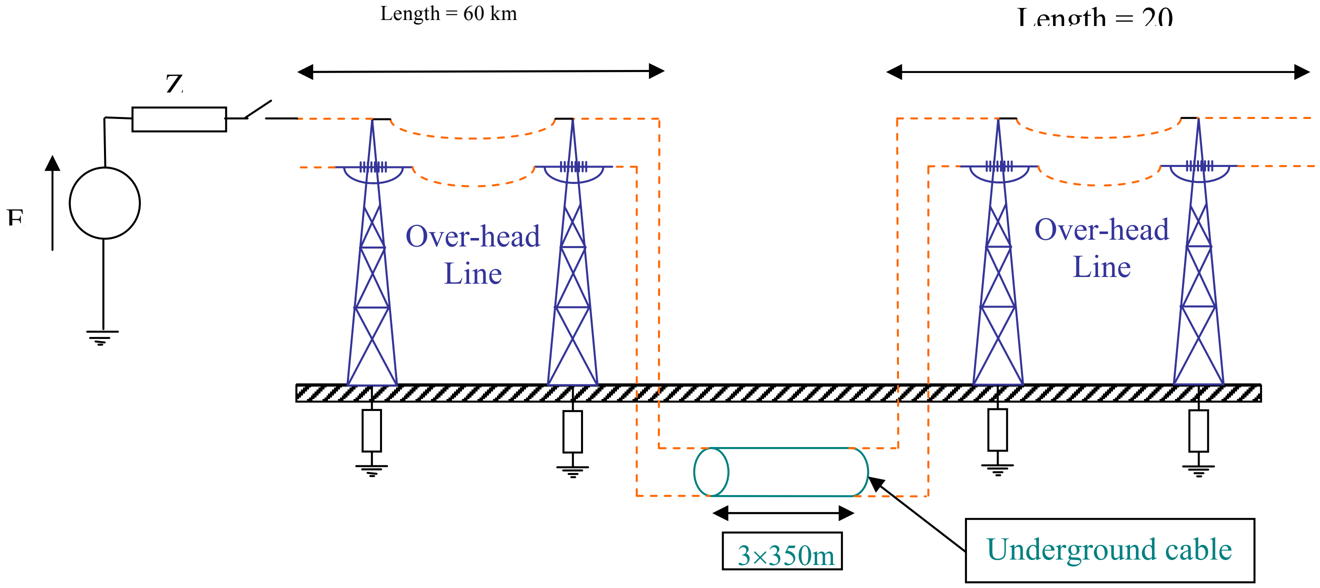


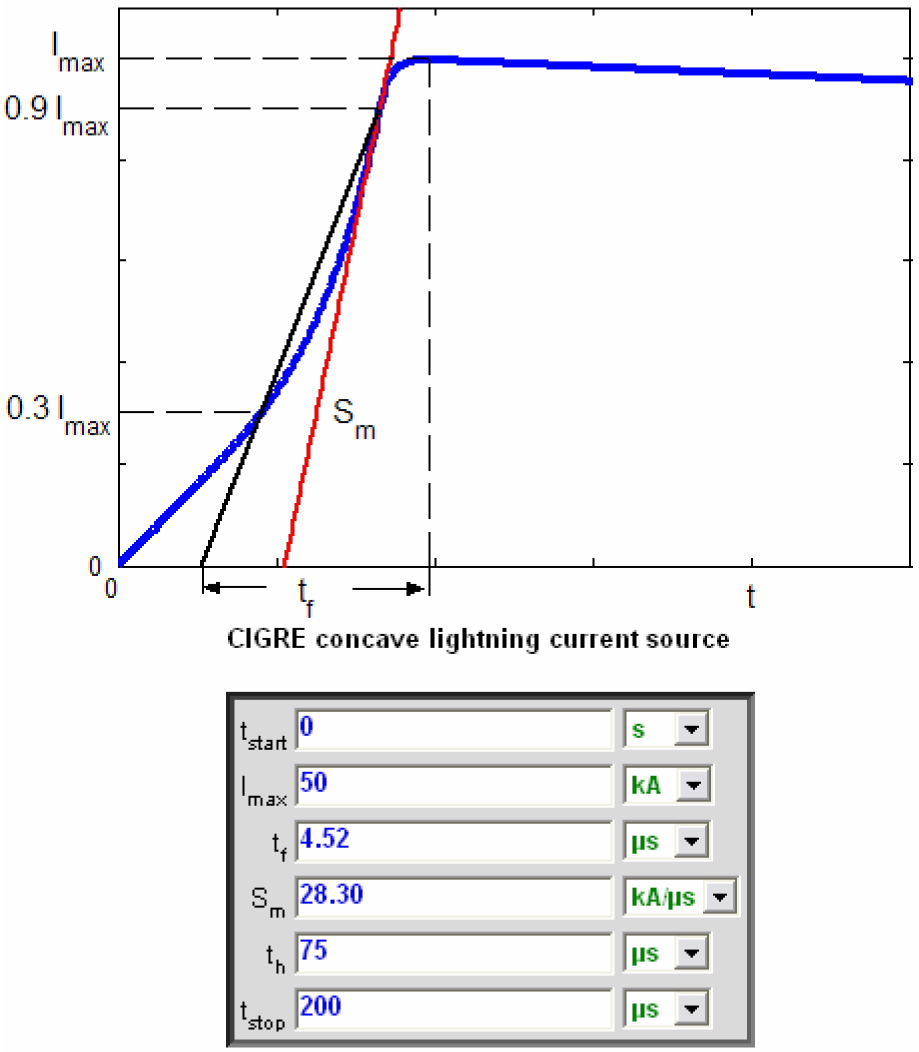
Figure J18 : case of line re-energization. The 225kV single circuit line is 80km long. The source is represented by a Thevenin's equivalent

4.8.16 Model and parameters used for the lightning strike current

The lightning strike has been represented by a current source, based on the model CIGRE concave proposed by the CIGRE (see figure J19). The parameters used are detailed in table J11.

Table J11:

Crest value (kA)	t_f (µs)	Sm (kA / µs)
3	2.18	14.48
7	2.55	16.7
20	3.11	20.03
50	4.52	28.3
100	6.01	36.72
150	7.1	42.77
200	8.47	47.65



t_{start} 0 s

I_{max} 50 kA

t_f 4.52 µs

S_m 28.30 kA/µs

t_h 75 µs

t_{stop} 200 µs

Figure J19

4.8.17 Characteristic of the arrester used to protect the main insulation.

The 225kV surge arrester (SA) characteristic has been obtained based on the characteristic of a 96kV SA.

Current (A)	Voltage (V)
100.	187.E+3
500.	200.E+3
700.	203.E+3
1.E+3	208.E+3
2.E+3	218.E+3
4.E+3	228.E+3
5.E+3	233.E+3
8.E+3	246.E+3
10.E+3	251.E+3
15.E+3	266.E+3
20.E+3	279.E+3
30.E+3	299.E+3
40.E+3	316.E+3
50.E+3	336.E+3
60.E+3	354.E+3
70.E+3	372.E+3
80.E+3	387.E+3
90.E+3	402.E+3
100.E+3	414.E+3

Table J12: Voltage characteristic U(I) of an arrester (rated voltage : 96 kV)

4.8.18 Characteristic of the 6kV SVL used to protected the sheaths and the sectionalising joints

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

Table J13 Typical Characteristic of a 6kV / 5 kA sheath voltage limiter

4.9 EMTP/ATP Considerations

4.9.1 Introduction

EMTP (and ATP) provides the most thorough of calculation models for representing transient conditions in high voltage systems. The model is a sophisticated impedance matrix approach which models both the self and mutual effects of conductors in a system together with the surrounding environment and any external paths. EMTP studies are normally carried out by experts in this field and require a degree of judgement in particular areas of the modelling, given (a) the limitations of the EMTP model and (b) the less defined parameters in the study. The WG has therefore provided observations and guidelines as detailed below based on experience with EMTP. Whilst this is intended to help other users of EMTP with cable system modelling, it is also strongly recommended that such modelling be carried out only by experts and not be considered as a routine design tool but as a specialist system study approach.

4.9.2 Cable System Model

At the time of this report it is understood that the EMTP cable model is under review. Comment can only therefore be made concerning the present established cable model.

The individual cable model in EMTP/ATP comprises conductor, insulation, cylindrical metallic sheath or screen and outer non-metallic sheath. Not included are semiconducting screens, composite screen constructions or non-cylindrical sheaths such as corrugated sheaths. A judgement is therefore required on simplifying the actual cable construction to fit into the EMTP model.

