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EARTH POTENTIAL RISES IN SPECIALLY BONDED SCREEN SYSTEMS

Task Force
B1.26

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cigré

WG B1. 26

Earth potential rises in specially bonded screen systems

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1. INTRODUCTION

CIGRE WG B1.18 issued in 2005 a brochure [1] giving recommendations on the design of cross bonding systems, updating previous articles in Electra 28, 47 and 128 [2,3,4]. The brochure considered in summary, the question of Earth Potential Rise (EPR) in underground systems and published the following broad conclusion:

Where a link connecting two substations with low earth resistances is considered, EPR at the ends and at the cross-bonding locations may generally be disregarded. Conversely, for siphon systems EPR has to be taken into account since sheath to earth voltage may exceed the nominal withstand level and the SVL energy handling capability if they are star connected with earthed neutral point.

Subsequent field experience has served to question the validity of the TB conclusions, particularly in respect of EPR in urban underground systems. For this reason, CIGRE SC B1 decided in 2005 to launch a Task Force Group to consider EPR in underground systems in greater depth, with the TF terms of reference being as follows:

To improve the design of special bonded screen systems, dealing with EPR, providing:

- more information on EPR which may occur during single phase to earth faults
- details of a calculation method based on the Complex Impedance Model (CIM).
- calculation examples, especially for typical situations.

Generally in power systems analysis and substation design, EPR is considered more in terms of step, touch and mesh voltages and the calculation of hot zones around power installations. IEEE 80 [5] is one example of existing standards for assessing these features. The focus in these cases in mainly personnel safety within areas subject to EPR. Conversely the focus in WG B1.26 and in this report is the safety and security of the cable sheath earthing system and its associated SVLs when subject to EPR. The issue of personnel safety is not considered in this work and is outside of the remit of the TF.

One of the key parameters in EPR assessment is impedance to ground where the substation/cable/overhead line towers are earthed and this will also be the least certain of the data necessary for calculation. In addition, the ownership of required data will be divided between the Utility and the cable system Supplier and would usually require knowledge of the overall power system. However, in many cases an understanding of the order of magnitude of EPR in the cable sheath system may be sufficient to identify potential problems and this may enable simplified methods to be adopted.

This report describes both simplified and complex methods for assessing EPR in cable systems and identifies those systems most vulnerable to high EPR. Two worked examples of EPR calculation in simple cable systems are detailed and a more complex example is also included to illustrate how EPR can vary in a real-life substation/cable/overhead line system. Both internal (cable) and external faults are considered together with an analysis of the sensitivity of the EPR calculation to certain key parameters.

2. MAIN SYMBOLS AND PARAMETERS

ABBREVIATIONS	DEFINITION
UGL	Underground Link
OHL	Overhead line
SVL	Sheath voltage limiter
ecc	Earth continuity conductor
EPR	Earth potential rise
EMTP	Electromagnetic transient program
ATP	Alternative Transient Program
CIM	Complex Impedance Matrix
NV	Node Voltage

SYMBOL	DEFINITION	UNIT
Electrical		
e	largest voltage drop in the third minor section	V
E_S	screen/sheath voltage drop	V
E_c	voltage drop in the earth continuity conductor	V
EPR	magnitude of the EPR at fault location	V
EPRr	EPR at right end	V + j V
EPRl	EPR at left end	V + j V
Ifault	phase to earth short-circuit current	A
I_{scl}	phase to earth short-circuit current flowing from left end	A
I_{scr}	phase to earth short-circuit current flowing from right end	A
Ig	current flowing to the earth at fault location	A
I_{1E}	earth fault current in phase conductor 1	A
I_e	return current flowing in the equivalent ground conductor (ecc and/or metallic screens)	A
Isc1	phase to earth short-circuit current flowing in UGL	A
Isc3	3-phase short-circuit current flowing in UGL	A
$\overline{K}$	coefficient in formulae for EPR	complex
K	magnitude of K coefficient in formulae for EPR	
Rc	apparent resistance of the equivalent ground conductor	Ω/m
Rf	per-span tower footing impedance	Ω
Ri	earthing resistance between major sections.	Ω
R_L	earthing resistance at left end	Ω
R_r	earthing resistance at right end	Ω
R_s	a.c. resistance of cable screen	Ω
R'_E	equivalent a.c. resistance per unit length of earth return path	Ω/m
V	screen/sheath voltage referenced to local earth	V
V_d	voltage drop in major section	V
$\overline{V_0}$	coefficient in formulae for EPR	V/A + j V/A
V_0	cagnitude of V0 coefficient in the formula for EPR	V/A
V_{0sp}	coefficient in the formula for EPR relating to single-point bonding, between two substations	V/A
Vlim	maximum permissible potential rise at the cross-bonding point close to right end	V
Vmaxe	maximum potential rise at the cross-bonding point close to right end, during external phase to earth faults	V
Vmaxi	maximum potential rise at the cross-bonding point close to right end, during internal phase to earth faults	V
Vpn	maximum potential rise at the cross-bonding point close to right end, due to the superposition of positive and negative sequences	V
Vtri	maximum potential rise at the cross-bonding point close to right end, during three-phase faults	V
Vxb	maximum voltage rise at the cross-bonding point close to right end, due to zero sequence currents	V
Xc	p.u. length apparent self inductance of the equivalent ground conductor	Ω/m
Xm	p.u. length apparent mutual of the equivalent ground conductor with the faulted phase	Ω/m
x	proportion of the short circuit current flowing in the underground link to the overall short circuit current cable (single phase fault)	
Z'_e	p.u. length self impedance of equivalent ground conductor	Ω/m + j Ω/m
Z'_m	p.u. length mutual impedances of the equivalent ground conductor	Ω/m + j Ω/m
Z_c	p.u. length mutual impedance central/lateral cables	Ω/m + j Ω/m
Z_m	p.u. length mutual impedance core / screen	Ω/m + j Ω/m
Z_{out}	p.u. length mutual impedance for lateral cables (for a trefoil formation : $Z_{out} = Z_c$)	Ω/m + j Ω/m
Z_s	p.u. length self impedance of screen	Ω/m + j Ω/m
Z_{sw}	p.u. length self impedance of the skywire	Ω/m + j Ω/m
Z_{mw}	p.u. length mutual impedance phase / skywire	Ω/m + j Ω/m

Z0	p.u. length impedance relating to internal fault	Ω/m + j Ω/m
Zas	impedance equivalent to the skywire	Ω + j Ω
Z_R	impedance corresponding to Rr in parallel with Zas	Ω + j Ω
Z_L	impedance corresponding to R_L in parallel with Zas	Ω + j Ω
μ_o	permeability of free space	Hm^{-1}
μ	coupling factor of OHL	
μ'	coupling factor of UGL	
ρ_E	electric resistivity of soil	Ω.m
ω	angular frequency of system	rad/s

Dimensional

d	geometric mean sheath diameter	mm
D_E	equivalent depth of earth return path	mm
l	length of minor section in X-bonded link	m
L	length of UGL	m
L_s	span length of OHL	m
rs	cable screen radius	mm
S	axial spacing of adjacent cables in a regular three phase flat or trefoil formation	mm

Others

N	number of major sections in a cross-bonded UGL

3. VOLTAGE STRESSES RELATED TO EPR TO BE TAKEN INTO ACCOUNT IN THE DESIGN OF SPECIALLY BONDED SCREEN SYSTEMS

3.1 Introduction

When a phase to earth fault occurs in a transmission system, the fault current will return to the source via different paths (metallic return paths and earth) subject to each of these options being present in the transmission system:

- Earth conductor (skywire) of overhead lines, including tower earthing systems.
- Screens/sheaths of underground cables.
- Earth continuity conductors installed in the same trench as underground cables.
- Earthed telecommunication systems.
- Earth itself.

Connections to earth will usually occur at several locations in a transmission system. Where this happens, the injection of some fault current through the earth electrode will cause the electrode to increase in potential with respect to the reference earth. The flow of current through the surrounding soil will likewise raise the earth potential in the vicinity of the electrode. This earth potential rise (EPR) will however decrease with the distance away from the electrode.

3.2 Risk due to EPR in Specially Bonded Systems

In general, EPR may be harmful for the cable system insulations and SVLs which are stressed between cable sheath potential and earth potential. The items at risk are therefore cable oversheath, joint protection and SVLs. Conversely, insulations between cable sheaths or SVLs connected in delta formation are not at risk from EPR where due to external faults.

3.2.1 Single Point Bonding

Provided that a suitable parallel ecc is part of the system, the sheath to earth voltage under external fault conditions will always refer to the ecc. EPR is not therefore a concern for the SVLs, which bridge between the cable sheath and the ecc.

3.2.2 Cross Bonding

EPR is a major concern for SVLs which protect the sectionalising insulation in cross bonded joints, where the SVLs are star connected with neutral earthing. Generally such systems do not include an ecc and the influence of EPR due to an external fault is illustrated in figure 3.1.

In case of an external phase to earth fault, the returning fault current flows partly in the cable sheaths (*Is*) and partly in through earth (*Ig*) causing a potential rise (*EPR*) at the location of the fault. Remote from this location this potential decreases to zero. However, EPR transfers along the cable sheath to the joint positions and, in part, is superimposed with the normal sheath standing voltage *Es* which develops due to *Is*, the fault current returning via the sheath itself and the induced voltage related to the fault current Isc and the current Is in the other two cable sheaths. As an approximation therefore (over-estimation), the voltage across the SVL during an external phase to earth fault is the sum of *Es* and *EPR.*

Where it is necessary to remove the risk from EPR in a cross bonded system an ecc may be used, as illustrated in figure.3.2.

In this case the voltage across the SVL at the joint closest to the fault position is no more dependent on EPR and can be approximated (over-estimation) to the normal sheath standing voltage *Es*.

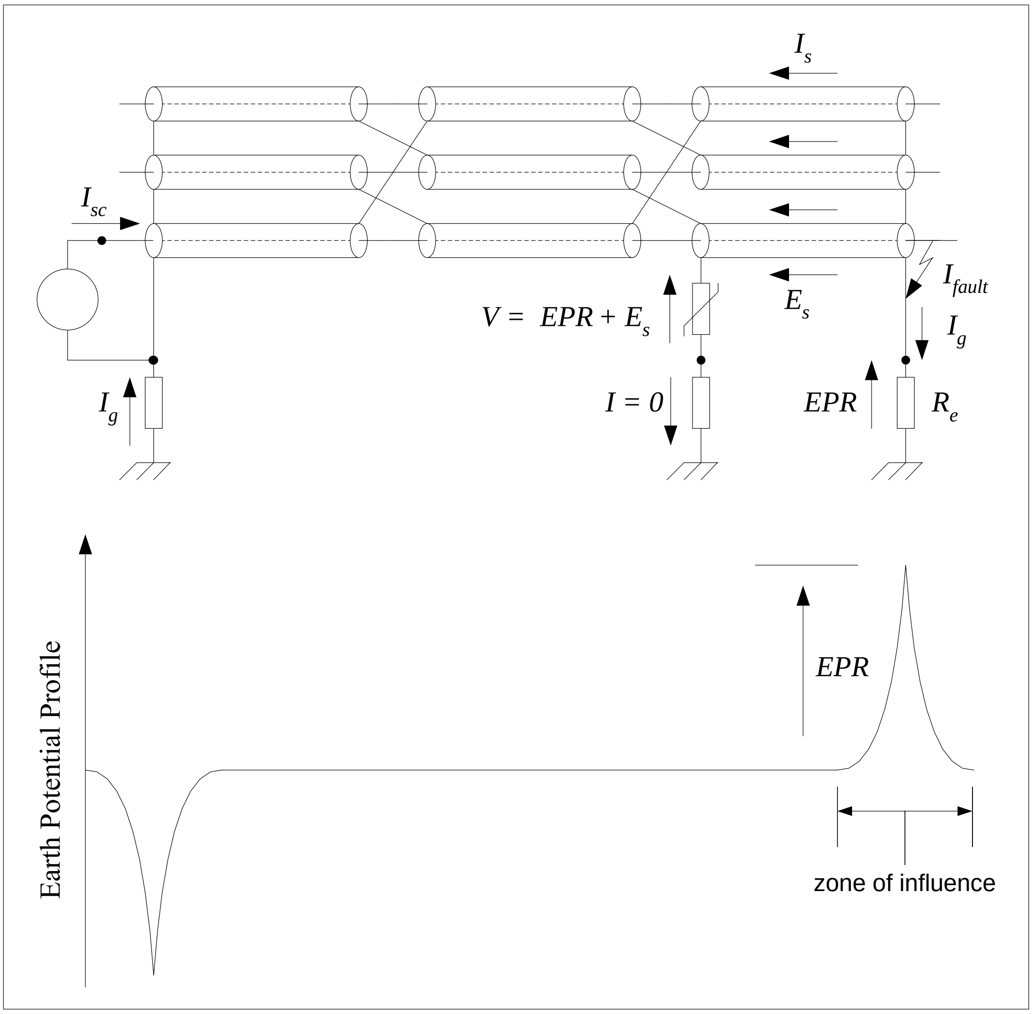


Fig.3.1: Influence of EPR in a Cross Bonded System Without an ecc

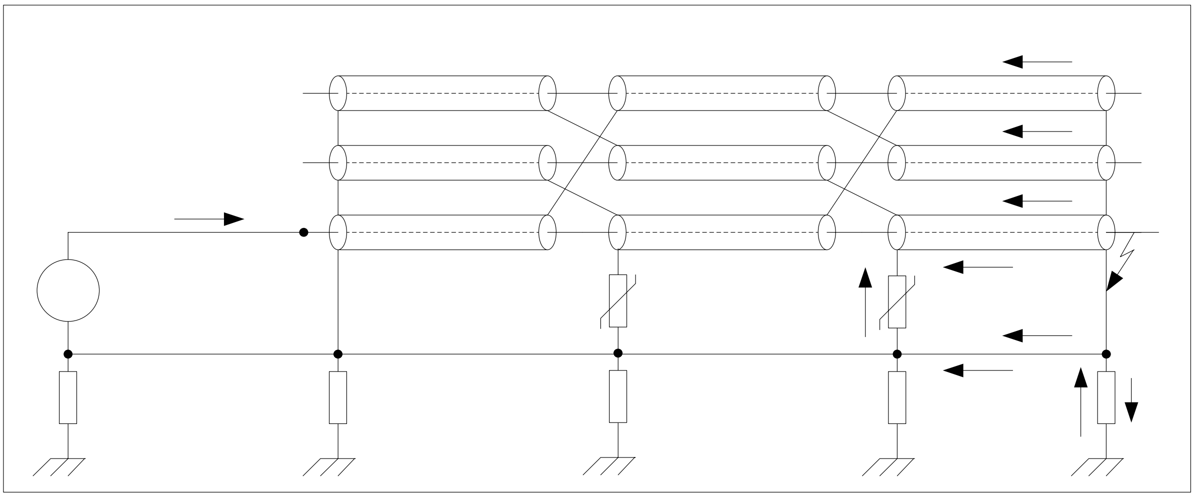


Fig.3.2: Influence of EPR in a Cross Bonded System with an ecc

3.3 System Variations

It would generally be expected that the earth fault current path through the cable system, via sheaths or earth continuity conductor, would be a favourably low impedance path, which combined with low earth impedance values at the terminations, would result in only modest levels of EPR. However, the same may not be true if the cable is connected to overhead lines in a siphon system or if the cable system terminates into a substation or compound having high earth impedance.

Accurate calculation of EPR and consequent sheath to earth voltages is complex because it depends on current distribution between cable sheaths, earth continuity conductor (if present), earth itself and also the values of earth impedance at locations where the cable sheaths are connected to earth. In that case, detailed calculations using CIM, NV or EMTP/ATP [6] are recommended.