4.9.3 Cross Bond Connections

EMTP enables cable configurations such as cross bonding to be modelled by applying cross connections to adjacent cable models. The actual cross linking connections themselves are less defined in EMTP/ATP and it is the judgement of the Designer as to, for example, whether to represent a bonding lead as an inductance or as a line model. In general for lightning transients (at frequencies < 1MHz), bonding leads can be modelled as an inductance, with mutual inductance between conductors being taken into consideration. The SVL, if present, can be modelled as a non linear resistor only.

4.9.4 Selection of EMTP Model

Of the different analysis models available in EMTP/ATP, the frequency dependent (FD) and constant parameters (CP) models are most typically applied to cable systems transient analysis. As implied by its name, the CP model is based on set values of R, L and C, whereas in practice these parameters will vary with frequency. Therefore the FD model is usually judged to be the most representative at the high frequencies required in transient analysis.

4.9.5 Customised Versions of EMTP

Experience has shown that simplified or customised versions of the software, which may be developed to reduce the complexity of cable system modelling or to make the program more user-friendly to non-experts, should be treated with considerable caution. Customising of the program requires making assumptions about both the software and the system model and can lead to inaccurate results and misleading conclusions and should generally be avoided.

4.9.6 Injected Transient Current or Overvoltage

When building a system transient model, certain key parameters need to be either known or assumed:-

- Type of transient – e.g, lightning or switching
- Position of strike in the system
- Magnitude and waveshape of transient
- Level of attenuation along cable

Additionally, the Designer may make judgements over, for example, the historical or probabilistic incidence of transient overvoltages in a given location, when building a transient model.

Where such transient data is reliably available for a prospective system then it may clearly be applied to the analysis, although this should of course also be included in the Utility specification, within its overall responsibility for its insulation coordination.

Where such comprehensive data is not secure or specified for a particular system study a suitable approach is to set up the transient model to respect the lightning and switching levels specified by the Utility. By this approach, lightning or switching currents are injected at the cable terminals to the magnitudes necessary to raise phase to earth transient voltage to BIL or SIL.

4.9.7 Attenuation of Transient

The level of attenuation calculated using EMTP/ATP is lower than measured values, possibly because phenomena such as skin effect at high frequencies are not taken into account. Consequently the lower attenuation evident in EMTP/ATP can be considered as a conservative value.

4.9.8 Modelling the SVL in EMTP/ATP

The SVL is normally considered as an ideal switch, which is “off” for all power frequency applications and “on” during transient overvoltages. In reality the conduction through an SVL is capacitive in nature and should ideally be modelled as a non-linear resistor having some parallel capacitance. However, as stated in 4.9.3, for lightning transient studies the SVL can be modelled as a non linear resistor only.

4.9.9 External Environment

Most previously published measurements of system transients, including all of the systems referred to in Electra 47 [2] are on direct buried systems, where a level of estimation may be made of ground resistance, although it is recommended that each case be considered individually and that EMTP/ATP analysis should not be based on generalised values. Such differences are well illustrated in existing published papers of EMTP/ATP analysis with different systems and it has to be acknowledged that modelling of the external environment with reasonable accuracy may not be entirely possible unless validated measurements exist.

A future facility in EMTP/ATP study is to include a “soil ionisation” model which under transient overvoltage conditions replicates local earth potential rise and effectively extends the dimensions of the earth electrode. In respect of sheath voltage to earth this facility should provide a more conservative result. However it is recommended not to include the ionisation model in cable system studies, for reasons of over-complication.

Ground resistance value influences the voltage between sheath and earth but not from sheath to sheath. Most important is the ground resistance at the cable terminations, since by reducing this value so sheath to earth voltages will also be reduced. In practice of course the Designer has little control over the parameter of ground resistance and has to deal with the ground conditions as presented.

Cables installed in air, whether in “open air”, tunnels and basements or air-filled ducts etc, will experience a substantially different external environment to buried systems and would be expected to show higher levels of transient sheath voltage than in buried systems. Given that precise modelling of an in-air environment is difficult and also that transient sheath voltages would be higher than for buried systems, it is considered safer practice to include SVLs throughout such installations.

4.9.10 Verification of EMTP Studies

Previous experimental studies have shown a close agreement between measured voltages and EMTP/ATP for most scenarios of transient current injection. The following cases gave good alignment:-

- Phase conductor to sheath (coaxial mode)
- Sheath to earth
- Phase conductor to phase conductor
- One phase conductor to two phase conductors in parallel

Two scenarios only gave some discrepancy (the measured attenuation is stronger than the value computed):-

- Sheath to sheath
- One sheath to two sheaths in parallel

The above results are of course based on a good understanding of both the injected transient and the specific cable system external environment.

5.0 SPECIAL CONSIDERATIONS

5.1 Cross Bonding Without SVLs

5.1.1 Introduction

This section describes the philosophy and approach taken in Belgium for the elimination or reduction of SVL units in 70kV and 150kV cross bonded systems.

5.1.2 Philosophy and technical arguments for abandoning the use of Sheath Voltage Limiters (SVLs)

There is a tendency in Belgium to replace the lead sheath of underground cables by an aluminium screen sometimes containing copper wires.

This type of screen presents several advantages, amongst which :

- The lesser weight of the cable;
- The possibility to have greater lengths on a drum, thereby reducing the numbers of joints;
- An ecological advantage, by not having lead in the soil. A European directive in force since 1999 forbids incorporating lead in low-voltage equipment. So far there is no directive concerning high-voltage cables or high-voltage equipment.

The drawbacks of this type of sheath relate to the possibly greater losses in the screen (depending on the aluminium screen thickness), resulting in :

- A lower transmission capacity of the link
- much higher losses over the entire lifetime of the link (and therefore much higher overall costs of losses)

In order to reduce these losses in the sheath, cross-bonding of the sheaths has to be applied. It needs to be mentioned that even when cables with lead sheaths are used, cross-bonding is applied systematically in order to raise the transmission capacity of underground 150 kV links.

Until recently the installations with cross-bonding joints were equipped with SVLs at the interruption of the sheaths of the power cables, protecting these joints against screen overvoltages. However, the use of these SVLs requires yearly inspections, entailing long-term costs. Furthermore, in Belgium these SVLs are installed in aboveground link boxes, which have a very low public acceptance.

Taking into account the advances in insulation materials technology, a study was performed in order to determine to what extent the dielectric withstand voltage of the joints at the interruption of the sheaths could be raised, rendering unnecessary the use of SVLs and, hence, the use of aboveground link boxes.

This system of cross-bonding without using SVLs, also called “ direct cross-bonding”, has already been tested successfully and applied systematically for 150 kV joints and is recently approved for 70kV joints.

5.1.3 Underground link design

The underground 70 and 150 kV links are composed of :

- 3 single-phase cables, usually placed in a close trefoil formation
- 1 or 2 earth conductors, in order to reduce the returning current along the sheaths of the cables during a short-circuit

At the end of the underground link, the sheaths of the power cables and the cores of the earth conductors are connected to the sub-station’s earthing system (or to a local earth in the case of a transition between an overhead line and an underground link).

When cross-bonding is applied, the sheaths of the power cables and the earth conductors are connected to each other without earthing after each full cycle of cross-bonding (i.e. after each major section).

At the cross-bonding joints, the earth conductors are connected straight through, without earthing.

Before the SVLs were abandoned, the interrupted sheaths of the power cables at the cross-bonding joints were raised to aboveground link boxes by means of coaxial cables. In these link boxes, the sheaths were exchanged and equipped with star-connected SVLs isolated from the earth.

Since the SVLs have been abandoned, the interrupted sheaths of the power cables at the cross-bonding joints are directly cross-bonded by means of a 150 mm^2 Cu cable (identical to the earth conductors used) and therefore no longer raised to an aboveground link box.

It needs to be mentioned that in Belgium, unlike the usual practice in many other countries, the joints are fully buried underground, i.e. not accessible aboveground or via an inspection chamber.

5.1.4 Overvoltages and Simulations

The amplitude of the overvoltage that may arise determines the installation of SVLs at the interruption of the screens in a cross-bonded system.

Two types of overvoltage have been investigated, being the transient overvoltages and those at power frequency (50-60 Hz).

5.1.5 Transient overvoltages

The main transient overvoltages that may affect an installation are:

- overvoltage due to lightning surges: mixed connections, i.e. an underground link connected to an overhead line, are exposed to lightning surges, which often represent the most severe overvoltage conditions;
- overvoltages due to network switching : underground links that are not connected to an overhead line or outdoor busbar link are only affected by overvoltages that arise due to switching or faults. The amplitude of these overvoltages is less than those incurred through lightning surges.

Since lightning surges represent generally the severest overvoltage condition, the determination of the dielectric withstand voltage of the cross-bonding joints at the interruptions of the sheaths is based on these lightning surges.

The main defining factors of the overvoltage values due to lightning are the amplitude and steepness of the lightning's wave front. The largest overvoltages will arise between the sheaths of the successive phases, at the place of their interruption.

The EMTP/ATP program made it possible to run various simulations.

The various network components (the overhead line, the towers, the transition between overhead line and underground link and the cables) are modeled according to their electrical properties and dimensional characteristics (refer also to figure K1).

It is assumed that the lightning strikes at the top of a tower or in the middle of a span, with flashover on a phase at the insulation set. The characteristics of the lightning surge are : 100kA peak – 1.2/50µs. The interruption of the sheaths of the power cables at the cross-bonding joints is performed without protection by SVLs.

The results of a first simulation (the underground link consisting of one major section; refer also to figure K1) indicates that :

- The overvoltages at the interruption of the sheaths of the first direct cross-bonding joint amount to 250kV peak, and 155kV peak at the interruption of the sheaths of the second direct cross-bonding joint. These values are obtained with a lightning strike on the first tower after the transition between the overhead line and the underground link or in the first span.

Additional simulations, varying several parameters relating to the lightning surge and the network structure, demonstrate that :

- The greater the amplitude of the lightning surge, the greater the overvoltage at the interruption of the sheaths of the cross-bonding joints;

- The steeper the wave front, the greater the overvoltage;
- By adding additional ternary sections, the value of the overvoltage at the interruptions of the sheaths of the cross-bonding joints drops very sharply as the distance from the cable inlet increases. However, the value of the overvoltage in the first ternary section does not vary, leading to the conclusion that adding of ternary sections does not lower the maximum value;
- If the first ternary section is protected with SVLs (Ur : 12kV; the value based on the most severe condition between a three-phase, two-phase and single-phase-to-earth fault), i.e. the first and the second direct cross-bonding joints, the value in the first ternary section is substantially reduced (135kV peak at the first direct cross-bonding joint), but the maximum value is shifted to the second ternary section, be it slightly reduced (150kV peak);
- If the value of the substation's earthing system is changed, this has hardly any impact on the value of the overvoltages;
- The configuration of the cables (trefoil or flat formation) has only a very limited impact on the value of the overvoltages.

A value of 150kV peak was imposed as the dielectric withstand voltage at the interruption of the sheaths of the power cables of the direct cross-bonding joints. The cross-bonding joints in the first major section , having also this withstand voltage of 150kV peak, always have to be protected with SVLs in case of a mixed connection.

The value for the dielectric withstand voltage between screen-earth : 75kV peak

A later study concerning 70kV direct cross-bonding joints resulted in a value of 100kV being retained as the dielectric withstand voltage at the interruption of the sheaths of the power cables of direct cross-bonding joints. (The value for the dielectric withstand voltage between sheath-earth : 50kV)

5.1.6 Power Frequency Overvoltages (50 Hz)

Compared to the transient overvoltages, these overvoltages have a lesser amplitude and they are mainly caused by failures in the link (short-circuits, earthing faults).

The amplitude of these overvoltages is determined by the value of the fault current, by the location at which the fault arises, by the way in which the cables are earthed and by the presence of an earth conductor.

A study concerning the increase of the overvoltage due to a single phase-to-earth fault has demonstrated that, for a normal link equipped with one or two earth conductors, the overvoltages in the sheaths of the power cables do not exceed the limit value of 8kV eff , i.e. the minimum value related to the insulation level of possible nearby underground installations of other utility companies. It can also be noted that earth conductors are always used in order to reduce the maximum voltage rise to a maximum value of 8kV due to a fault.

For longer links, the presence of two earth conductors is often insufficient to retain this value of 8kV eff. Intermediate earthing will be required at the locations where the interrupted sheaths of the power cables are connected to the earth conductors (i.e. after a major section).

Taking into account this limit value of 8kV eff., which is very low compared to the overvoltages under transient conditions it is not necessary to include SVLs for power frequency overvoltage studies.

5.1.7 Specified Tests

The following tests are carried out on the cables, equipped with their accessories in order to approve the direct cross-bonding joints, developed by the supplier :

Tests at the factory of the supplier of the joints :

- Type tests on cable with its accessories, according to IEC 60840;
- Prequalification tests on the cable with its accessories, as stipulated by the Engineering department :
    - Heating cycle voltage test;
    - Impulse voltage test at elevated temperature;
    - Power frequency voltage test.

Field tests after construction of the underground link :

- Tests on the outer sheath of the power cables with joints;
- The alternating current dielectric strength tests on the entire installation.

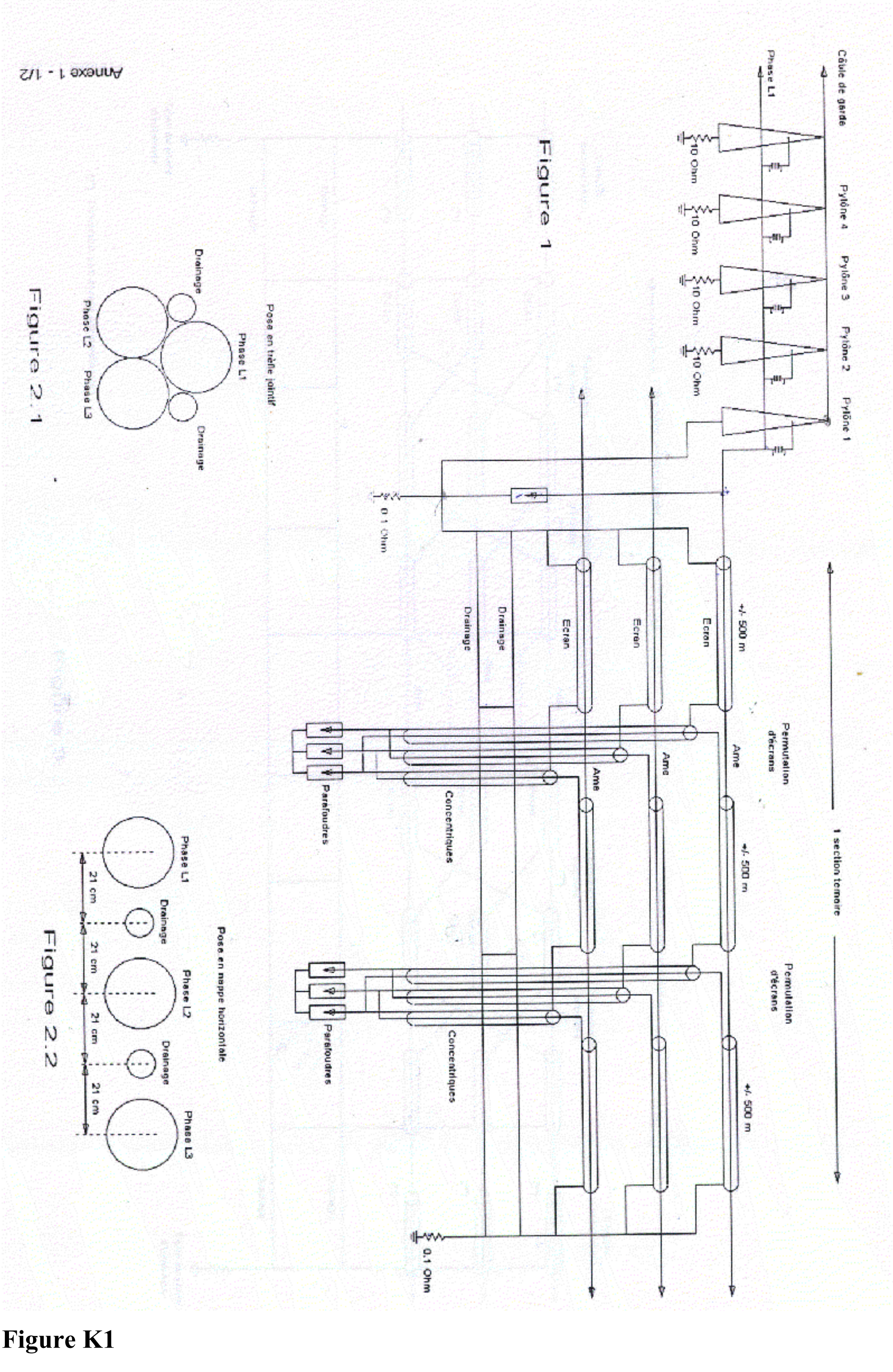

Câble de garde
Phase L1
Pylône 4
Pylône 3
Pylône 2
Pylône 1
10 Ohm
10 Ohm
10 Ohm
10 Ohm
0.1 Ohm
Figure 1
1 section ternaire
+/- 500 m
+/- 500 m
+/- 500 m
Ecran
Ecran
Ecran
Drainage
Drainage
Permutation d'écrans
Permutation d'écrans
Ame
Ame
Ame
Concentriques
Concentriques
Parafoudres
Parafoudres
0.1 Ohm
Pose en trèfle jointif
Phase L1
Phase L2
Phase L3
Drainage
Drainage
Figure 2.1
Pose en nappe horizontale
Phase L1
Drainage
Phase L2
Drainage
Phase L3
21 cm
21 cm
21 cm
21 cm
Figure 2.2
Annexe 1 - 1/2