In siphon systems the skywire impedance and the impedance to earth of the towers are also important, as well as the value of earth resistivity itself. For such complex arrangements, accurate modelling of the complete system requires a level of design data usually beyond the scope and knowledge of the local cable system design function. In addition, the system data pertinent to EPR calculation is held primarily by the Utility and less so by the cable Supplier. However, simplified formulae which ignore the current paths beyond the concerned substations and assuming low earth impedance values at the cable terminations, could be used to give a rough estimation of the value of EPR for cross bonded systems. It will be seen that simplified analysis may provide the correct order of magnitude result, which may be sufficient to identify a potential EPR threat.

Accurate values of earth impedance at substations or other locations may not be fully known or understood. The earth impedance at a substation depends not only on the grid itself but also on the incoming overhead lines and cables. Furthermore, the value of soil resistivity is not always known. Earth impedance is therefore a complex parameter which is difficult and expensive to accurately measure. Care is needed when using earth impedance values in order not to produce misleading results.

Different system variations and conditions are discussed and illustrated in subsequent sections of this report.

4. CALCULATION METHODS

4.1 General

The Complex Impedance Matrix (CIM) method described in the WG B1-18 technical brochure [1] is in general suitable to model EPR in power cable systems. Another solution, known as Node Voltage (NV) method, may also be used. This method is common for calculation of voltages in electrical networks by means of computer programs because the rules to establish the equation system can be formalized quite well. Many commercially available network analysis programs use that method which is appropriate for calculation of electrical networks containing cable circuits as shown below (with a worked example given later in Appendix A). Commonly available spreadsheet calculation programs may also be satisfactory for small or medium sized models. The NV method may be more attractive than CIM method, if multiple earthing points are to be considered (i.e. intermediate earthings in cross-bonded circuits)

In this section, both methods are described, together with the simplified power frequency impedance model, which is a simplification to CIM method. Considerations to UGL and OHL are also given.

4.2 Basics Common to All Calculation Methods

As only power frequency voltages and currents are concerned, the following simplifications can be made to the general impedance model :

- Ignoring the capacitive currents;

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

Provided that the soil is uniform and homogeneous, the parameters of this equivalent conductor can be determined as follows:

$$R_E^{'} = \frac{\omega \cdot \mu_0}{8} \qquad (4.1)$$

$$D_E = \frac{1.85}{\sqrt{\dfrac{\omega \cdot \mu_0}{\rho_E}}} \qquad (4.2)$$

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 ($\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am)
ρ_E	-	Electric resistivity of soil

The electric resistivity of the soil can vary over a wide range. If no information about the type of soil is known, a value of 100Ω·m may be used.

4.3 Structure of the Equation System for CIM

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

The term "conductor" in the scheme refers to the phase conductors as well as to any other parallel metallic structure such as 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:

$$(\underline{V}) = (\underline{Z}) \cdot (\underline{I}) \qquad (4.3)$$

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.

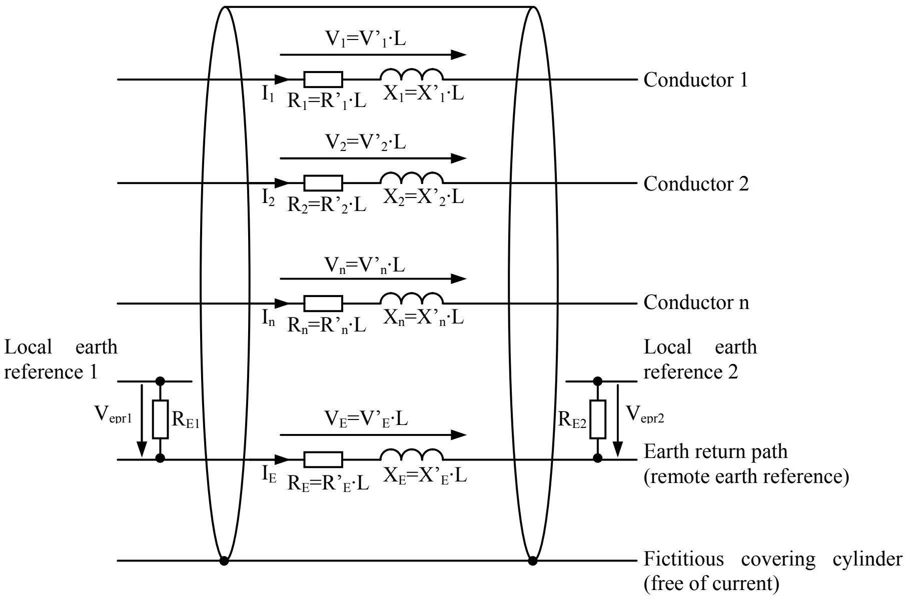


Fig. 4.1:Equivalent scheme of a high voltage cable system

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

$$\underline{Z}_{mn} = \underline{Z}'_{mn} \cdot L = \left(R'_{mn} + j\,X'_{mn}\right) \cdot L \qquad (4.4)$$

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:

$$R'_{mn} = R'_m \qquad \text{(for m = n)} \qquad (4.5a)$$

$$R'_{mn} = 0 \text{ (for m} \neq \text{n)} \qquad (4.5b)$$

$$X'_{mn} = \frac{\omega \cdot \mu_0}{2\pi} \cdot \ln \frac{r_{cov}}{g_{mn}} \qquad (4.6)$$

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)

$$g_{mm} = \alpha \cdot r_m \qquad (4.7)$$

The coefficient α is generally about 0.78 (see table A1 in CIGRE Brochure [1])

- For mutual impedance between two conductors (m ≠ n)

$$g_{mn} = a_{mn} \qquad \text{(non-coaxial conductors)} \qquad (4.8a)$$

$$g_{mn} = \max(\bar{r}_m ; \bar{r}_n) \qquad \text{(coaxial conductors)} \qquad (4.8b)$$

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

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 (4.1) 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. 4.1).

4.4 Calculation of Voltages and Currents Using Complex Impedance Matrix (CIM) Method

Equation (4.3) may be written as

$$(0) = (\underline{Z}) \cdot (\underline{I}) - (\underline{V}) \qquad (4.9)$$

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):

$$\underline{I}_{const\,m} = \underline{I}_m \qquad (4.10)$$

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

$$0 = \underline{I}_m \qquad (4.11)$$

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

$$0 = \underline{V}_m - \underline{V}_E - \underline{V}_{epr1} + \underline{V}_{epr2} \qquad (4.12)$$

In case (c) the earth potential rise at both ends has to be taken into account (see fig. 4.1).

The complete final equation system has the following structure:

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

(4.13)

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 the boundary condition is in accordance with equation (4.10) or zero, if the boundary condition is in accordance with equations (4.11) or (4.12)). The last equation in (4.13) 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 (4.13) accordingly. The system is solved using commonly known algorithms (i.e. Gauss algorithm). The solution vector then contains all relevant currents and voltages.

4.5 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 [7], it is possible to derive simplified equations for induced voltages, which can be handled with simple tools such as pocket calculators or universal spreadsheet programs, without the need of special numerical computer programs.

The following assumptions may be made:

- Phase currents are known
- 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)
- The geometric arrangement of the cables is a regular trefoil or flat formation and does not vary along the route.

Moreover the three screens in parallel in cross-bonded systems may be considered as a single conductor, and description of the different spans of OHL may be avoided, assuming constant span lengths and tower footing resistances, as explained below.

4.6 Node Voltage Analysis Method

4.6.1 Principle of the Node Voltage Analysis Method

The node voltage (NV) analysis method is a calculation method, which is derived from the basic equations of the electrical network analysis (Ohm's law, Kirchhoff's current law). It uses the independent node voltages as unknowns. The structure of the equation system is as follows:

$$(\underline{I}) = (\underline{Y}) \cdot (\underline{V}) \qquad (4.14)$$

with $(\underline{I})$ - Vector of current sources
$(\underline{Y})$ - Matrix of self and mutual admittances
$(\underline{V})$ - Vector of node voltages

The dimension of the equation system (rank of the matrix) is equal to the number of independent nodes in the circuit to be calculated. This is usually one less than the total number of nodes in the circuit because one of the nodes has to be selected as reference node whose node voltage is therefore equal to zero. Consequently that node is not represented by a particular equation because its node voltage is not unknown.

In a first step the total admittance matrix and vector of the current sources (including the reference node) are build up using formalized rules which are described in detail later in that document. Then, one of the nodes is selected as the reference node. The row and column representing the reference node is then deleted from the node admittance matrix and the vector of the current sources. This (reduced) equation system is then solved using one of the usual methods (matrix inversion, Gauss algorithm or others). The solution gives the voltages of the independent nodes related to the potential of the reference node.

The currents in a particular branch can be calculated afterwards as the product of the voltage difference between both nodes and the admittance of that branch.

4.6.2 Representation of Two-Port Elements

Circuit elements having two connection leads (ports) such as single impedances or sources are represented within the vector of current sources and the admittance matrix using the following formalized simple rules:

Single impedance

Passive components between nodes *i* and *j* which are characterized by a single complex impedance $\underline{Z}$ such as resistors, inductors (without magnetic coupling to other inductors), capacitors or any serial combination of these elements are added to the node admittance matrix as follows:

$$\underline{Y}_{ii} = \underline{Y}_{jj} = +\frac{1}{\underline{Z}} \qquad (4.15) \qquad\qquad \underline{Y}_{ij} = \underline{Y}_{ji} = -\frac{1}{\underline{Z}} \qquad (4.16)$$

The values have to be added to the existing contents of the relevant cells of the total node admittance matrix.

Current sources

For a current source with magnitude $\underline{I}_s$ between nodes *i* and *j* (directed towards node *i*) the vector $(\underline{I})$ is:

$$\underline{I}_i = +\underline{I}_s \qquad (4.17) \qquad\qquad \underline{I}_j = -\underline{I}_s \qquad (4.18)$$

The value of the source current $\underline{I}_s$ has to be added to the existing contents of the two relevant cells *i* and *j* of the vector $(\underline{I})$ considering the polarity (direction) of the source.

Voltage sources

The node voltage analysis method can only handle real voltage sources having non-zero internal impedance. A voltage source with the magnitude $\underline{V}_s$ and the internal impedance $\underline{Z}_s$ must be transformed into an equivalent current source having the magnitude $\underline{I}_s$ and the internal admittance $\underline{Y}_s$ as follows:

$$\underline{I}_s = \frac{\underline{V}_s}{\underline{Z}_s} \qquad (4.19) \qquad\qquad \underline{Y}_s = \frac{1}{\underline{Z}_s} \qquad (4.20)$$

So the vector of current sources and the node admittance matrix have to be modified as follows:

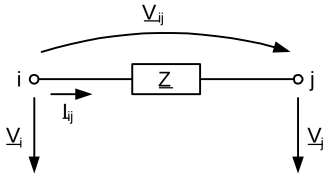
$$\underline{I}_i = +\frac{\underline{V}_s}{\underline{Z}_s} \qquad (4.21) \qquad\qquad \underline{I}_j = -\frac{\underline{V}_s}{\underline{Z}_s} \qquad (4.22)$$

$$\underline{Y}_{ii} = \underline{Y}_{jj} = +\frac{1}{\underline{Z}_s} \qquad (4.23) \qquad\qquad \underline{Y}_{ij} = \underline{Y}_{ji} = -\frac{1}{\underline{Z}_s} \qquad (4.24)$$

Single impedance

Matrix $(\underline{Y})$

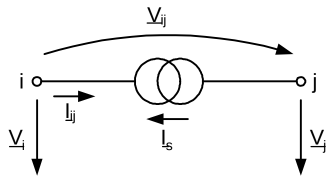
	...	*i*	...	*j*	...
...	...	...	...	...	...
i	...	$+\frac{1}{\underline{Z}}$	...	$-\frac{1}{\underline{Z}}$	...
...	...	...	...	...	...
j	...	$-\frac{1}{\underline{Z}}$		$+\frac{1}{\underline{Z}}$	...
...	...	...	...	...	...



Current sources

Vector $(\underline{I})$

...	...
i	$+\underline{I}_s$
...	...
j	$-\underline{I}_s$
...	...



Voltage sources

Vector $(\underline{I})$

...	...
i	$+\frac{\underline{V}_s}{\underline{Z}_s}$
...	...
j	$-\frac{\underline{V}_s}{\underline{Z}_s}$
...	...

Matrix $(\underline{Y})$

...	*i*	...	*j*	...
...	...	...	...	...
...	$+\frac{1}{\underline{Z}_s}$	...	$-\frac{1}{\underline{Z}_s}$	...
...	...	...	...	...
...	$-\frac{1}{\underline{Z}_s}$		$+\frac{1}{\underline{Z}_s}$	...
...	...	...	...	...

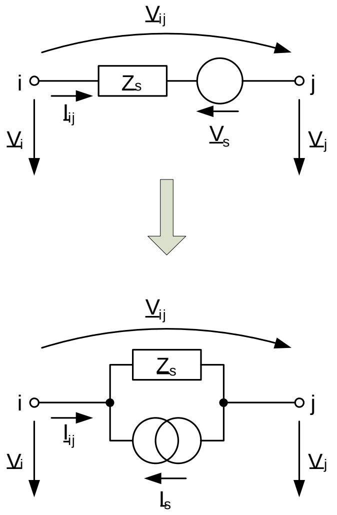


Figure 4.2 : Representation of basic elements

4.6.3 Representation of a Cable Circuit Section

A cable circuit consisting of the power cables of all phases, the earth continuity conductors, any additional conductors (if existing) and the earth return path is modelled as a “multi-port black box”. The following sketch illustrates the principle using a model with three inputs and three outputs:

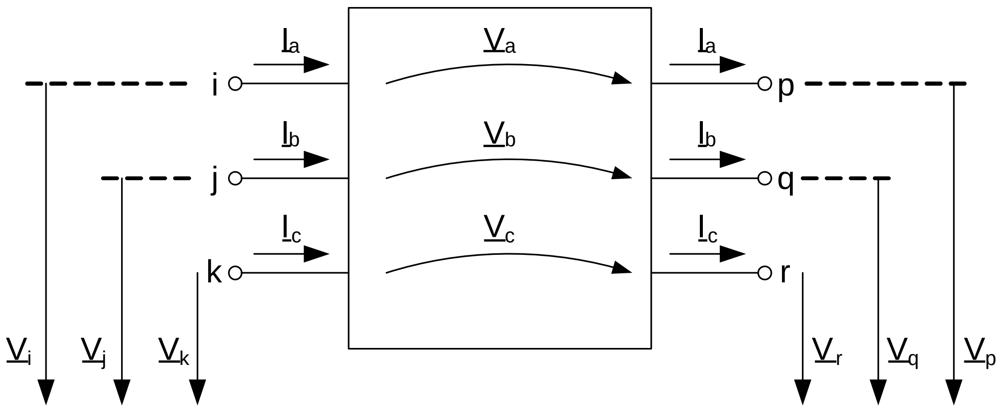


Figure 4.3 : Cable circuit representation

The voltage drop along the cables and the currents are linked together via the complex impedance matrix *(Z)* as known from the CIM method.

$$\begin{pmatrix} \underline{V}_a \\ \underline{V}_b \\ \underline{V}_c \end{pmatrix} = \begin{pmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ba} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ca} & \underline{Z}_{cb} & \underline{Z}_{cc} \end{pmatrix} \cdot \begin{pmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \end{pmatrix} \qquad (4.25)$$

Using the admittance matrix *(Y)* as the inverse of the impedance matrix *(Z)*

$$\begin{pmatrix} \underline{Y}_{aa} & \underline{Y}_{ab} & \underline{Y}_{ac} \\ \underline{Y}_{ba} & \underline{Y}_{bb} & \underline{Y}_{bc} \\ \underline{Y}_{ca} & \underline{Y}_{cb} & \underline{Y}_{cc} \end{pmatrix} = \begin{pmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ba} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ca} & \underline{Z}_{cb} & \underline{Z}_{cc} \end{pmatrix}^{-1} \qquad (4.26)$$

the equation system becomes

$$\begin{pmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \end{pmatrix} = \begin{pmatrix} \underline{Y}_{aa} & \underline{Y}_{ab} & \underline{Y}_{ac} \\ \underline{Y}_{ba} & \underline{Y}_{bb} & \underline{Y}_{bc} \\ \underline{Y}_{ca} & \underline{Y}_{cb} & \underline{Y}_{cc} \end{pmatrix} \cdot \begin{pmatrix} \underline{V}_a \\ \underline{V}_b \\ \underline{V}_c \end{pmatrix} \qquad (4.27)$$

The voltage drop along the cables, screens and conductors is represented by the node voltage differences as

$$\begin{pmatrix} \underline{V}_a \\ \underline{V}_b \\ \underline{V}_c \end{pmatrix} = \begin{pmatrix} \underline{V}_i \\ \underline{V}_j \\ \underline{V}_k \end{pmatrix} - \begin{pmatrix} \underline{V}_p \\ \underline{V}_q \\ \underline{V}_r \end{pmatrix} \qquad (4.28)$$

So the equation system can be expressed as

$$\begin{pmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \end{pmatrix} = \begin{pmatrix} \underline{Y}_{aa} & \underline{Y}_{ab} & \underline{Y}_{ac} \\ \underline{Y}_{ba} & \underline{Y}_{bb} & \underline{Y}_{bc} \\ \underline{Y}_{ca} & \underline{Y}_{cb} & \underline{Y}_{cc} \end{pmatrix} \cdot \begin{pmatrix} \underline{V}_i \\ \underline{V}_j \\ \underline{V}_k \end{pmatrix} - \begin{pmatrix} \underline{Y}_{aa} & \underline{Y}_{ab} & \underline{Y}_{ac} \\ \underline{Y}_{ba} & \underline{Y}_{bb} & \underline{Y}_{bc} \\ \underline{Y}_{ca} & \underline{Y}_{cb} & \underline{Y}_{cc} \end{pmatrix} \cdot \begin{pmatrix} \underline{V}_p \\ \underline{V}_q \\ \underline{V}_r \end{pmatrix} \tag{4.29}$$

The voltages $\underline{V}_i$, $\underline{V}_j$, $\underline{V}_k$, $\underline{V}_p$, $\underline{V}_q$ and $\underline{V}_r$ are the node voltages for the node voltage analysis. Therefore the part of the admittance matrix concerning the nodes *i, j, k, p, q* and *r* will be as follows:

	i	**j**	**k**	**p**	**q**	**r**
i	$+\underline{Y}_{aa}$	$+\underline{Y}_{ab}$	$+\underline{Y}_{ac}$	$-\underline{Y}_{aa}$	$-\underline{Y}_{ab}$	$-\underline{Y}_{ac}$
j	$+\underline{Y}_{ba}$	$+\underline{Y}_{bb}$	$+\underline{Y}_{bc}$	$-\underline{Y}_{ba}$	$-\underline{Y}_{bb}$	$-\underline{Y}_{bc}$
k	$+\underline{Y}_{ca}$	$+\underline{Y}_{cb}$	$+\underline{Y}_{cc}$	$-\underline{Y}_{ca}$	$-\underline{Y}_{cb}$	$-\underline{Y}_{cc}$
p	$-\underline{Y}_{aa}$	$-\underline{Y}_{ab}$	$-\underline{Y}_{ac}$	$+\underline{Y}_{aa}$	$+\underline{Y}_{ab}$	$+\underline{Y}_{ac}$
q	$-\underline{Y}_{ba}$	$-\underline{Y}_{bb}$	$-\underline{Y}_{bc}$	$+\underline{Y}_{ba}$	$+\underline{Y}_{bb}$	$+\underline{Y}_{bc}$
r	$-\underline{Y}_{ca}$	$-\underline{Y}_{cb}$	$-\underline{Y}_{cc}$	$+\underline{Y}_{ca}$	$+\underline{Y}_{cb}$	$+\underline{Y}_{cc}$

Figure 4.4 : Partial admittance matrix

The upper left and the lower right quarter of the partial node admittance matrix contain the admittance matrix of the cable circuit (i.e. the inverted impedance matrix) with positive sign. The upper right and the lower left quarter contain the same admittance matrix with negative sign.

This partial node admittance matrix of the cable circuit is then added to the whole node admittance matrix by adding all elements to the cells belonging to the corresponding nodes. Sometimes the case may occur, that several leads (ports) of the cable circuit are linked to the same node of the whole circuit (i.e. a node representing local earth potential). In that case the sum of all elements related to any of the leads which are connected to that node is added to the content of the appropriate cells accordingly.

4.6.4 Building up the Total Node Admittance Matrix and Solving the Equation System

The total admittance matrix of the system to be calculated contains as many rows and columns as nodes exist in the system. So every row and respective column number represents a particular node. The total node admittance matrix is built up by adding the contents of all cells of the partial node admittance matrices of all circuit elements to those cells of the total node admittance matrix which belong to the nodes where the particular circuit element is connected to. The same is done for the total vector of current sources.

The total node admittance matrix in that form is singular because no reference node has been selected so far and the set of node voltages is therefore not linearly independent. Therefore one particular node has to be selected as the reference node whose node voltage is defined as zero. The corresponding row and column has to be deleted from the total node admittance matrix and the total current source vector. The remaining reduced matrix is no longer singular and the equation system becomes resolvable.

The solution of the resulting equation system gives directly the voltage of all nodes related to the selected reference node. Please note that practical hints for handling complex matrices and equation systems are shown in Appendix A. Therefore any voltages in the circuit may be calculated as the difference of the node voltages of the appropriate nodes. The currents in branches containing a single passive element only (without sources) may be simply calculated from the voltage drop multiplied by the admittance of that element. If the branch is a voltage source the branch current is the voltage drop minus the source voltage divided by the source impedance. For a cable circuit section the currents are calculated by multiplying the matrix of the branch admittances by the vector of the voltage drops as shown above.

4.7 UGL and OHL Simplified Modelling

a) Modelling of UG Cables

For cross-bonded links, the screens of the cables of a major section can be compared to a single conductor characterized by a self-impedance and a mutual impedance with the faulty phase conductor, the expressions of which are given below :

$$Z_e' = \frac{1}{3}.\left[Z_s + 2.Z_c - 2.\frac{(Z_c - Z_s).(Z_{out} - Z_c)}{3.(Z_s - Z_c) + (Z_{out} - Z_c)} \right] \quad (4.30)$$

$$Z_m' = \frac{1}{3}.\left[Z_m + 2.Z_c - 2.\frac{(Z_c - Z_s).(Z_{out} - Z_c)}{3.(Z_s - Z_c) + (Z_{out} - Z_c)} \right] \quad (4.31)$$

with :
Z'_e ,Z'_m : p.u. length self and mutual impedances of the equivalent ground conductor.
Z_s: p.u. length self impedance of screen.
Z_m : p.u. length mutual impedance core / screen.
Z_c : p.u. length mutual impedance central/lateral cables.
Z_{out} : p.u. length mutual impedance for lateral cables (for a trefoil formation : $Z_{out} = Z_c$)

The UGL coupling factor is defined as :

$$\mu' = \frac{Z_m}{Z_s} \quad (4.32)$$

Modelling of OH lines

In OH lines, the fault current return path involves the skywire(s), the towers and the earth. In every span of the OH line, an induced voltage is generated due to the phase conductor / skywire coupling. This can be modelled as a voltage source resulting in a current flowing in the skywire and returning to the source, with magnitude μ.Isc, where μ is the coupling factor and Isc the short-circuit current :

$$\mu = \frac{Z_{mw}}{Z_{sw}} \quad (4.33)$$

Z_{sw} is the self-impedance of the skywire and Z_{mw} is the mutual impedance between the faulted phase and the skywire

This current flowing is constant along the skywire, there is no current through the towers and the voltage drop due to its flow through the voltage source is zero.

The current flowing to the earth through the skywire and the towers is then (1-μ).Isc.

The impedance of the return path looking from the fault terminals is the impedance of a ladder network, involving the self-impedance of the sky-wire and the resistances of the tower footings.

This impedance may be estimated for long lines, with constant tower footing resistances as :

$$Z_{as} = Z(\infty) \qquad Z(m) = Z_{sw}.L_s + \frac{R_f.Z(m-1)}{R_f + Z(m-1)} \qquad Z(1) = Z_{sw}.L_s + R_f \qquad (4.34,\ 4.35,\ 4.36)$$

i.e.:

$$Z_{as} = \frac{Z_{sw}.L_s + \sqrt{(Z_{sw}.L_s)^2 + 4.R_f.Z_{sw}.L_s}}{2} \approx \sqrt{R_f.Z_{sw}.L_s} \qquad (4.37)$$

where Rf is the per-span tower footing impedance and Ls is the span length.

5. TYPICAL SITUATIONS

5.1 General

The location of the underground link in the grid has a large influence on the EPR that may occur during single-phase to earth faults.

Whilst there are many possible situations, three ”typical” situations may be considered as the most frequent ones, namely:

- a UG connection between two urban substations
- a substation fed by an OH line through a UG link
- a siphon system

In these typical situations, the fault may be fed by sources located at one end or at both ends. In some cases, where a predominating source exists, feeding from one end only may be assumed. In other cases, the actual fault may be considered as the superposition of two situations, each one assuming a predominating source located at one end.

In practice, four elementary ”simple” configurations, involving only one source, may be identified, from which an actual situation may be studied, using superposition. This is illustrated on figure 5.1, considering external faults, i.e. faults occurring outside the UG link. Typical situations are located on the left side (only the fault location is different in the second and fourth drawings), elementary situations on the right side.

Generally, precise calculations require solving a large set of equations, even for these elementary situations.

Fortunately, if we are interested in the order of magnitude of EPR, which may be the first step in order to decide whether an in-depth study is necessary or not, the set of equations may be made easier to handle using appropriate modelling and reasonable assumptions, such as :

- The cable type is constant within a given link. The laying conditions are more or less the same in the various elementary sections …
- The ground electrode resistances and the tower footing resistances or the spans, have the same order of magnitude on the cable or line route .

Moreover, where the UG link involves several sections, considering only one section, with a length equal to the total length leads to an overestimate of the EPR, which may be sufficient as a first step.

In the following, first, the main features of the elementary situations are presented, then EPR formulae and computation results are displayed for the three typical situations, resulting from studies on elementary situations, which are summarized in figure 5.2.

EPR formulae were derived from relatively simple calculations, based on the modelling of a UGL and OHL as detailed in § 3, leading to a “slim” format for CIM. Whenever it was possible, calculations were carried out using these formulae. CIM computations were performed as a check, or where formulae were not available.

Finally, voltages applied to the SVLs in cross-bonded systems are dealt with.

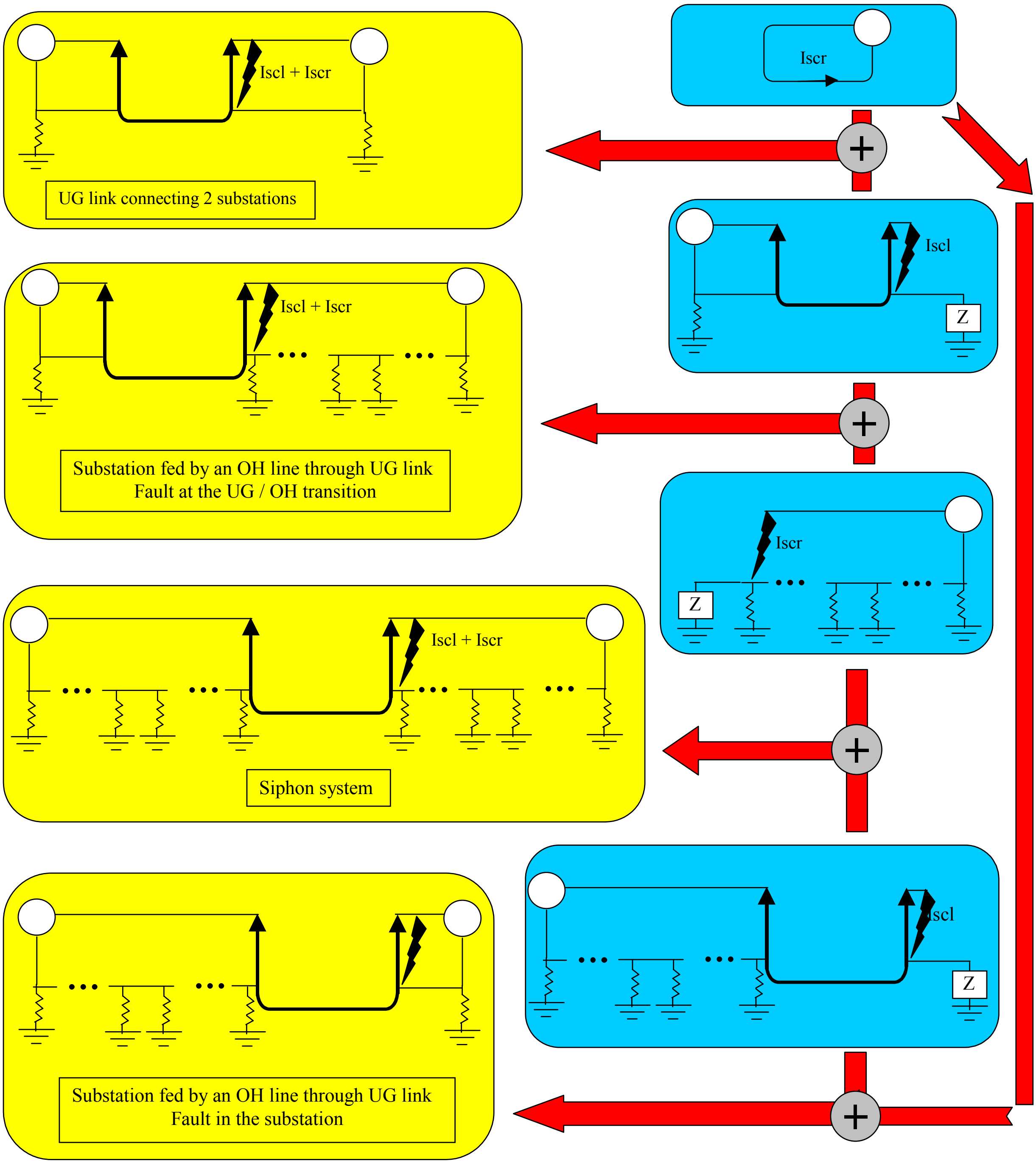


Figure 5.1 : Typical and Elementary Situations

5.2 Elementary Situations

5.2.1 Fault in a Substation on a Busbar to which a UG link is Connected.

The fault is assumed to be fed by sources located in the substation only and the short-circuit current is assumed to be returning directly to the sources, without flowing in the earth. This situation is a particular one, excluding y-connected transformers, grounded autotransformers and grounded generators. This is the simplest elementary situation, which does not need complex studies since the path for the short-circuit current do not involve the earth grid, and, so, EPR is not occurring.

5.2.2 Fault Fed Through a UG link Directly Connected to the Short-Circuit Current Source

In the case of a UG link between two substations, the impedance Z in figure 5.2 is simply the earth resistance of the faulted substation. Where the UG link is connected to an OH line with skywire(s), the impedance Z is representative of the ladder network composed of the skywire(s) and the towers.

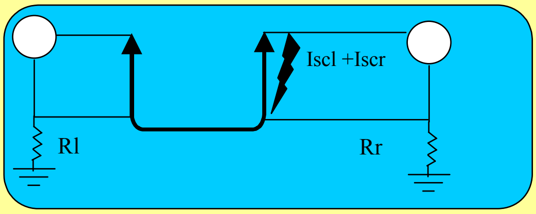
5.2.3 Fault at a UG/OH Transition, Fed through the OHL; No Short-Circuit Current in the UGL.