Figure K1

5.2 SVL Voltage Taking account of d.c. Component

5.2.1 Asymmetry of the fault current

The fault current includes an exponentially decaying d.c. component:

$$i(t) = I_{rms}\sqrt{2}\left[\cos(\omega t - \varphi) - \cos(-\varphi)e^{-t/\tau}\right] \qquad \text{(L1)}$$

The amplitude of this component depends on the angle (φ) of the voltage wave at which the fault occurs. The time constant τ of the d.c. component typically varies between 0.05 and 0.15sec. on high voltage systems. The sub-transient component related to the rotating machines is usually small and is neglected. The amplitude of the first crest can therefore reach close to two times that of the a.c. component of the fault current (see figure L1).

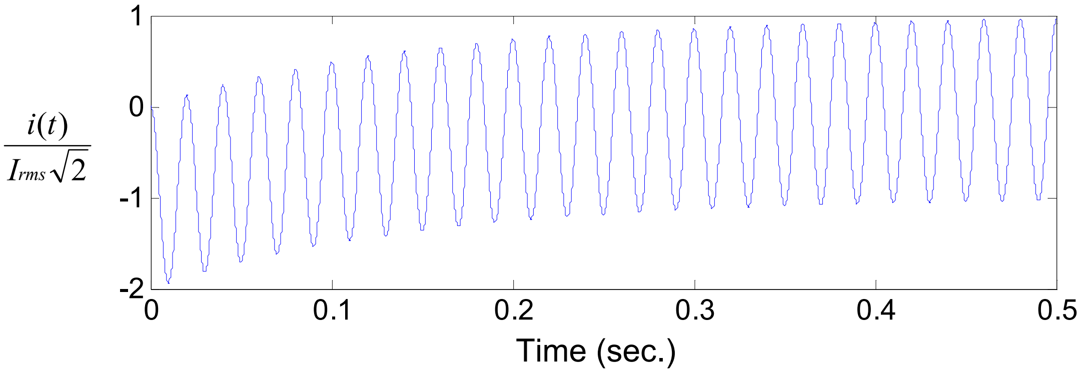


Figure L1 ***i(t)* for ω = 314 sec.$^{-1}$, τ = 0.15 sec. and φ = 0°**

This d.c. component can contribute to increase the voltage across the SVL and the voltage rating of the latter should be increased accordingly.

The d.c. voltage causes both resistive and inductive voltage drops. Voltages resulting from mutual and self inductances are proportional to the derivative of the current. The derivative of the fault current is given by:

$$\frac{di}{dt} = I_{rms}\sqrt{2}\left[-\omega\sin(\omega t - \varphi) + \frac{1}{\tau}\sin(-\varphi)\,e^{-t/\tau}\right] \qquad \text{(L2)}$$

The d.c. component of the derivative is typically 15 to 50 times smaller than the a.c. component. The d.c. component of the derivative is maximum for φ = 90° and, as shown in figure L2, can be neglected. Furthermore, for values of τ giving the maximum d.c. component of the current (φ = 0°), the d.c. component of the derivative is nil. As a consequence, the contribution of the current asymmetry to the voltage across the SVL is mostly due to resistive voltage drop in the cable sheaths and in the ecc.

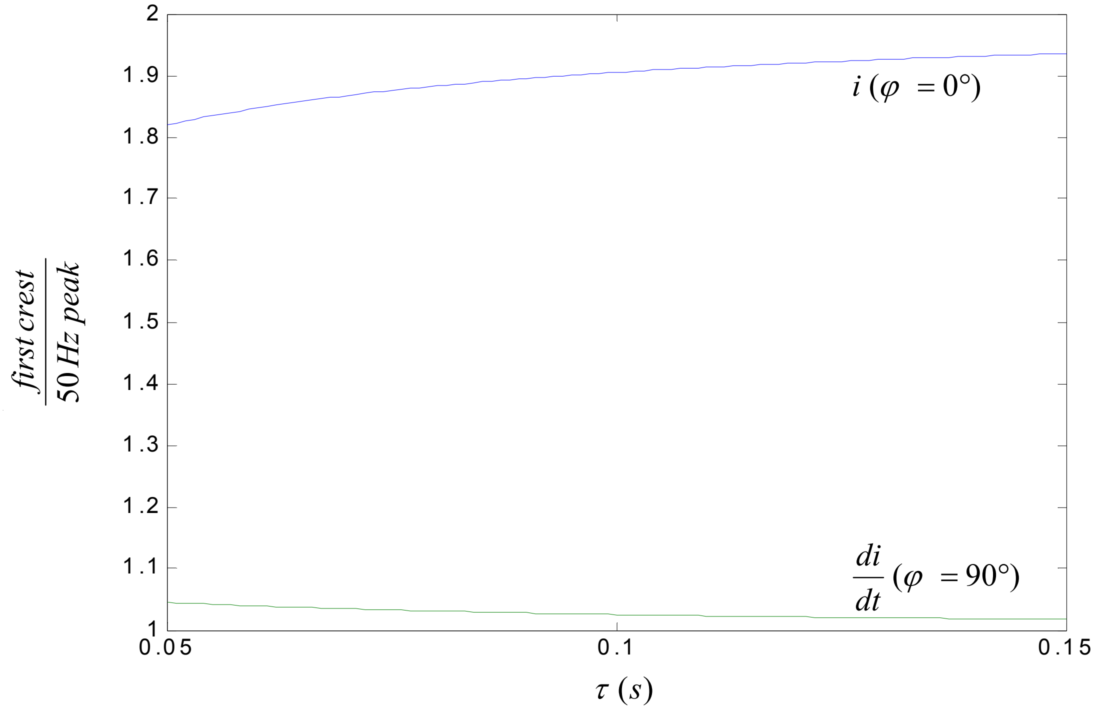


Figure L2 Peak value to 50Hz peak ratio for the current ($\varphi = 0^o$) and the derivative of the current ($\varphi = 90^o$)

5.2.2 Two- (isolated from earth) and Three-Phase Faults

For two- (isolated from earth) and three-phase faults, the current in the earthing network (sheaths and/or ecc, earth electrodes) is nil. Voltages across SVLs depend only on induced voltages. The d.c. component of the fault current has therefore no significant impact on voltages across SVLs in those cases.

5.2.3 Single- and Two-Phase-to-Earth Faults

For single and two-phase-to-earth faults, the d.c. component of the fault current produces a voltage drop in the resistive component of the impedance of sheaths, the ecc and the earthing network that contributes to increase the voltage across the SVLs. The calculation of the contribution of the d.c. component requires a detailed representation of the system. The Complex Impedance Method described in clause 3.1 or programs such as EMTP/ATP can be used. Simplified circuits are presented with a view to identify the most influential parameters.

In the case of single-point bonded systems, the voltage across the SVL due to the d.c. component is proportional to the resistive voltage drop on the ecc (see figure L3). This voltage therefore increases with the resistance of the ecc. Higher earth resistances contribute to increase the current in the ecc and the d.c. voltage across the SVL. A test case is presented in 5.2.4.

Most HV cable circuits are located in urban areas or connect major substations. In those cases, the impedance of the earthing system is low and values of 0.1Ω or less are typical. In the example of section 5.2.4 the d.c. component contributes to increase the amplitude of the first peak by 28% (see Table L1) for R_e=0.1Ω and R_c=0.1Ω/km (a 240mm^2 Cu conductor has a resistance of 0.08Ω/km).

In the case of a cable circuit inserted in the middle of an overhead line, the earth impedance can be much higher than 0.1Ω. The latter depends on the soil resistivity, if skywires are used and if so, if steel (high resistance) or aluminum (low resistance) conductors are used. The amplitude of the first peak is increased by 35% for R_e=10^6Ω and R_c=0.1Ω/km.