The impedance Z in figure 5.2 is for the metallic screens of the cables and/or the ecc and either the earth resistance of a substation or the ladder network composed of the skywire(s) and the towers of a OH line.

5.2.4 Fault at a UG/OH Transition, Fed Through the OHL, with Short-Circuit Current in the UGL.

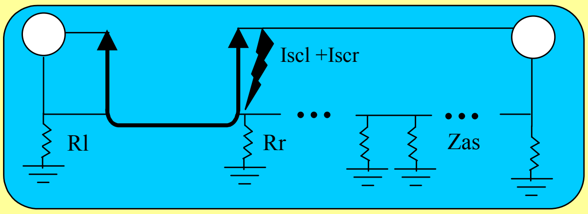
This is the more complex case, since different induced voltages are generated in the screens and/or the ecc in the UG part and in the skywire(s) in the OH part. Again, this situation may be dealt with using the superposition principle.

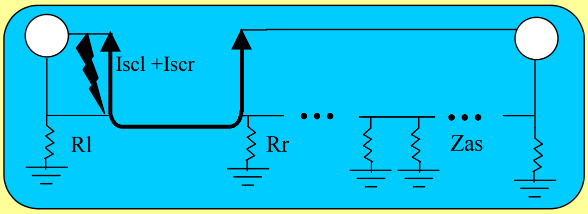
Connection between 2 substations



$$EPR_r = R_r \cdot \frac{Z'_e - Z'_m}{Z'_e.L + R_r + R_l}.L.I_{scl} \qquad (5.1)$$

Substation fed through an OHL



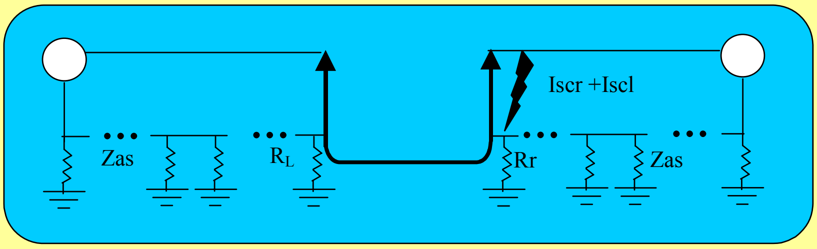


$$EPR_r = Z_R \cdot \frac{Z'_e - Z'_m}{Z'_e.L + Z_R + R_l}.L.I_{scl} + Z_R \cdot \frac{Z'_e.L + R_l}{Z'_e.L + Z_R + R_l}.(1-\mu).I_{scr} \qquad (5.2)$$

$$EPR_l = R_l \cdot \frac{Z'_e.L + Z_R}{Z'_e.L + Z_R + R_l}.(1-\mu)I_{scr} - R_l \cdot \frac{Z'_e.L}{Z'_e.L + Z_R + R_l}.(\mu' - \mu)I_{scr} \qquad (5.3)$$

$$Z_R = \frac{R_r.Z_{as}}{R_r + Z_{as}} \qquad (5.4)$$

Siphon system



$$EPR_r = Z_R \cdot \frac{Z'_e.L + Z_L}{Z'_e.L + Z_R + Z_L}.(1-\mu).(I_{scr} + I_{scl}) - Z_R \cdot \frac{Z'_e.L}{Z'_e.L + Z_R + Z_L}.(\mu' - \mu).I_{scl} \qquad (5.5)$$

$$Z_R = \frac{R_r.Z_{as}}{R_r + Z_{as}} \qquad Z_L = \frac{R_L.Z_{as}}{R_L + Z_{as}} \qquad (5.6)\ (5.7)$$

Z'e , Z'm self impedance and mutual impedance with faulted phase of the equivalent ground conductor in UG links
Zas : impedance of the skywire(s) and towers - µ coupling factor of OHL - µ' coupling factor of UGL
L : length of the UGL.

Figure 5.2 : Diagram for a Connection Between 2 Substations.

5.3 Connection Between Two Substations.

5.3.1 General

Figure 5.3 illustrates a fault occurring on a connection between 2 substations

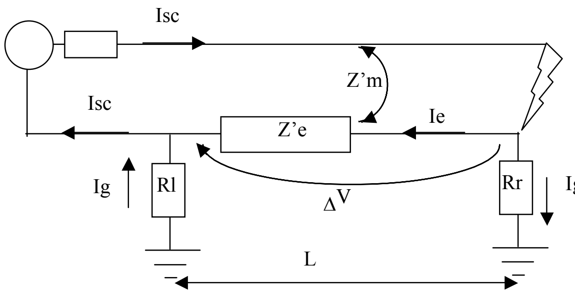


Figure 5.3 : Diagram for a connection between 2 substations.

Rr and Rl are the earth resistance of the right and left side substation, respectively.
Z'e is the p.u. length self impedance of the earth conductor equivalent to the ecc and/or the metallic screens ; Z'm is the p.u. length mutual impedance between the faulted phase conductor and the ecc or the earth conductor equivalent to the metallic screens.
L is the length of the UG link.

The EPR at the fault location (right end) and at the other end may be easily derived as :

$$EPR_r = R_r.I_g = R_r.\frac{\left(Z_e^{'} - Z_m^{'}\right)L}{Z_e^{'}.L + R_r + R_l}.I_{sc} \qquad EPR_l = -R_l.I_g \qquad (5.8), (5.9)$$

It can be seen that an outstanding parameter is the ratio between the sum of the ground electrode resistances and the ground conductor impedance.

In the following, considerations refer to the EPR at the faulted end, but they hold for the other end mutatis mutandis.

The EPR at the faulted end may be written :

$$EPR = \frac{R_r}{R_r + R_l}.K.V_0.I_{sc} \qquad (5.10)$$

with :

$$K = \frac{\dfrac{R_r + R_l}{L}}{\sqrt{\left[\left(R_c + R_E^{'}\right) + \dfrac{R_r + R_l}{L}\right]^2 + X_c^2}} \qquad V_0 = \sqrt{R_c^2 + \left(X_c - X_m\right)^2}.L \qquad (5.11), (5.12)$$

- Rc is the apparent resistance of the equivalent ground conductor
- Xc is the apparent self inductance of the equivalent ground conductor
- Xm is the apparent mutual of the equivalent ground conductor with the faulted phase
- R_E' is the equivalent ground resistance.

5.3.2 Cross Bonded links

V_0 may be estimated as (the relationship being exact for trefoil laying):

$$V_0 \approx \frac{R_s}{3}.L \qquad (5.13)$$

K is displayed on figure 5.43 as a function of the ratio sum of the ground resistances to the link length, where cables are laid in trefoil, two values of the cable spacing and screen resistance ranging from 0.018 to 0.40 Ohm/km.

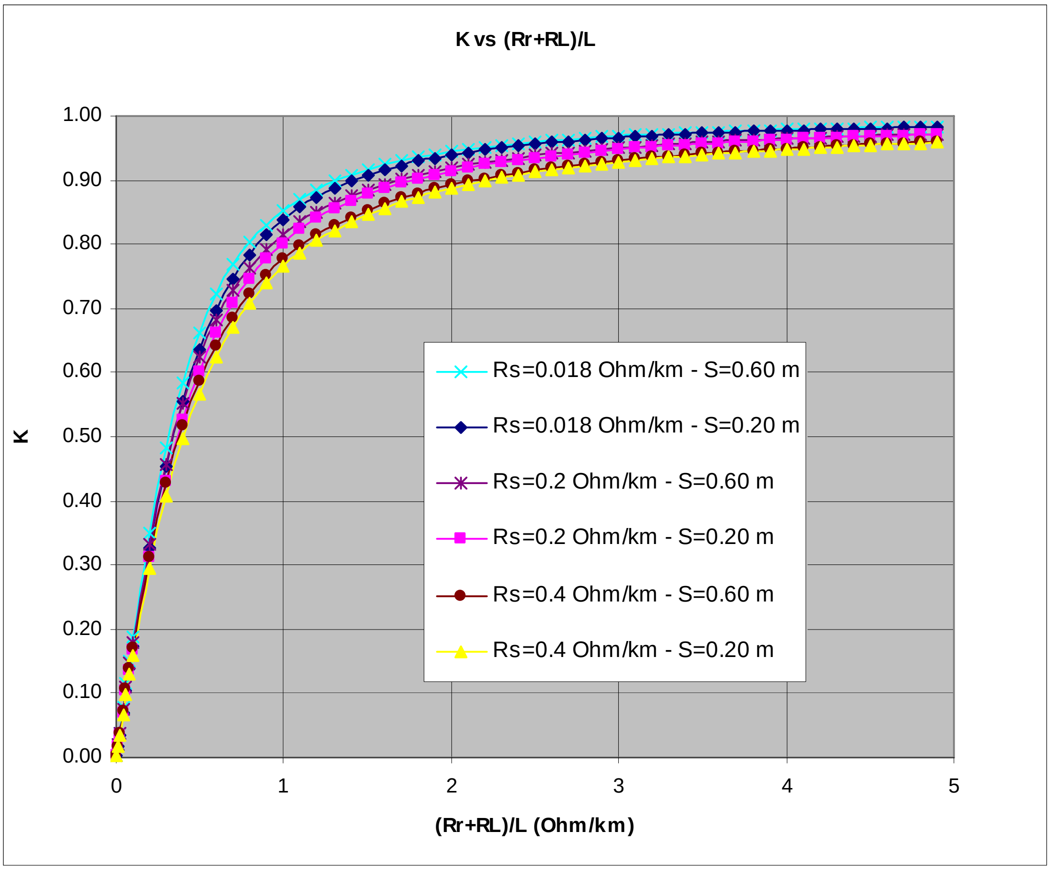


Figure 5.4 : K Factor Versus the Substation Resistances Referenced to the UG Length

It may be pointed out that the EPR is roughly independent of the laying conditions and that the maximum value is simply the voltage drop in the screens, assuming that the whole of the short-circuit current returns through the screens.

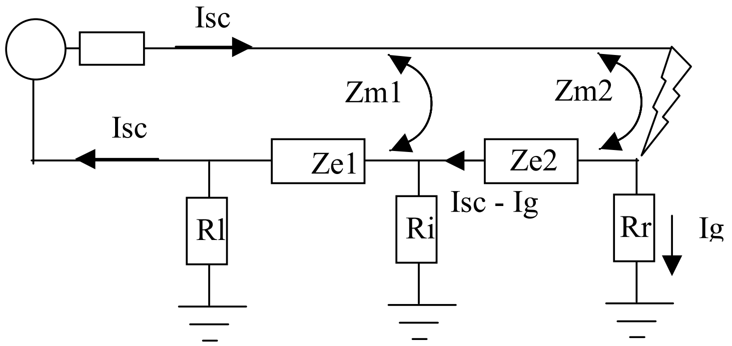
5.3.3 Cross Bonded Links with Several Sections

Where the UG link involves two or three sections, not too complex formulae for EPR may be derived.
The impact of the length of elementary sections and intermediary ground resistances may be assessed;

As stated in the introduction, consideration of only one section leads to an overestimate of the EPR.

In figures 5.5 and 5.6 for EPR, the asymptotic value corresponds to the case where the intermediary resistance(s) are infinite, i.e. the value for one section with the link length.

Where the ground resistances at cross bonding points are large (e.g. 1 or 2 Ohms), the link behaves like a line with one section. Conversely, where the resistance at a cross bonding point is very close to 0, then the line behaves like a line with one section, the length of which is the distance from the cross bonding point to the end.



$$EPR = R_r.\left(Z'_{e2} - Z'_{m2}\right).\frac{\left[L_2 + \frac{\left(Z'_{e1} - Z'_{m1}\right)}{\left(Z'_{e2} - Z'_{m2}\right)}.L_1\right].R_i + .\left[Z'_{e1}.L_1 + R_l\right].L_2}{\left[Z'_{e1}.L_1 + Z'_{e2}.L_2 + R_l + R_r\right].R_i + \left[Z'_{e1}.L_1 + R_l\right].\left[Z'_{e2}.L_2 + R_r\right]}.I_{sc}$$

(5.14)

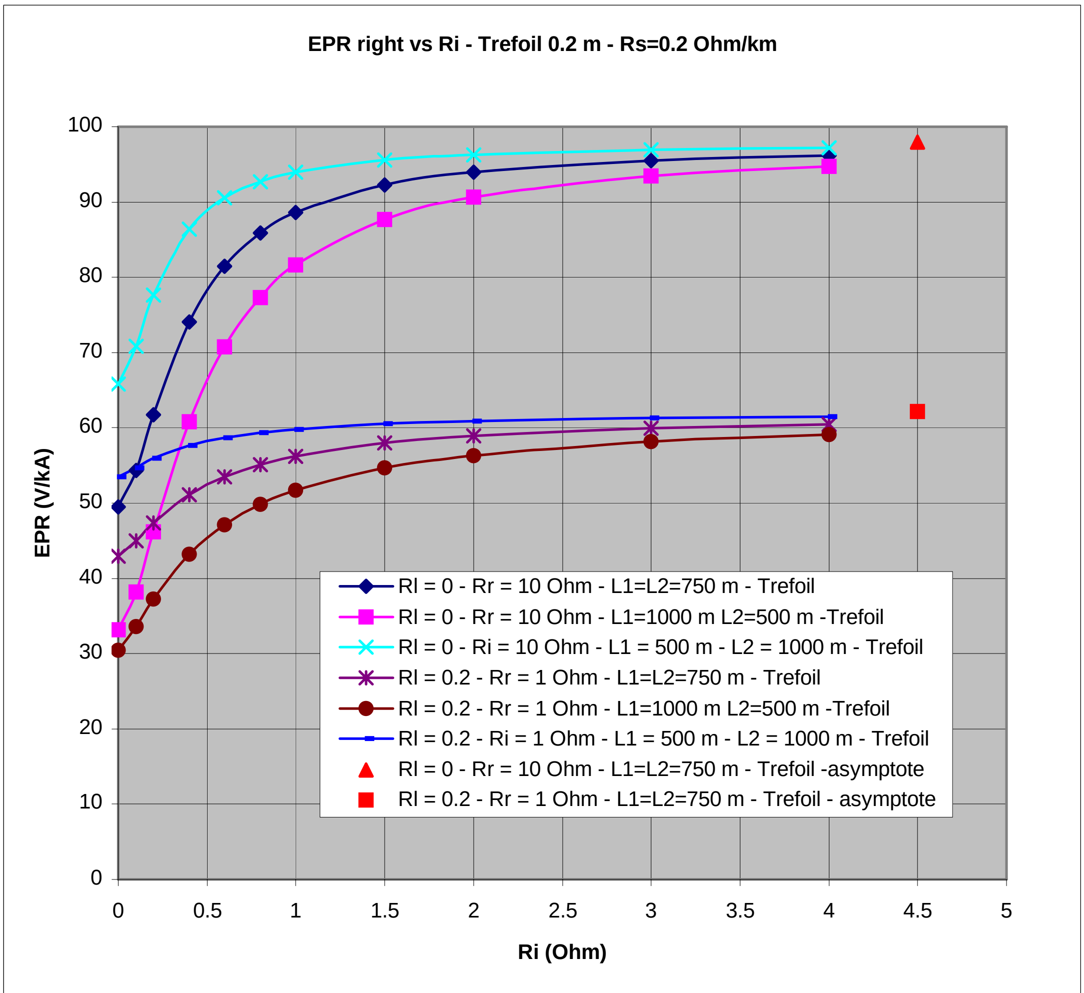


Figure 5.5 :Cross-Bonded UG Link Involving Two Sections - Diagram and EPR Formula

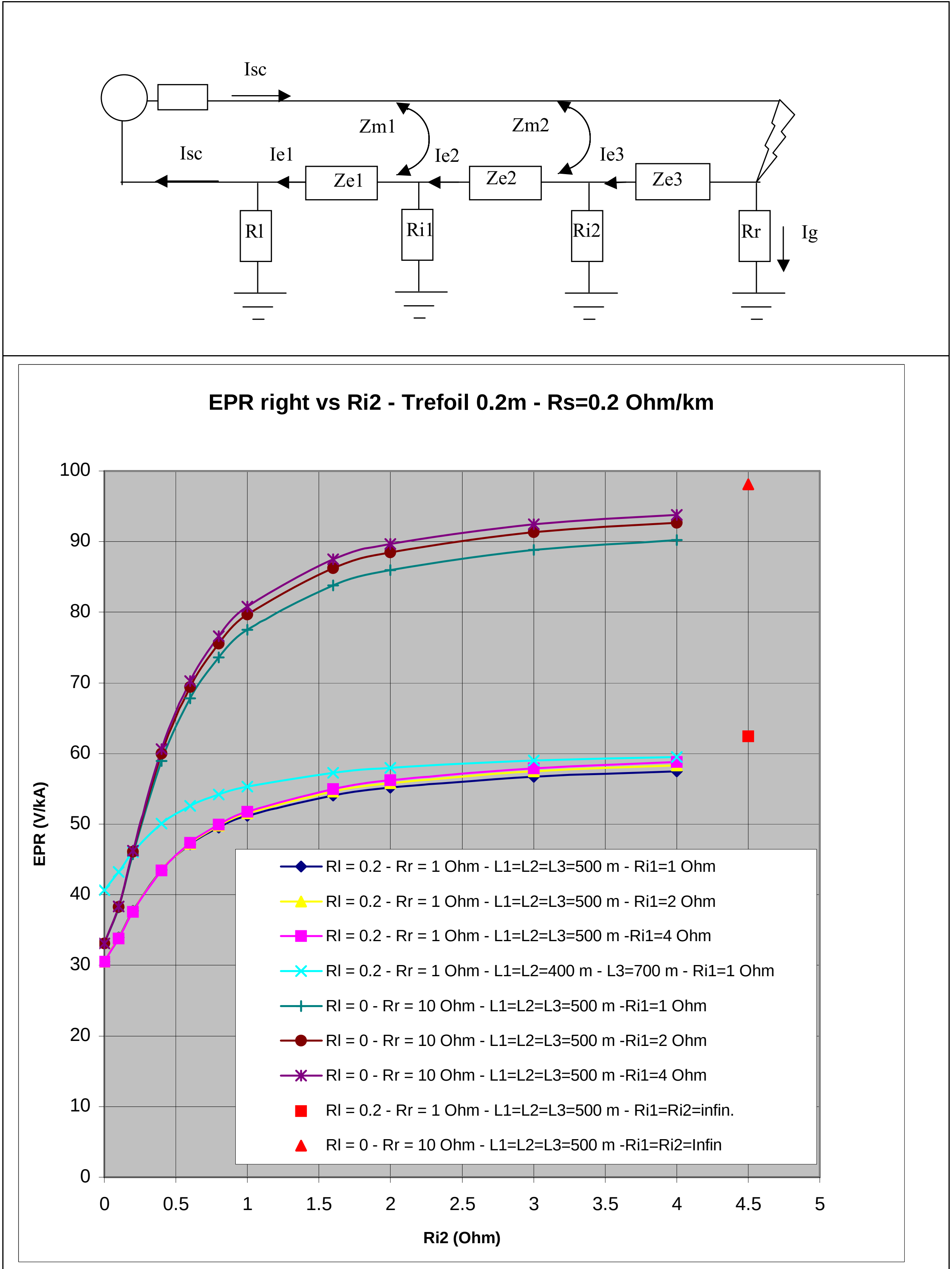


Figure 5.6 : Cross Bonded UG Link Involving Three Sections

5.3.4 Cross Bonded Links with ecc

Laying an ecc in parallel with the cable system results in a small decrease of the EPR (see table 5.1).

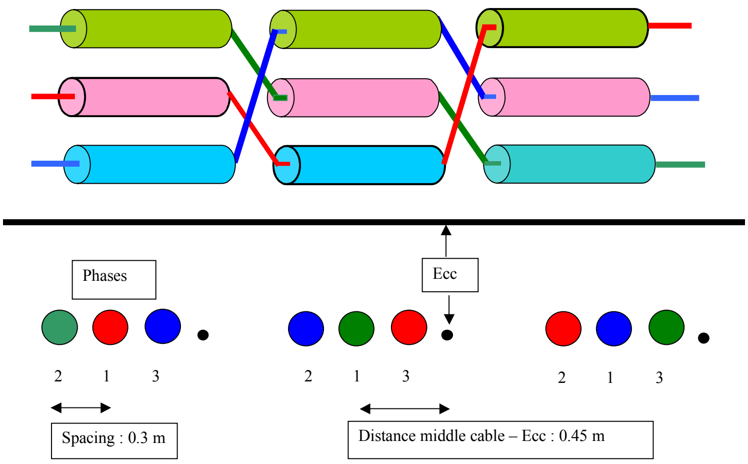


Figure 5.7 : Cross Bonded UG Link With an ecc

EPR right (V/kA)						
Rl (Ohm)	0	0	0	0	0.2	1
Rr (Ohm)	10	4	2	1	1	1
EPR (V/kA) with an ecc	9.4	9.0	8.3	6.9	6.6	5.8
EPR (V/kA) without ecc	17.3	16.8	15.6	13.0	11.6	7.8
Rs=0.035 Ohm/km – Ri1=Ri2=2 Ohm – ecc : 240 mm²						

Table 5.1 : EPR With and Without an ecc

It has to be kept in mind that, while the EPR is reduced, the voltages at the cross bonding points are increased, as shown in following figures 5.8 and 5.9.

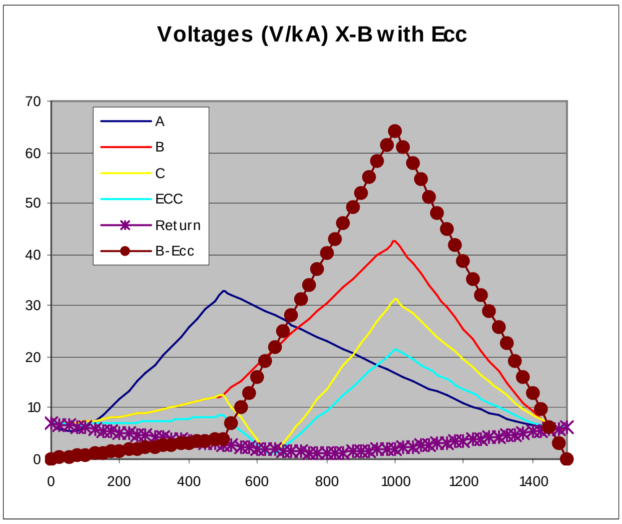


Figure 5.8 : Screen Stresses With an ecc

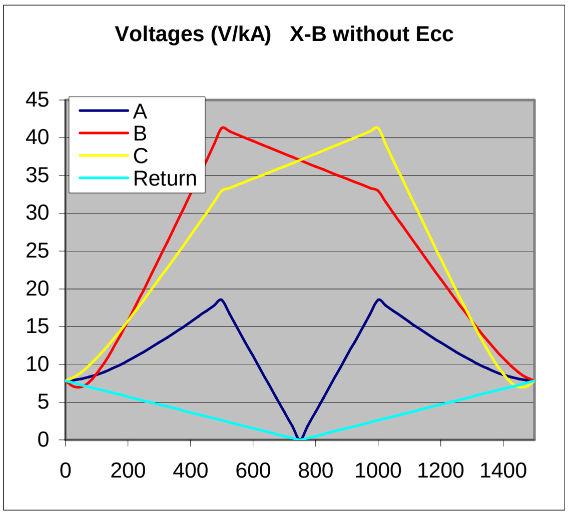


Figure 5.9 : Screen Stresses Without an ecc.

A,B,C refer to screen circuits. Return refers to the voltage drop due to the zero-sequence component
B-ecc refers to the voltage occurring between screen circuit B and the ecc

5.3.5 Single-Point Bonded Links

The general formula for the EPR at the faulted end may be written:

$$EPR = \frac{R_r}{R_r + R_l} . V_{osp} . L . I_{sc} \qquad V_{0sp} = \frac{\frac{R_r + R_l}{L}}{\sqrt{\left[\left(R_c + R_E^{'} \right) + \frac{R_r + R_l}{L} \right]^2 + X_c^2}} . \sqrt{R_c^2 + \left(X_c - X_m \right)^2} \qquad (5.15), (5.16)$$

where:

- Rc is the resistance of the ecc
- Xc is the self inductance of the ecc
- Xm is the mutual inductance between the ecc and the faulted phase

V0sp is shown in figure 5.10. The leading parameters are the ecc resistance, the laying conditions and the ratio of the sum of the ground electrode resistances to the link length.

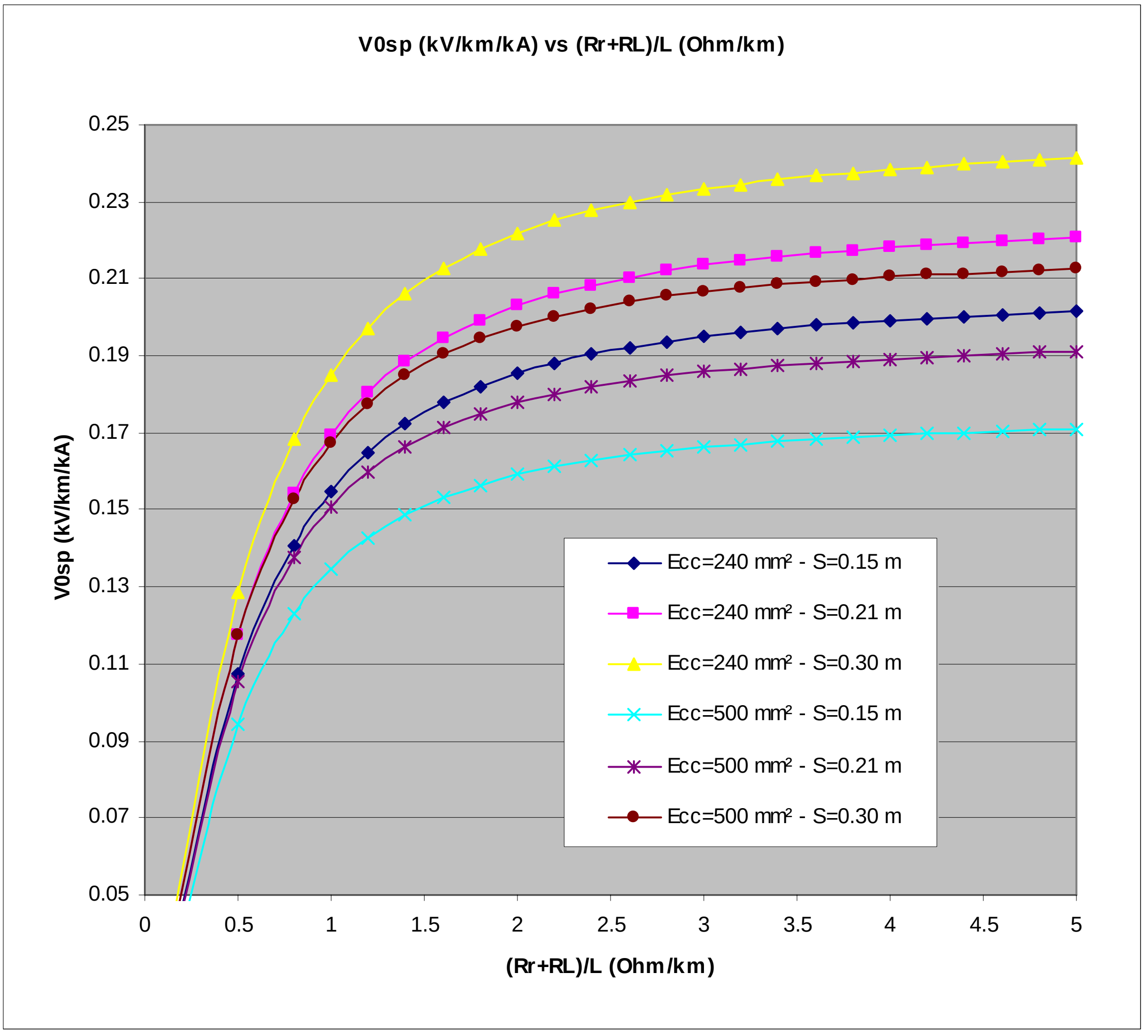
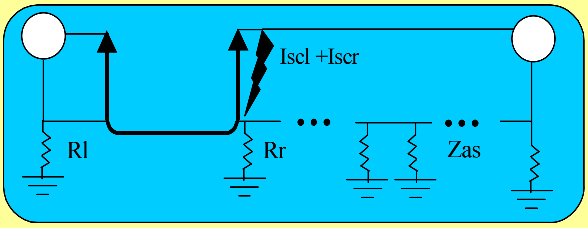


Figure 5.10 : Single-Point Bonded Link Between Two Substations

5.4 Substation Fed Through an OH line.

The highest EPR occurs at the UGL/OHL transition, for a fault located in this transition.

Substation fed through an OHL



$$EPR_r = \overline{K}.\overline{V_0}.\left[I_{scr} + I_{scl}\right] \qquad (5.17)$$

$$\overline{V_0} = Z_R.\frac{Z_e^{'}.L + R_L}{Z_e^{'}.L + R_L + Z_R}.(1-\mu)$$

$$\approx Z_R.\frac{Z_e^{'}.L}{Z_e^{'}.L + Z_R}.(1-\mu) \qquad (5.18)$$

$$\overline{K} = 1 - \frac{I_{scl}}{I_{scr} + I_{scl}}.\left[1 - \frac{Z_e^{'}.L}{Z_e^{'}.L + R_L}.\frac{(1-\mu')}{(1-\mu)}\right] \qquad (5.19)$$

$$Z_R = \frac{R_r.Z_{as}}{R_r + Z_{as}} \qquad (5.20)$$

Figure 5.11: Diagram and Formulae for a UG link Connected to a Substation and an OHL

These formulae are more or less similar to the formulae which may be derived for a connection between two substations.

- The coupling factor for UGL being replaced by the coupling factor for OHL.
- The substation earth resistance R_R being replaced by the impedance Z_R as the result of the earth resistance at the OHL/UGL transition in parallel with the apparent impedance of the skywire.

While the coupling factor for UGL is close to 1, the coupling factor for the OHL is much lower. As a consequence, the effect of the short-circuit current flowing through the OHL is likely to produce higher voltages

Conversely, the impedance Z_R tends to Zas for large values of R_R , contributing to lowering the voltage stress.

Figure 5.12 displays V0 as a function of the UGL length, assuming Rl = 0 (being the earth resistance of a substation, Rl is expected to be low) for two kinds of skywires.

The cable screen resistance and the laying conditions are not very sensitive (the inductance being the leading parameter, depending only weakly of the cable spacing).
The skywire resistance is a very sensible influencing factor.

Figure 5.13 displays K as a function of the short-circuit current flowing in the UGL as a function of the overall short-circuit current, for various UGL lengths and electrode resistances Rl.