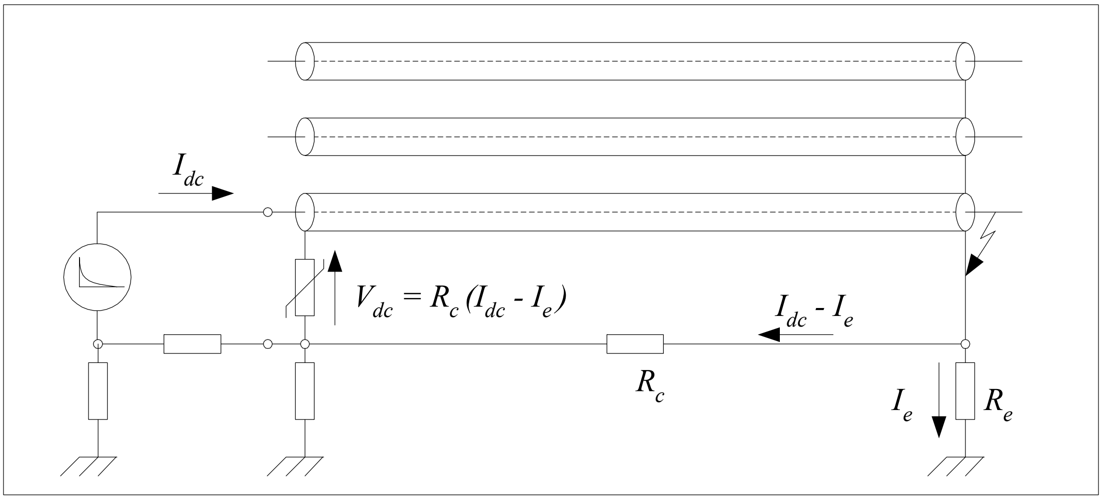


Figure L3 Simplified circuit illustrating the contribution of the d.c. component of the fault current to the voltage across the SVL (single-point bonded systems)

In case of cross-bonded systems, the voltage across the SVL due to the d.c. component is negligible if the SVLs are delta connected or star connected with the neutral point isolated from earth because the d.c. current in the three cable sheaths is almost the same. If the SVLs are star connected with the neutral point earthed, the voltage across the SVLs depend both on resistive voltage drop on the cable sheaths (E_s) and on the EPR (earth potential rise) (V_e) at the end of the cable section (see figure L4).

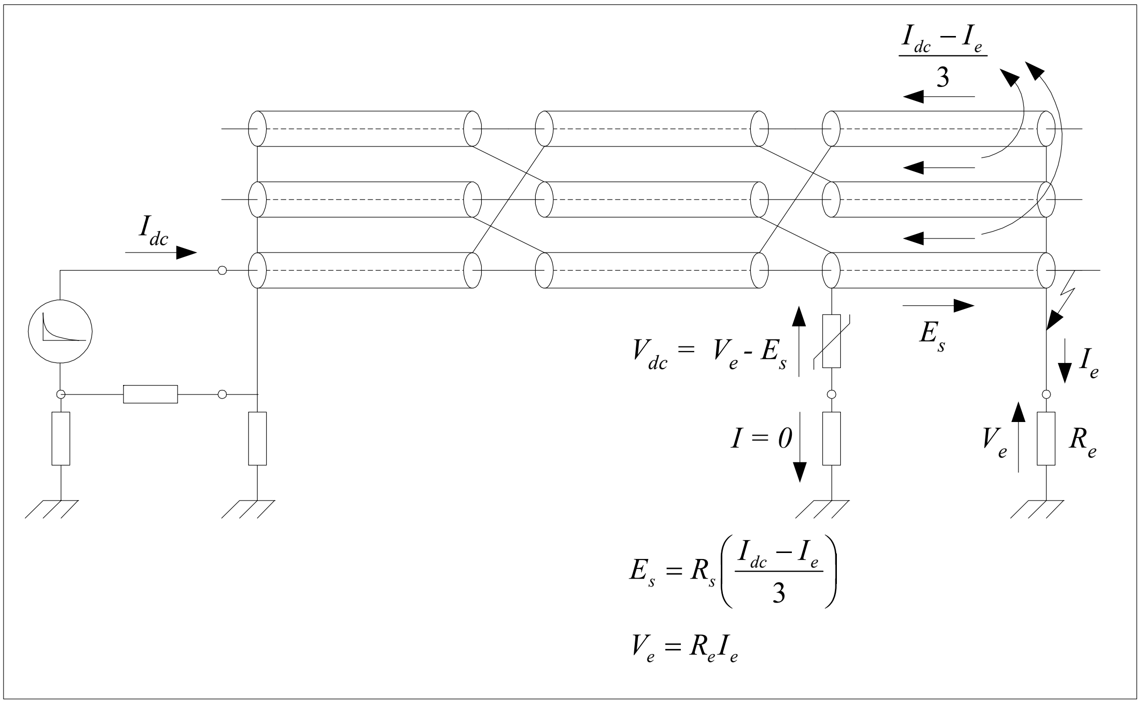


Figure L4 Simplified circuit illustrating the contribution of the d.c. component of the fault current to the voltage across the SVL (cross bonded systems)

The resistive voltage drop on the cable sheaths (E_s) is typically lower for cross-bonded- compared to single-point bonded systems due to the low resistance of the three sheaths in parallel. However, the EPR (V_e) at the end of the cable section is transferred at the SVL location. The earth impedance has therefore a greater impact on the SVL voltage on cross-bonded systems. If EPRs of the order of 1 or 2kV are typical in highly urbanized areas, they can reach values exceeding 20kV in the case of cable circuits inserted in the middle of an overhead line. Since the amplitude of the a.c. component of the EPR is similar, the voltage at the first crest can almost double.

The SVL does not have the energy handling capability to limit voltages during power faults. In cases where the voltage exceeds 20 to 30kV (including the d.c. component), the SVL should have a voltage rating of at least 15kV_{rms}. Such an arrester would produce voltages in the order of 50kV under transient conditions. The voltage across the sheath interrupt reaches 100kV (two SVLs in series) to which the voltage drop across the bonding leads must be added. These voltages may reach or exceed the BIL of the sheath interrupt.