The following estimate may be assumed :

$$K \approx 1 - 0{,}9.\frac{I_{scl}}{I_{scl} + I_{scr}} \qquad (5.21)$$

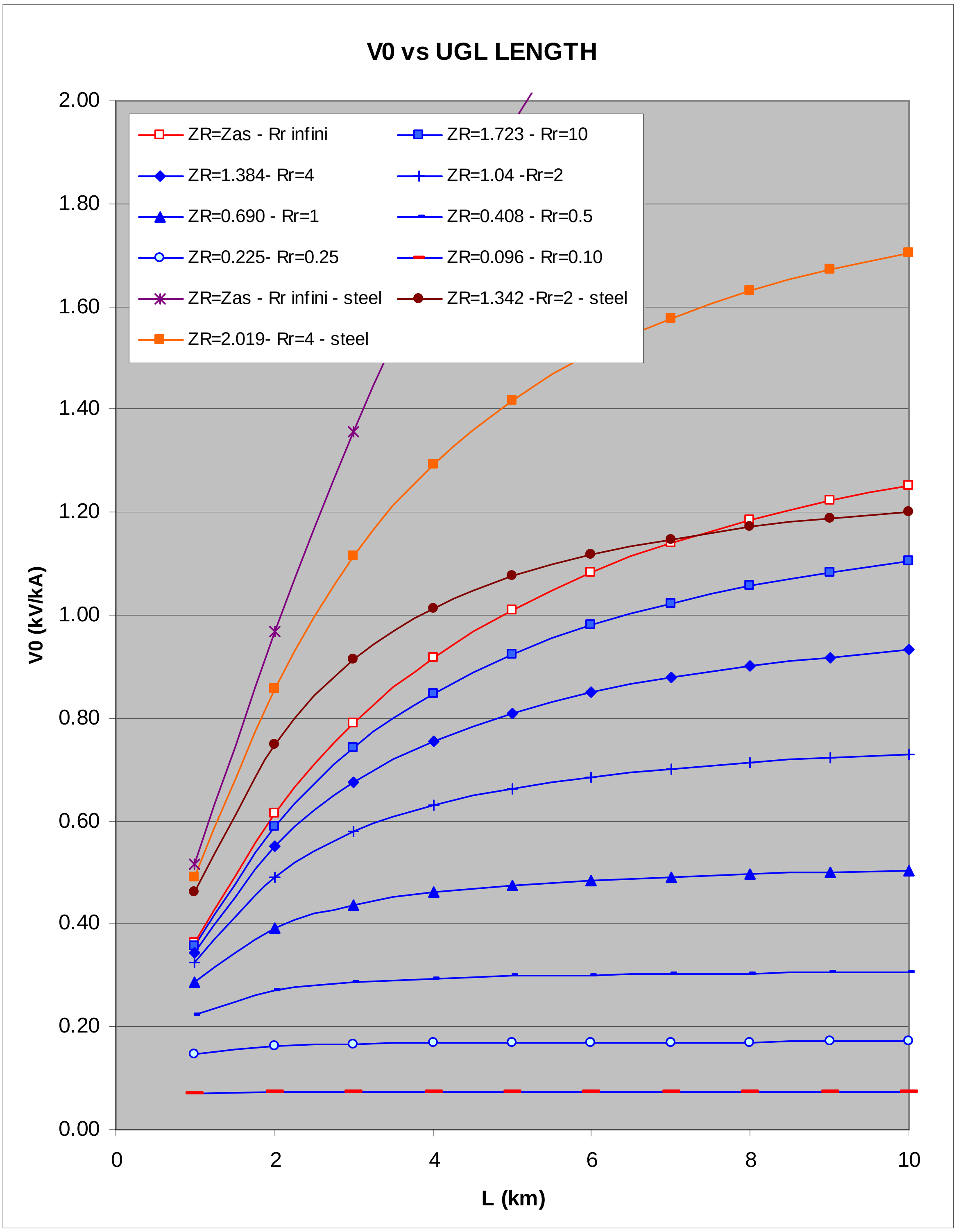


Figure 5.12: V0 as a Function of the UGL Length

Component	UGL	OHL skywire 1	OHL skywire 2 steel
Main characteristics	X-bonding Flat formation Spacing 20 cm	Span length 350 m Footing resistances : 10 Ohm Skywire diameter : 20 mm	
Resistance (Ω/km) **cable screen or skywire**	0.2	0.65	3.30
Zas		1.85+j0.87	4.03+j0.50
Coupling factor µ	0.975+j0.117	0.25+j0.17	0.03+j0.04
Modulus of 1-µ	0.12	0.77	0.97

Table 5.2 : UGL and OHL Main Features

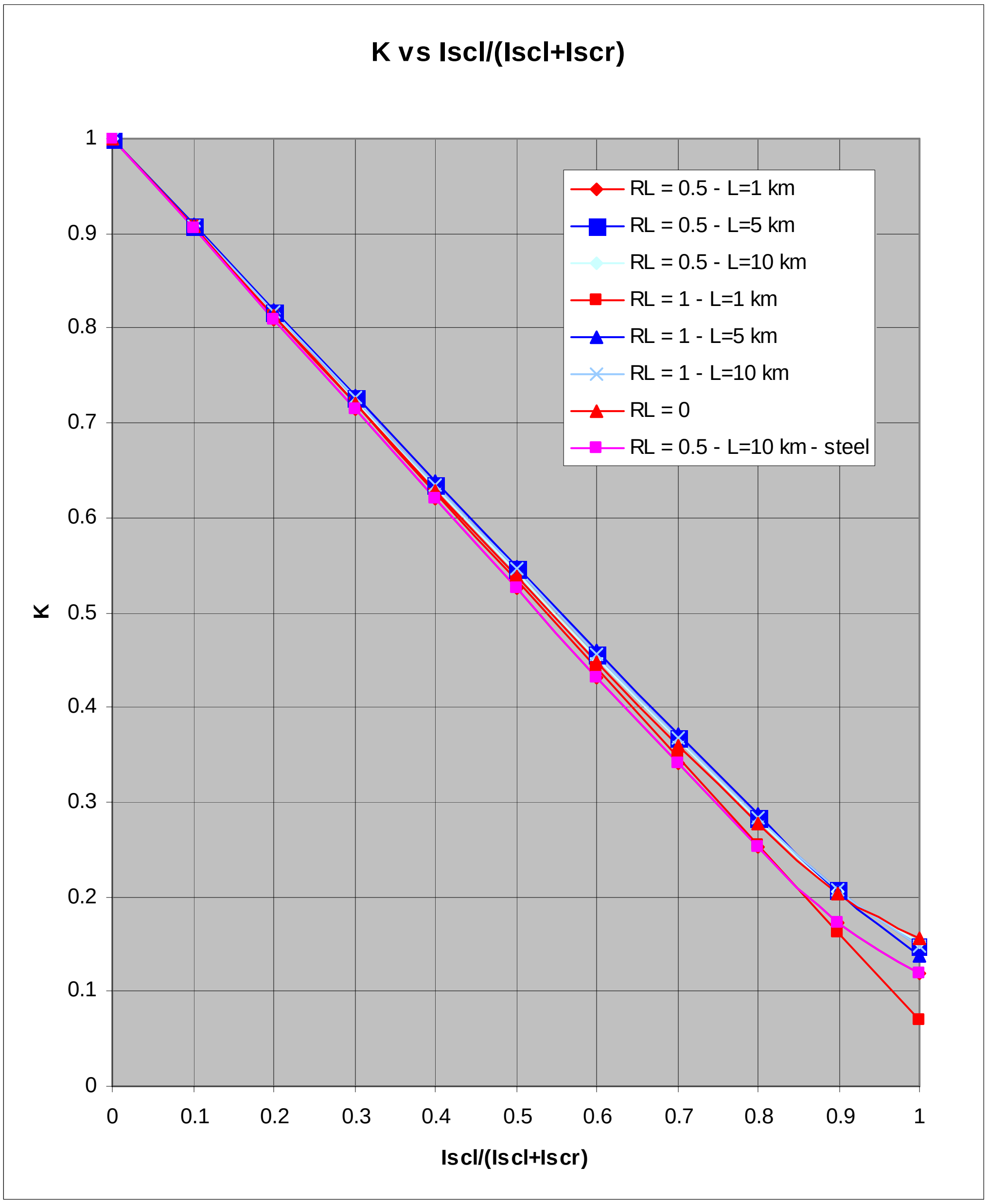


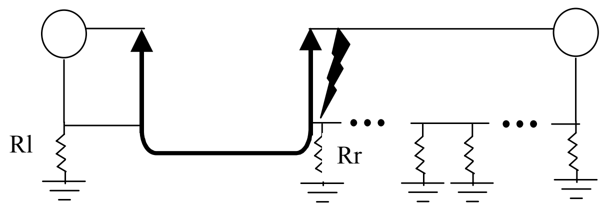
Figure 5.13 : K as a Function of the Short-Circuit Current Flowing in the UGL As a function of the Overall Short-Circuit Current

Influence of the number of sections

Table 5.3 below shows that considering a link having three sections as a link with only one section results in only modest errors for the EPR.

Ri is the earthing resistance between major sections.

EPR at right side end



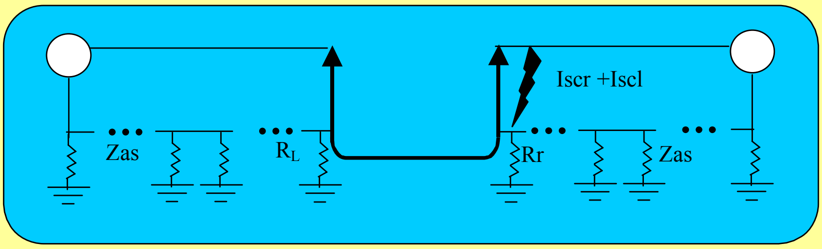
Rl (Ohm)	Rr (Ohm)	Ri (Ohm)	Iscl/(Iscl+Iscr) (%)	EPR computation	Modulus (V/kA)	Error (*) (%)
				UG length : 1 x 1.5 km		
0.2	4		50	CIM and formula	253	
				Formula with approx.K	250	-1.3
			90	CIM and formula	95	
				Formula with approx.K	86	-9.0
			10	CIM and formula	421	
				Formula with approx.K	413	-1.9
0.2	8		50	CIM and formula	266	
				Formula with approx.K	263	-1.2
0.2	1		50	CIM and formula	187	
				Formula with approx.K	185	-1.1
0.5	4		50	CIM and formula	267	
				Formula with approx.K	261	-2.3
				UG length : 1 x 4.5 km		
0.2	4		50	CIM and formula	422	
				Formula with approx.K	413	-2.2
0.5	4		50	CIM and formula	420	
				Formula with approx.K	408	-3.0
				UG : 3 x 1.5 km		
0.2	4	4	50	CIM	374	
				Formula	413	10.3
0.2	4	8	50	CIM	397	
				Formula	413	-2.2

(*) represents the error from the formula compared to CIM

Table 5.3: EPR for One or Three Major Sections

5.5 Siphon System

Siphon system



$$EPR_r = \overline{K}.\overline{V_0}.(I_{scr} + I_{scl}) \quad (5.22)$$

$$\overline{V_0} = Z_R.\frac{Z_e^{'}.L + Z_S}{Z_e^{'}.L + Z_R + Z_L}.(1-\mu) \qquad \overline{K} = 1 - \frac{Z_e^{'}.L}{Z_e^{'}.L + Z_L}.\frac{\mu' - \mu}{1-\mu}.\frac{I_{scl}}{I_{scr} + I_{scl}} \quad (5.23) \quad (5.24)$$

$$Z_R = \frac{R_r.Z_{as}}{R_r + Z_{as}} \qquad Z_L = \frac{R_L.Z_{as}}{R_L + Z_{as}} \quad (5.25) \quad (5.26)$$

Figure 5.14: Diagram and Formulae for Siphon Systems

V0 and K are plotted in the following figures as functions of the UG link length, where x is for the ratio of the left side short-circuit current to the total short-circuit current. A close estimate of V0 and K is obtained assuming R_L is equal to 10 Ω (thus leading to Z_L close to Zas) where the UG link is more than about 4 km

The K factor reduces significantly the maximum EPR only where none of the two sources is predominant. Even in this case, the reduction is less than about 40 %.

The case where the fault occurs at the other end may be easily handled; it is necessary to exchange Rr with R_L, and Iscr with Iscl.

The worst case depends on the ratios Iscl : Iscr and Rr : R_L.