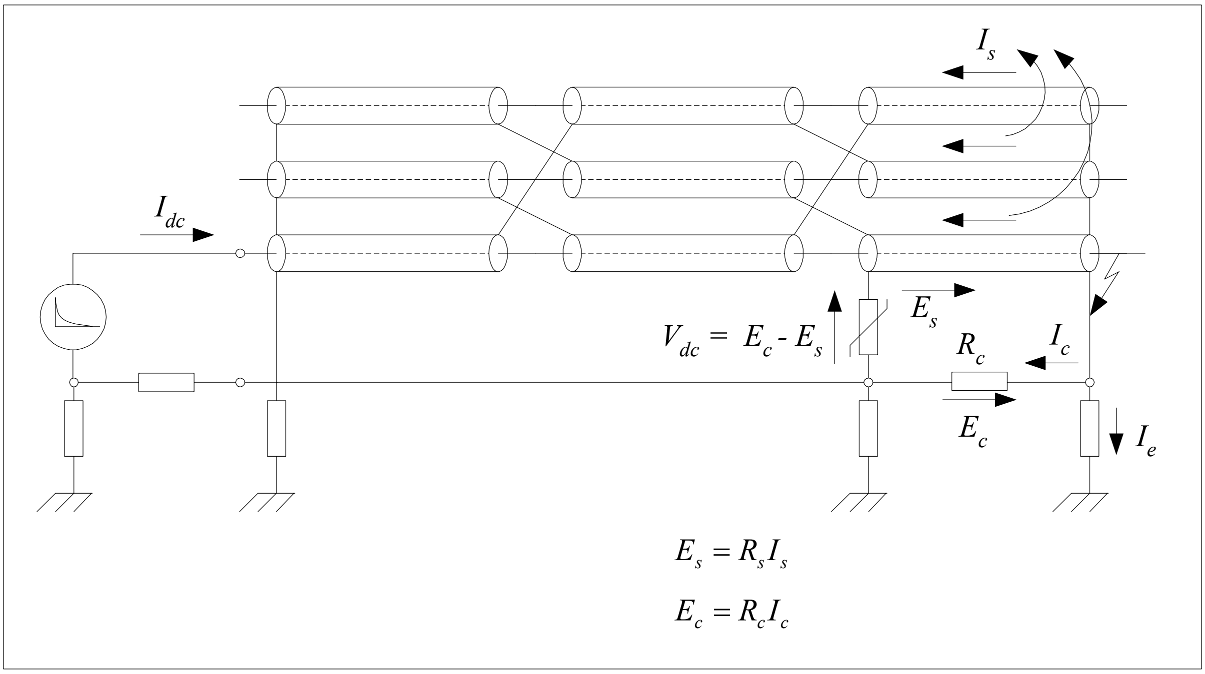


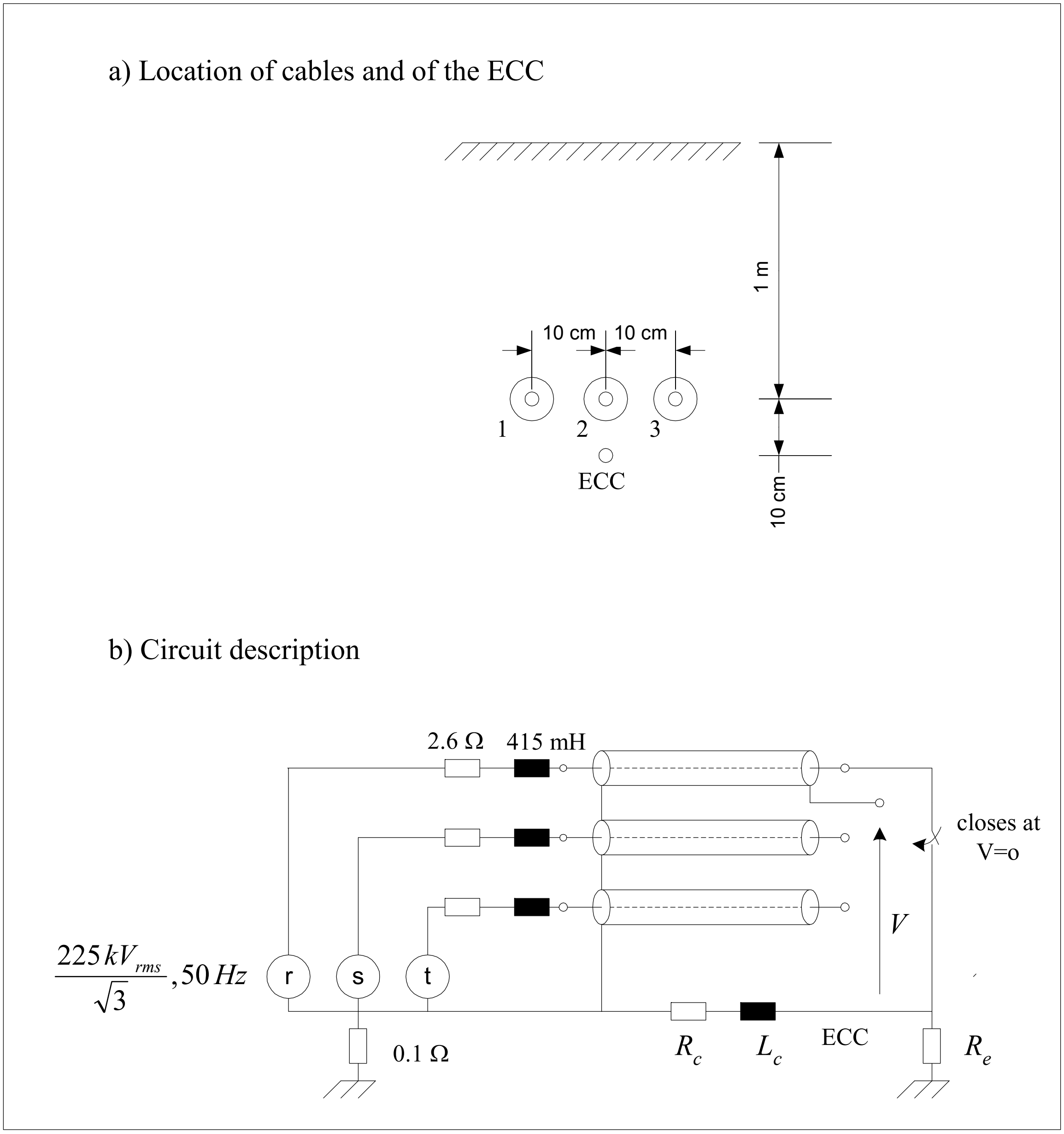
Figure L5 Simplified circuit illustrating the contribution of the d.c. component of the fault current to the voltage across the SVL (cross bonded circuit with an ecc)

In such cases, lower voltage ratings for the SVLs can be used if the neutral point connection of the SVLs is isolated from earth. Another option is to install an ecc (see figure L5). The voltage across the SVL is no more dependant of the EPR. The contribution of the ecc to the reduction of the voltage across the SVL has been illustrated in the study case in 3.3.5 for the a.c. component of the current.

5.2.4 Study case

This example looks at the influence of the resistance to earth (R_e) and the resistance of the earth conductor (R_c) on the voltage across the SVLs due to the current asymmetry on single-point bonded systems. Figure L6 presents the circuit considered and solved in EMTP. A single phase-to-earth fault is located at the end of the 1km cable circuit. Cable sheaths are bonded and earthed at one end and floating at the other end. The source impedance limits the 50Hz fault current component to

1kA$_{peak}$ and the time constant (*L/R*) is equal to 160ms. The fault occurs at V=0 in order to obtain the maximum asymmetry of the fault current.



a) Location of cables and of the ECC

b) Circuit description

Figure L6 Description of the circuit used for the evaluation of the voltage across the SVLs due to the current asymmetry on single point bonded systems

R_e takes two values: 1MΩ and 0.1Ω; the latter value is typical for urban HV substations in urban areas on the HQ system. The resistance of the earth conductor (R_c) takes two values: 0.1 and 0.23Ω/km.

Table L1 summarizes the results. For systems with low earth resistance (0.1Ω), the d.c. component contributes to increase the amplitude of the first crest by 28% for R_c=0.1Ω/km and 39% for R_c=0.23Ω/km. For high earth resistance values (R_e=1 MΩ), the amplitude of the first crest is increased by 35 and 64% respectively.

Table L1 **Components of the sheath-to-earth voltage on phase 1 (*V*) for a fault on phase 1 (V/km) (see figure L6)**

R_c (Ω/km)	R_e (Ω)	First crest (V_{peak})	50 Hz (V_{peak})	First crest/ 50 Hz (peak)
0.1	0.1	314	245	1.28
	10^6	361	268	1.35
0.23	0.1	415	298	1.39
	10^6	552	337	1.64

The maximum asymmetry appears on the phase with the lowest voltage (see Table L2). However, the maximum sheath-to-earth voltage appears on the faulted phase. The asymmetry on the faulted phase should therefore be used for the design of the SVL system.

Table L2 **Components of the sheath-to-earth voltage (*V*) on the three phases for a fault (see figure L6) on phase 1 (V/km) (R_c = 0.23 Ω/km and R_e = 1 MΩ)**

phase	First crest (V_{peak})	50 Hz (V_{peak})	First crest/ 50 Hz (peak)
1	552	337	1.64
2	479	263	1.82
3	468	253	1.85

5.2.5 Summary of the results

Figure L7 summarizes the influence the d.c. component for the different configurations considered.