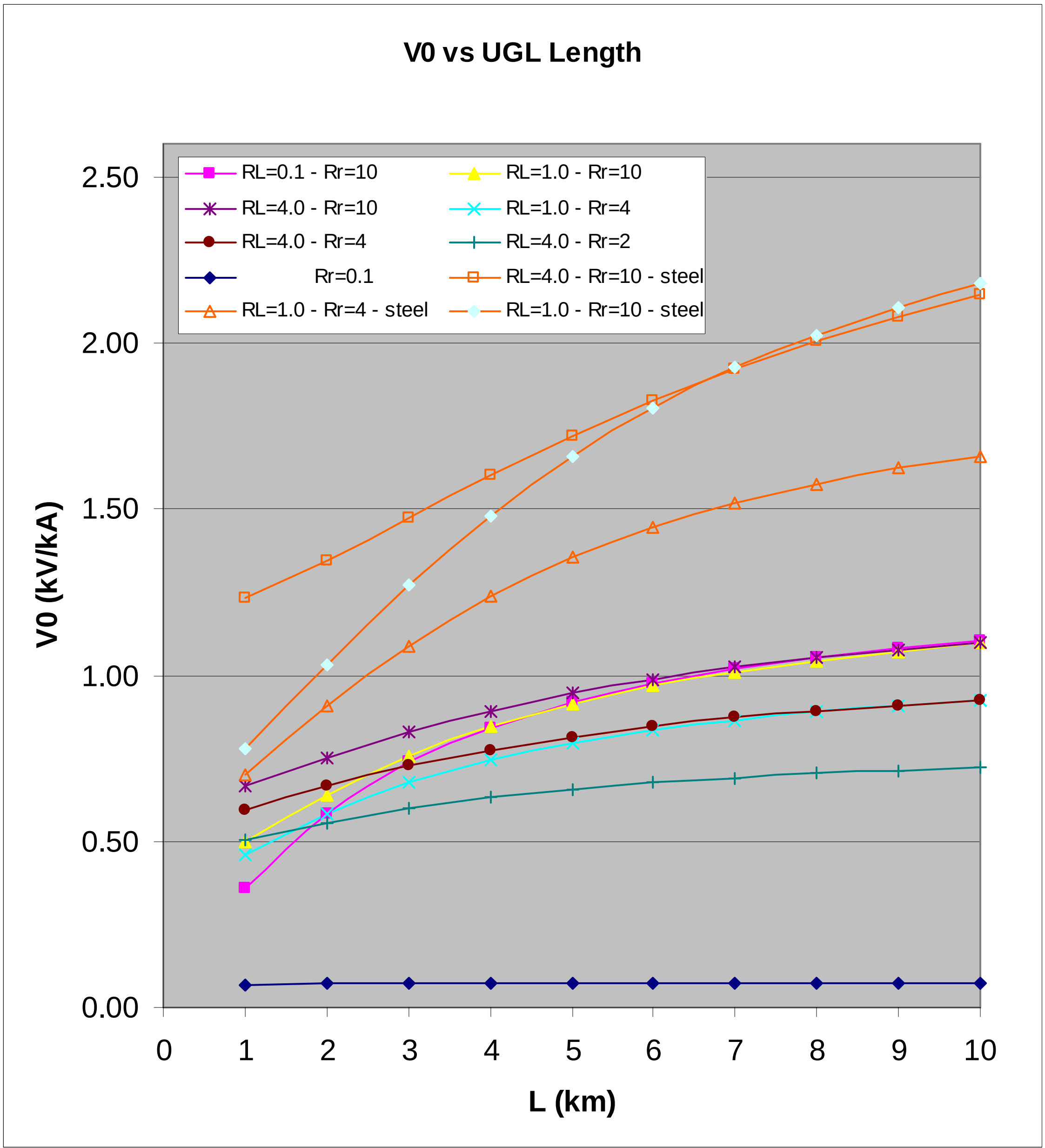


Figure 5.15: V_O for a Siphon System

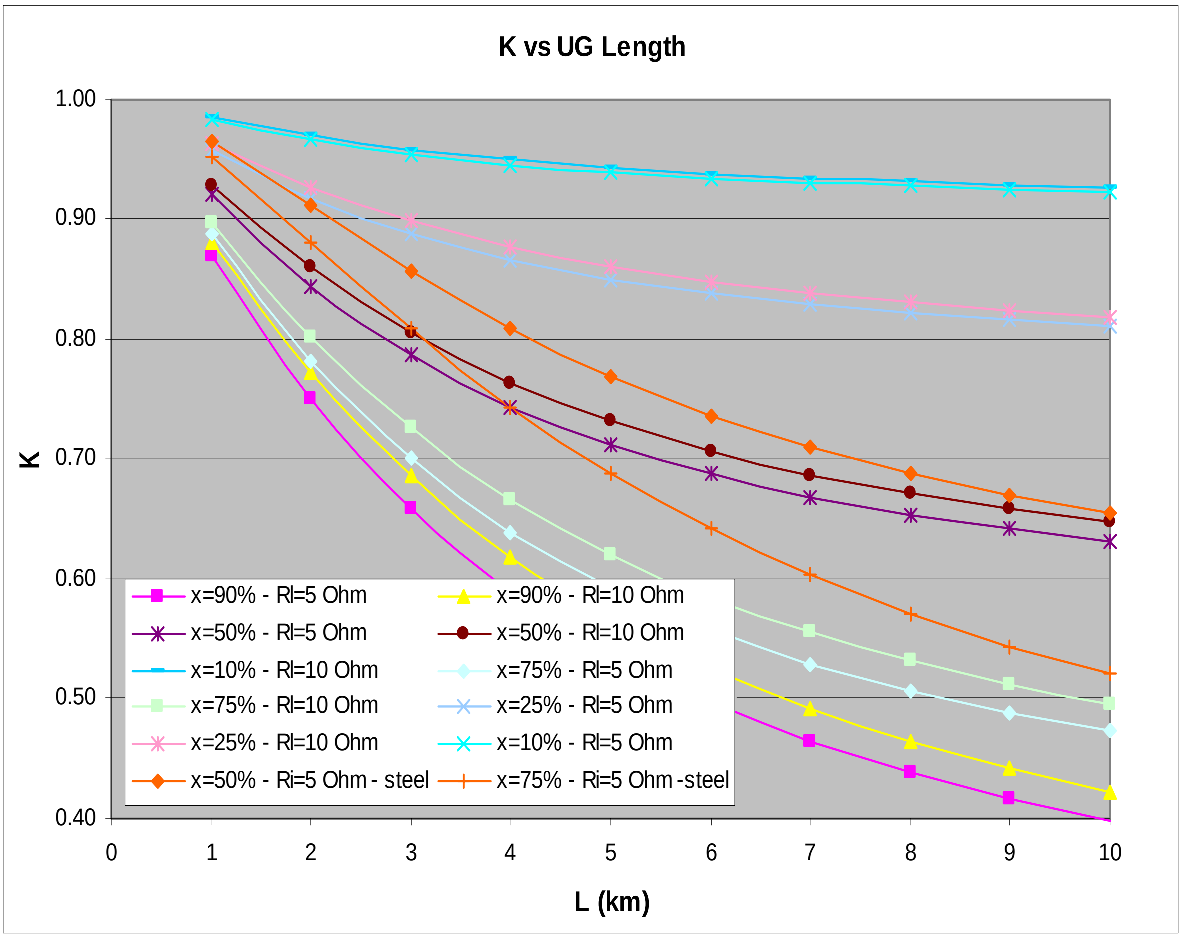


Figure 5.16: K Factor for a Siphon System, R_L 5-10 Ohms

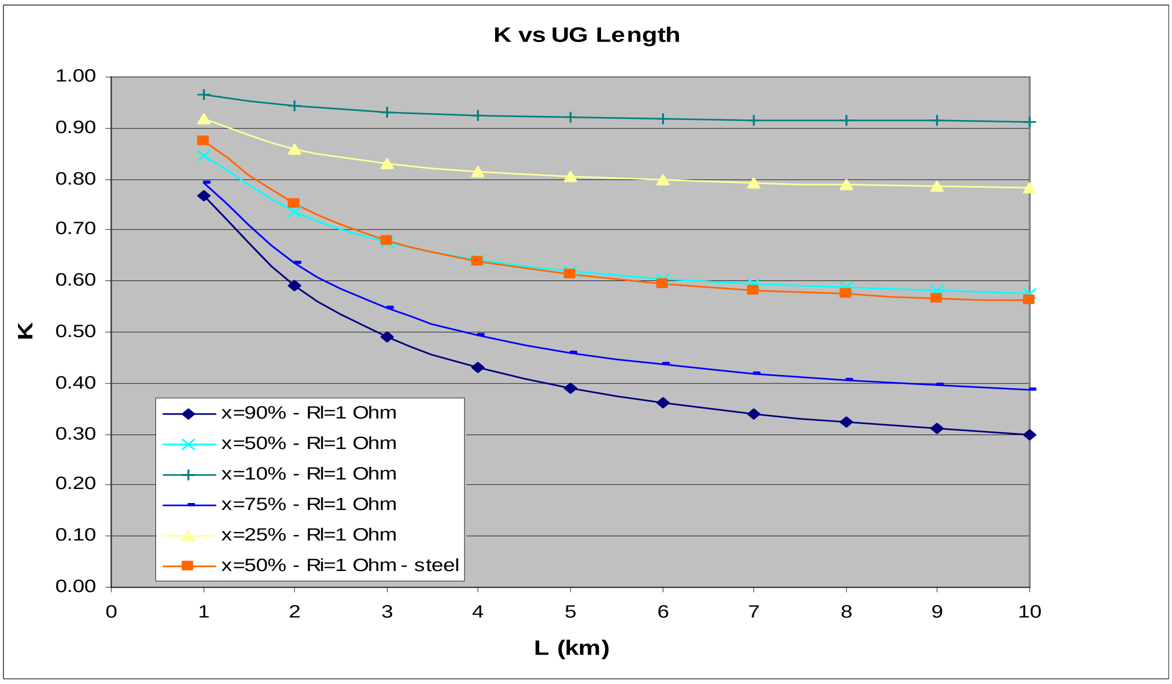


Figure 5.17: K Factor for a Siphon System, $R_L = 1\Omega$

5.6 Voltage Stresses Applied to the SVLs in Cross-Bonded Systems

Voltages along the screen circuits may be explained through symmetrical components composition.

A single-phase fault may be considered as the resultant of a positive, a negative sequence and a zero-sequence, each with a core current equal to one third of the short-circuit current.

Normal operation or three-phase faults are purely a positive sequence.

In the negative sequence, as in the positive one, induced voltages in the screens from the cores are different in the three elementary sections and their sum is zero for a major section, causing no circulating currents in the screens.

In the zero sequence, identical currents flow within every core, causing constant and identical circulating currents in the screens.

The maximum potential rise Vpn due to the superposition of positive and negative sequences is twice the potential rise due to a positive sequence.

As a result, this maximum potential rise may be linked to the maximum voltage occurring during three-phase faults :

$$V_{pn} = 2.V_{tri} \cdot \frac{I_{sc1}/3}{I_{sc3}} \qquad (5.27)$$

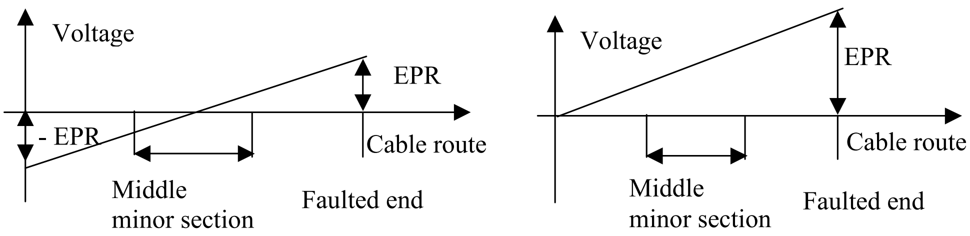
During a single-phase fault, the maximum screen/sheath voltage rise occurs at the cross-bonding nearest to the end where the EPR is the higher, which may be the left or right end, depending on the value of short-circuit current from each substation and their earth resistances.

The voltage drop in the screens between this point and the end may be easily calculated providing that the short-circuit current returning through the screens is known. Alternatively, it may be derived as one third of the difference between the EPRs at both ends.

Note
The voltage superimposed on an SVL configuration is calculated by assuming that the magnitude of the symmetrical components is each 33% of total. This assumption is generally not fully correct since, for instance, symmetric components based on Fortescue's analysis do not apply for cables in flat formation (requiring for instance Clarke's analysis). Nevertheless, the error involved, compared to direct calculations on various arrangements, was recognized negligible.

5.6.1 Connection Between Two Substations

In this case, the maximum EPR is assumed to occur for a fault at the right hand end of the cross bonded system. The voltage drop in the link is in the range from EPRr (where the earth resistance at the sound end is zero) to 2.EPRr (where the earth resistances at both ends are equal, leading to opposite EPRs). The voltage drop due to zero-sequence currents between the faulted end and the nearest cross-bonding being one third..



Same earth resistances at both ends

Earth resistance null at left end

Figure 5.18 : Zero-Sequence Voltages

Therefore, the maximum voltage rise in zero sequence conditions, at the cross-bonding level is between 2/3 to 1/3 EPR. Exact formula being :

$$V_{xb} = \frac{2.R_r - R_l}{3.R_r}.EPR_r \qquad (5.28)$$

As a consequence, ignoring phase shifts, an overestimate to the maximum voltage rise is :

$$V_{\max e} = \frac{2}{3}.\left[EPR + V_{tri}.\frac{I_{sc1}}{I_{sc3}} \right] \qquad (5.29)$$

EPR does not need to be taken into account if Vmaxe is lower than Vtri, i.e. if the following condition is fulfilled :

$$EPR < V_{\lim} \qquad V_{\lim} = \frac{3}{2}.V_{tri}.\left[1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}} \right] \qquad (5.30)$$

Introducing the expression for the EPR and an underestimate of Vlim :

$$I_{sc1} < \frac{3}{2}.\frac{\sqrt{\left[\left(R_c + R_E^{'} \right) + \frac{R_r + R_L}{L} \right]^2 + X_c^2}}{R_r.R_s}.V_{tri} \qquad (5.31)$$

Figures 5.19 and 5.20 plot the maximum permissible short-circuit current from the substations as a function of the link length, with the SVL voltage Vtri, the earth substation resistance Rr and the screen resistance Rs as parameters

Figure 5.19 relates to the worst case (RL=0); figure 5.20 relates to the case where the earth resistances of both substations are equal (Rr=RL).

It follows that EPR does not appear as a concern :

- in the worst case, where the right end substation earth resistance is below 1Ω, the permissible current is higher than 28 kA, even if the screen resistance is as high as 0.4Ω/km. The current is 40kA if the screen resistance is 0.2Ω/km.
- where the earth resistance of the substations, at both ends, are equal and lower than 3Ω, permissible currents are higher than 29 kA

Where the UGL involves several major sections, an estimate of the voltage rise due to the return current in the screens, at the cross-bonding point close to the fault location, is obtained assuming no currents flowing in the earth resistances between major sections as:

$$V_{xb} = EPR.\left[1 - \frac{1}{3.N} \right] \qquad (5.32)$$

where Rl=0 is assumed and N is the number of major sections.

This leads to a more stringent condition:

$$V_{\lim} = \frac{3.N}{3.N - 1}.V_{tri}.\left[1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}} \right] \qquad (5.33)$$

For instance, the coefficient 3/2 in the relationship for Isc1 above (equation 5.30) shall be replaced by 6/5, where there are 2 sections; 9/8 where there are 3 sections and so on, with the minimum value being 1.
Nevertheless, taking into account the very high permissible currents found for one section, the conclusion that EPR is not likely to be a problem, still holds.

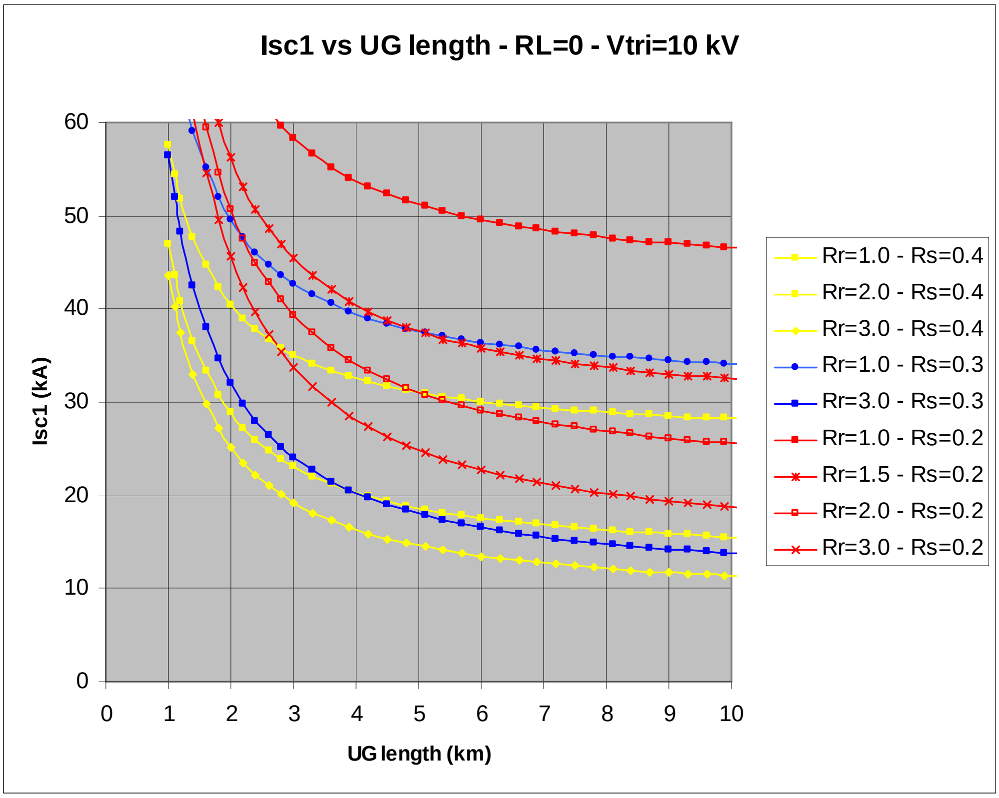


Figure 5.19: Maximum Allowable Value of.Isc1 as a Function of the UGL length

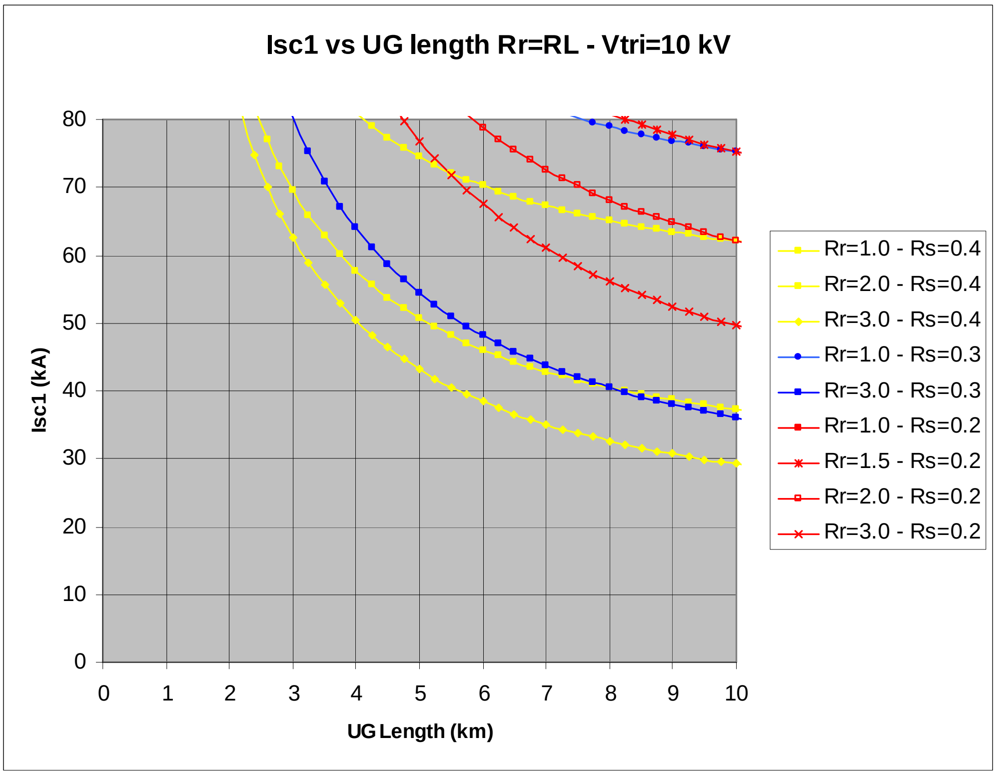


Figure 5.20: Maximum Allowable Short-Circuit Current where the Earth Resistances of Both Substations are Equal.