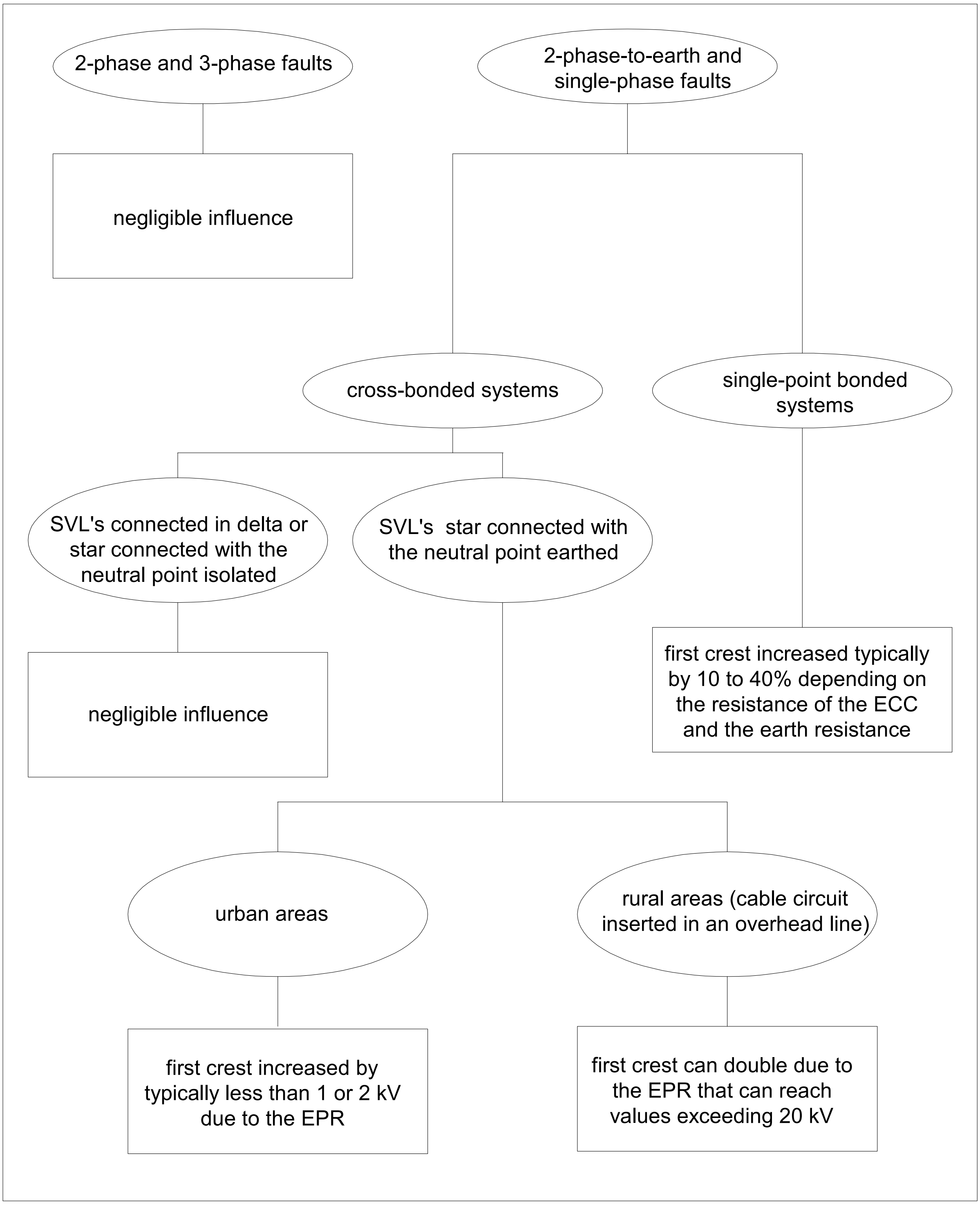


Figure L7 Diagram summarizing the influence of the d.c. component of the fault current on the voltage across SVLs

5.3 Configuration of Bonding Leads Through and Around Current Transformers (CTs)

Where CTs are fitted around cables close to terminations the following sheath bonding lead arrangements are recommended.

(a) At Solidly Earthed Terminations (Solidly bonded and cross bonded systems)

Where single core bonding leads are used, the lead from the cable termination earth connection must pass back through the CT en-route to the main system earth (figure M1). This is to nullify the influence of any sheath circulation current on the CT measurement.

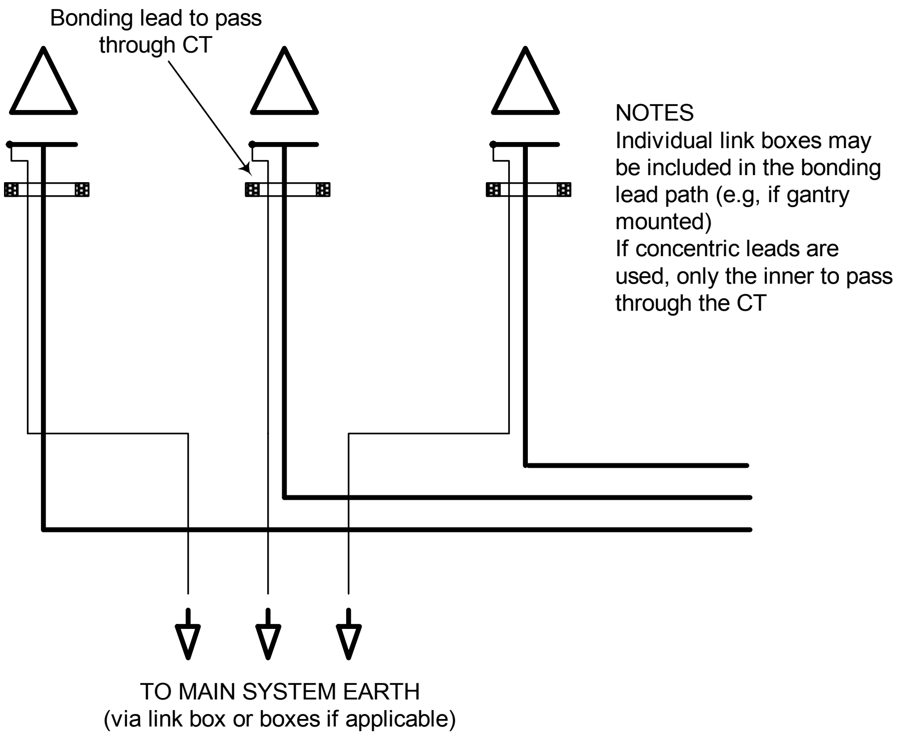


Figure M1

(b) At Unearthed Terminations (Single point bonded systems)

At the unearthed positions of single point bonded systems there is no conduction though the bonding leads under power frequency or fault conditions and therefore there is no issue of nullifying sheath currents where a CT is present. However, it is considered possible that for this arrangement the bonding lead should still be passed through the CT in case there may be some influence on the protection system.

Where concentric bonding leads are used, the inner conductor is assumed to connect the cable sheath at the termination to the unearthed side of the SVL. The outer conductor is assumed to connect from the termination support structure directly or indirectly (via a link enclosure) to the earth continuity conductor and thence to the main system earth. In these circumstances only the inner conductor may pass back through the CT en-route from cable sheath connection to SVL (figure M2).

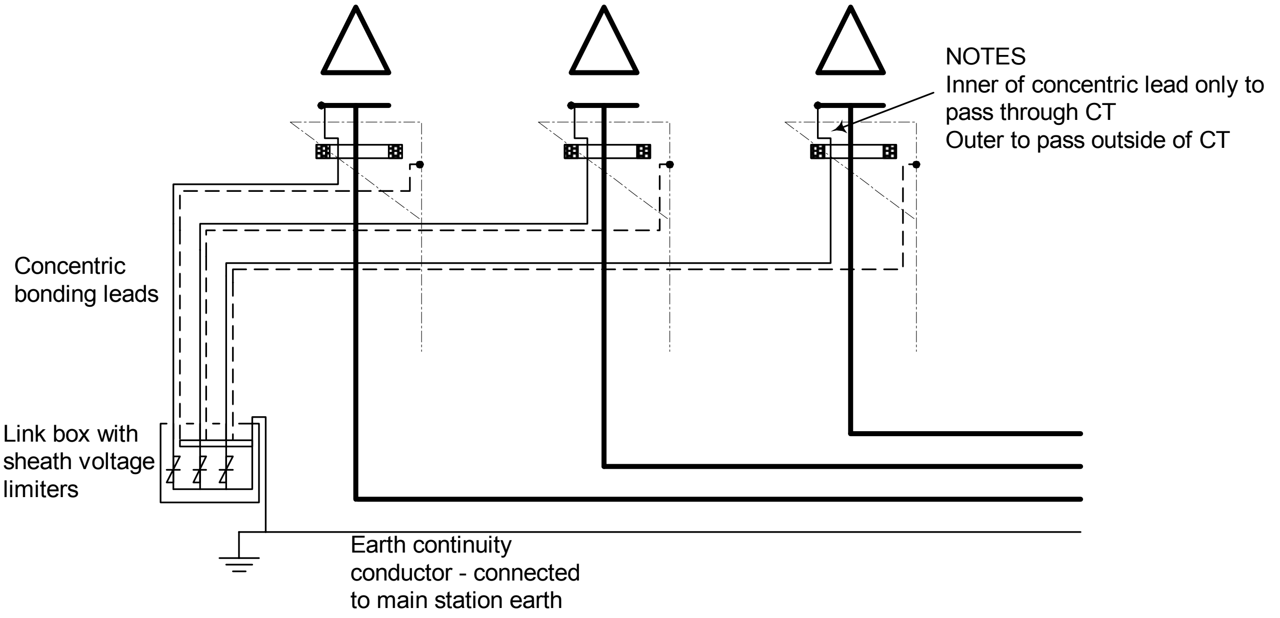


Figure M2

Other arrangements are possible, e.g, where protected SVL units are employed without the use of link boxes or enclosures. In such cases it is recommended that bonding lead length is kept to a minimum (<3m) and that any bonding lead connection between the earth side of the SVL and the ECC or earthed structure, be passed through the CT for the reasons given above.

6.0 RECOMMENDATIONS

6.1 Introduction

Special sheath bonding is recommended for large or highly loaded underground high voltage cable systems for the following reasons:

- To optimise the transmission capacity of new high voltage underground links: This is achieved in part by eliminating or reducing to a minimum the sheath circulating currents. Other considerations such as the installation technique used as well as environment conditions will also play a major role in achieving the optimum rating.
- To reduce cable losses and thus to reduce the operating cost of the link.

In the design of special screen bonding systems as well as the selection of their main components such as SVL's, bonding cables, both power frequency and transient voltages should be considered. The following data should be verified:

- System configuration
- Different short circuit levels and duration.
- Installation technique (directly buried, in ducts, in tunnels etc.).
- Cable arrangement and earth conductor position. (trefoil formation, flat formation, etc.)
- Earthing arrangements and earth resistivity

System data should be as close as possible to the actual values. To simplify calculations, any assumptions are made in some preliminary design stages. These assumptions should be re-examined prior to the final selection of bonding system components. It should be borne in mind that the accuracy of the calculation results will depend on the accuracy of any assumptions made in the values chosen for different parameters.

6.2 Power Frequency Conditions

Previously published Electra formulae [1] [3] are quite suitable for estimating power frequency voltages in normal operation and during 3-phase short-circuits. When considering the phase-to-earth fault, the sheath to sheath stresses at sectionalising joints for cross-bonding systems are also correctly evaluated.

Conversely, the use of more sophisticated calculation methods is required for estimating induced voltages under the following conditions:

- sheath to local earth voltages during phase-to-earth (external and internal) faults.
- sheath to sheath voltages during phase-to-earth internal faults.
- sheath to local earth voltages during phase-to-phase faults

The Complex Impedance Matrix method is quite suitable for these applications.

If software devoted to transient studies is used to study power frequency applications, the cable model has to be carefully selected (e.g. the Pi model for EMTP).

Where several parallel circuits or one or more earth continuity conductor(s) are to be considered formulae have been recommended and the study should not present undue difficulty.

Where a link connecting two substations with low earth resistances is considered, earth potential rises at the ends and at the cross-bonding locations may be disregarded. Conversely, when a siphon system is dealt with, earth potential rises have to be taken into account since, in this case, the sheath to earth voltage may exceed the sheath nominal withstand level and the SVL energy handling capability if they are star connected with earthed neutral point.

The installation of one or two earth continuity conductor(s) is a solution in order to reduce induced sheath voltages in cross bonded systems.

6.3 Transient Conditions

Lightning surges are normally the most severe condition as compared to switching surges and induced voltages are linked to the derivative of the current versus time.

When considering usual overhead line / underground cable systems with sky wires installed on the overhead line sections and surge arresters at the transition compound, the probability for higher overvoltages into the cable system is low. A back flashover with very high current striking close to the transition or wire shielding failure, still with high current, is needed in order to transmit high transient overvoltages into the cable system. However, if worst case conditions are considered, as is invariable the case with underground power system design, then more expensive designs will result, albeit providing the benefit of greater security.

If an optimized design is sought, then an estimation of the transient current or voltage levels becomes necessary, requiring a study which is far more complicated than for power frequency conditions.

Simple methods, using travelling waves, can give a reliable order of magnitude of the voltages resulting across the main cable insulation, although only a very rough estimate of transients in the sheath circuits is achievable.

EMTP (and ATP) provides the most thorough of calculation models for representing transient conditions in high voltage systems. The model is a sophisticated impedance matrix approach which models both the self and mutual effects of conductors in a system together with the surrounding environment and any external paths. EMTP studies are normally carried out by experts in this field and require a degree of judgement in particular areas of the modelling, given (a) the limitations of the EMTP model and (b) the less defined parameters in the study. The WG has therefore provided observations and guidelines based on experience with EMTP. The main problem is the modelling of bonding leads, which has a large impact on the final result.

Whilst this is intended to help other users of EMTP with cable system modelling, it is also strongly recommended that such modelling be carried out only by experts and not be considered as a routine design tool but as a specialist system study approach.

6.4 Design Methodology

6.4.1 Personnel Safety (e.g, Maintenance Crews)

The maximum allowed sheath to earth standing voltage under normal operation may be governed by national standards or utilities' rules. Where specified, this is normally the maximum permitted sheath standing voltage under conditions of normal service loading. It is a common requirement with specially bonded sheath systems to install a physical barrier to prevent personnel from accidentally contacting live metalwork at terminations (such as SVL connections at unearthed terminations in single point bonded systems). Also, works on live HV links are normally forbidden or strictly controlled. However, regarding the level of accepted sheath standing voltage, it should be kept in mind that the higher this voltage is, the larger is the risk of sheath corrosion in case of outersheath damage.

The level of sheath standing voltage does of course have a direct influence on the lengths of the minor section. For example, historically a voltage limit of around 60 – 65V was imposed by many Utilities for systems up to 132kV, resulting in relatively short elementary section lengths.

6.4.2 Sheath and Joint Protection

The SVL rating is linked to the voltages that may be applied to the cable sheath, and on the joint sectionalising insulation design limits (for cross-bonded systems) under transient conditions. Given the satisfactory experience with present designs, and taking account of WG calculation results, the withstand levels previously recommended in Electra [2] should be kept (except in the case of “long” 10m bonding leads for systems with 345kV BIL, where the level should be increased to 60kVp.

If the SVL residual voltage is about 10kV (for star connection), then the voltage drop in the bonding leads is in line with the withstand level of sheaths and joints. In such conditions, using concentric bonding leads or single-core leads (with close spacing) is allowable.

For VHV systems, SVL with higher ratings could be used taking into account the difference between calculated voltages and withstand levels (about 20kV for 225kV systems). If such an approach is intended, the power frequency withstand levels of the outersheaths, joint protection, even the joint sectionalising insulation have to be checked.

6.4.3 Length of elementary sections

For determining the maximum length of minor or elementary sections, there are two key parameters:

- The maximum allowed sheath to earth voltage under short-circuit conditions: This voltage is generally imposed by the SVL energy handling capability, but it may be appropriate to consider also the outersheath withstand level. The d.c. component of the short-circuit current has to be taken into account in the case of phase to earth faults : the first crest may be increased by 10 % (single point bonding) to 100 % (cross bonded siphon).

- The maximum sheath to sheath voltage under short-circuit conditions for cross-bonding systems: This voltage has to be compared to the sectionalising sleeve withstand level

6.4.4 The Omission or Reduction of SVLs

“Direct Cross Bonding”, where SVLs are either eliminated or used in limited locations is seen to be feasible under certain system conditions and environments although it is important to develop a representative system and environment model in order to assess the security of the cable and system against incoming transients. Where direct cross bonding is been applied, the following steps in design are recommended:

- Detailed system assessment using EMTP or similar method, with an accurate model of the intended system
- Use of line surge arrestors to limit incoming transients
- Design of sheath sectionalising insulation at cross bonding joint to withstand predicted barrier voltages under transient conditions.
- In the case of a mixed connection (overhead line – underground link), SVLs are retained for the cross bonding joints in the first major sections close to the overhead lines, because these sections are considered vulnerable to transient overvoltages above the withstand level of the sheath sectionalising insulation at joints.

The omission of SVLs in single point bonded systems is not recommended.

6.4.5 Past, Present and Future

Experience and new WG calculations show that existing designs of special bonding systems, based on previous Electra references [1][2][3] ensure satisfactory behaviour in operation.

The design of siphon systems needs to be reconsidered (as was suggested in Electra 128) in order to take into account earth potential rise due to current flowing through high ground resistances.

VHV system designs can be improved by using SVL of ratings differing from the previous rating assumed in Electra. However in this case, oversheath, joint protection and sectionalising insulation withstands have to be checked.

The omission or reduction where possible, of SVLs in cross bonded systems is an improvement, although at the present this solution seems a tailored one, requiring an accurate system model and transient calculations to be made before application. Also, where sectionalising insulation is not protected by SVLs, that insulation should be designed and type-tested for the highest transient voltage expected during fault conditions.

To achieve an optimised design of special bonded system, the main problem still pending is the modeling of bonding leads for transient studies, which should be assessed by testing.

7.0 REFERENCES

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