5.6.2 UG Link Connected to a Substation and an OH Line

An estimate of the EPR at the left end substation, where the UGL involves only one major section, is :

$$EPR_l \approx \frac{R_L}{Z_e^{'} + R_L}.EPR_r \qquad (5.34)$$

As the earth resistance of the substation Rl is expected to be low, this EPR may be disregarded.

As a consequence, an overestimate to the maximum voltage rise at the cross-bonding point close to the faulted end is :

$$V_{\max e} = \frac{2}{3}.\left[EPR + V_{tri}.\frac{I_{sc1}}{I_{sc3}}\right] \qquad (5.35)$$

EPR does not need to be taken into account if Vmaxe is lower than Vtri, i.e. if the following condition is fulfilled, as for a connection between two substations :

$$EPR < V_{\lim} \qquad V_{\lim} = \frac{3}{2}.V_{tri}.\left[1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}}\right] \qquad (5.36)$$

where EPR may be derived using the formula in figure 5.10, or values derived from figures 5.11 and 5.12.

In the case of several major sections, as for a connection between two substations, the following condition may be used :

$$V_{\lim} = \frac{3.N}{3.N - 1}.V_{tri}.\left[1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}}\right] \qquad (5.37)$$

5.6.3 Siphon Systems

The EPR at the sound end may be expressed in various ways, although none are easy to manage, e.g.

$$EPR = Z_S.(1-\mu).\left(1 - \frac{Z_e^{'}.L + Z_S}{Z_e^{'}.L + Z_R + Z_S}\right).(I_{scr} + I_{scl}) \qquad (5.38)$$

Neglecting the voltage drop between the two ends (in siphon systems, there are generally several major sections), the maximum voltage at the cross-bonding point close to the faulted end may be estimated as :

$$V_{\max e} \approx EPR + \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}}V_{tri} \qquad (5.39)$$

Consequently, screen/sheath potential rise does not need to be taken into account if :

$$EPR < V_{\lim} \qquad V_{\lim} = V_{tri}.\left[1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}}\right] \qquad (5.40)$$

where EPR may be derived from figures 5.13 to 5.16.

5.6.4 Worst Case

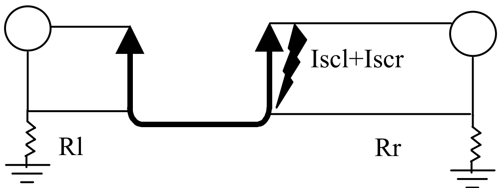
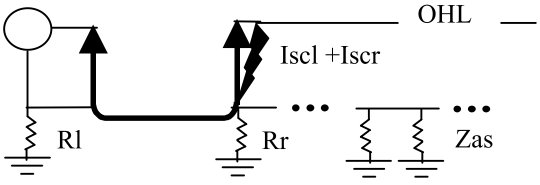
Higher stresses are likely to occur with siphon systems, but their order of magnitude is similar to those encountered on a link connected to a substation in the event of a fault at a transition to an OHL

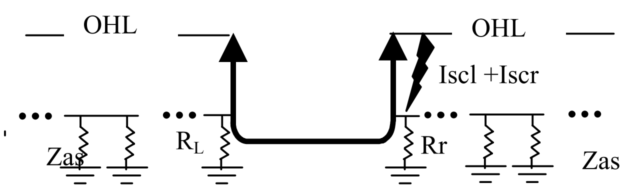
As an example, considering a fault on a 5 km long UGL at a transition to an OHL, with a grounding resistance of 4Ω at this transition and 1Ω at the other end (which may be connected to a substation or an OHL), the EPR is about 0.45 kV/kA where the fault is equally fed by both sides.

Conversely, the EPR is roughly half for a connection between 2 substations, and where the short-circuit current to be taken into account is only the short-circuit current from the sound end and not the overall short-circuit current.

This is illustrated in table 5.4

For the siphon system, lowering the grounding resistance at the transition from 4Ω to 2Ω leads to a 25 % decrease of the EPR, and, therefore, a 25 % increase of the permissible short-circuit current.

Situations	EPRr - Vmaxe Iscl = Iscr = 5 kA	Vlim – Isc max Iscl = Iscr
 $$V_{\max e} = \frac{3.N-1}{3.N}.EPR_r + \frac{2}{3}.\frac{I_{scl}}{I_{sc3}}V_{tri} \quad (5.41)$$ $$EPR_r = \frac{R_r}{R_r + R_l}K.V_0.I_{scl} \quad (5.42)$$	EPRr = 1,1 kV K = 0,80 according to Figure 5.6 V_0 = 0,33 according to Formula 5.6 V_{maxe}= 8,7 kV Vmaxe < Vtri	V_{lim}= 6 kV according to Formula 5.16 Iscl max = 28 kA
 $$V_{\max e} = \frac{3.N-1}{3.N}.EPR_r + \frac{2}{3}.\frac{I_{scl}}{I_{sc3}}V_{tri} \quad (5.43)$$ $$EPR_r = K.V_0.(I_{scl} + I_{scr}) \quad (5.44)$$	EPRr = 4,3 kV K = 0,54 according to Figure 5.12 V_0 = 0,80 according to Figure 5.11 V_{maxe}= 10,9 kV Vmaxe < Vtri	V_{lim}= 6 kV according to Formula 5.20 (Iscl +Iscr) max = 14 kA
	EPRr = 4,8 kV	V_{lim}= 4 kV according to

<table>
<tr>
<td>

$$V_{\max e} = EPR_r + \frac{2}{3} \cdot \frac{I_{scl}}{I_{sc3}} V_{tri} \qquad (5.45)$$

$$EPR_r = K.V_0 .(I_{scl} + I_{scr}) \qquad (5.46)$$</td>
<td>K = 0,60
according to
Figure 5.16

V_0 = 0,80
according to
Figure 5.14

V_{maxe}= 12,8 kV
Vmaxe > Vtri</td>
<td>Formula 5.23

(Iscl +Iscr) max = 8.3 kA</td>
</tr>
<tr>
<td colspan="3">Data</td>
</tr>
<tr>
<td>Isc1/Isc3 = 1
Vtri = 12 kV</td>
<td>N = 1 -L = 5 km
R_S = 0.2 Ohm/km</td>
<td>R_r = 4 Ohm -R_L = 1 Ohm
Zas = 1,87+j0.87 Ohm</td>
</tr>
</table>

Table 5.4: Comparison of EPR and permissible short-circuit current

Note
In the above studied configurations, the ground fault on an overhead line is always assumed to have an overhead ground wire to travel along.
If this is not the case, EPR are not likely to be a major concern as long as the fault occurs on the overhead line route; in the event of a fault at the transition a major proportion of the fault current may enter the cable system and cause a higher EPR compared to the situation with a skywire.
This situation may be dealt with considering that the total short-circuit current flowing in the overhead line is injected at the earth resistance at the transition, without reduction by the coupling factor of the overhead line and its skywire.

5.7 Conclusion

Typical situations may be studied through superposition of elementary situations involving only one current source.

The EPR at the fault location is obtained from the currents flowing to the earth in elementary situations which are simple enough to allow not too complex calculations, if some assumptions are agreed with.

Formulae are given which make it possible to obtain estimates of the EPR and voltages applied to SVLs for cross-bonded systems.

Whilst EPR is generally not a concern for a connection between two substations, excessive EPR is likely to occur at a UGL to OHL transition.

In these cases, especially where the grounding resistances are higher than 1Ω, voltages applied to the SVLs for cross-bonded systems, should be checked.

6. INTERNAL FAULTS IN UG LINKS

6.1 Internal Faults in Single Point Bonded UG Links

The CIGRE Brochure [1] deals with screen to local earth voltages that stress the SVL, both in the case of external and internal faults (§ 3.4.4 and § 3.4.7). Formulae are given (i.e. D6 and D12) which are applicable in any case; whereas simple formulae in previous Electra articles assumed that the whole of the short-circuit current returns through the ecc. This assumption, as mentioned, is nearly true for a connection between two substations, and, to a large extent, for a UGL connected to a substation at one end, but is unlikely to be correct for a siphon system.

In a siphon system, a significant part of the short-circuit current may flow to the earth, as illustrated in figure D1 of [1]. This results in lower voltages being applied to the SVL but it leads also to high EPR, which may be harmful to oversheaths or joint coverings outside the zone of influence of electrodes dissipating earth current.

Formulae for EPR calculation given in Section 5 for external faults can also apply when considering internal faults. This is illustrated in figure 6.1.

The whole of the short-circuit current flows in the metallic screen of the faulted cable. Short-circuit current from the right end flows in the core and returns through the screen, so that there is no induction into the ecc. Short-circuit current from the left end flows in the metallic screen which is coaxial to the core, so that the effect onto the ecc is the same as for an external fault.

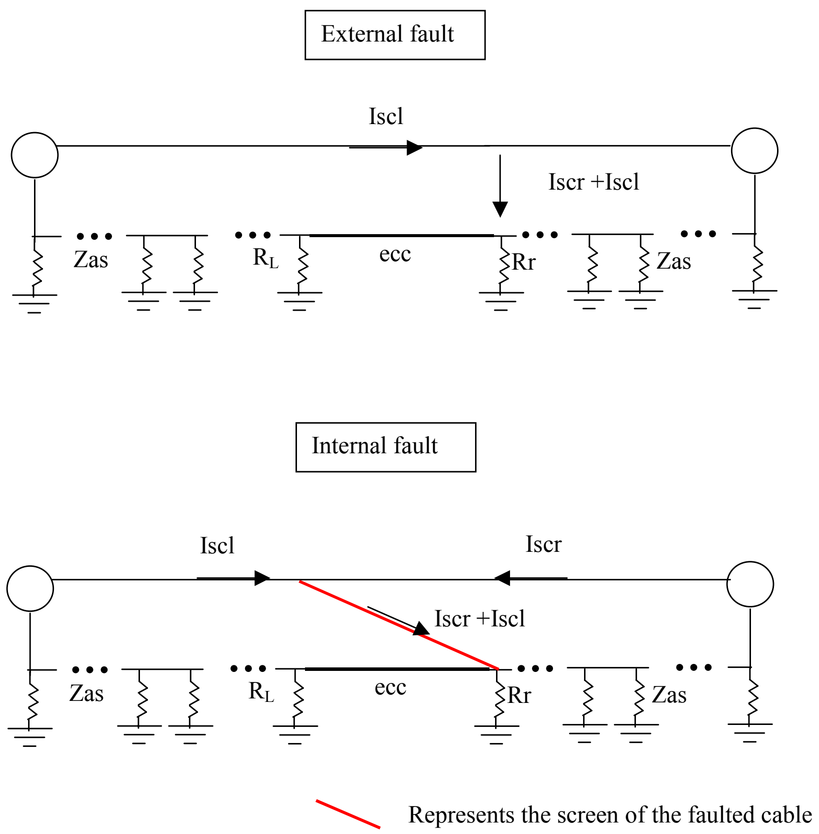


Figure 6.1: Comparison of Short-Circuit Current Paths in External and Internal Faults

6.2 Internal Faults in Cross Bonded UG Links

6.2.1 Introduction

For cross-bonded systems, the situation for internal faults is not significantly different to that of external faults. The order of magnitude of EPR is the same for both external and internal faults. However, the voltage stresses applied to the SVL may be far higher in the event of internal faults.

An internal fault occurring in the screen circuit 1 in the second minor section is illustrated in figure 6.2.

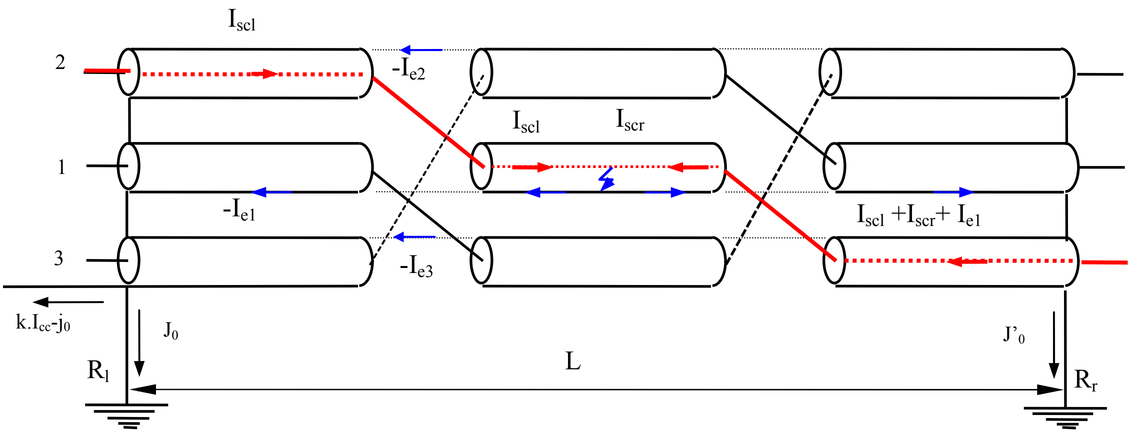


Figure 6.2: Internal fault in X-bonded link

The voltage profile in the faulted circuit is displayed in figure 6.3. The shape is similar to the voltage profile for an external fault, with the addition of a peak at the fault location.

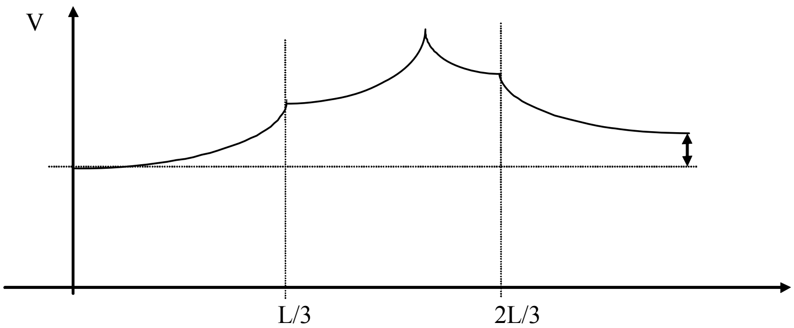


Figure 6.3: Screen voltage profile during internal fault

$$R_2.J'_0 - R_1.J_0 = -V_0 \qquad (6.1)$$

In practice, an internal fault may be considered (see figure 6.4) as superposition of :

- an external fault occurring on the right side
- a situation where the full short-circuit current returns to the right side and where the sound screen circuits form a closed loop with the faulted screen circuit.

In the second configuration, the path for every current is fixed. As a consequence, the sheath to sheath voltages do not depend on the short-circuit current return path, as for external faults.

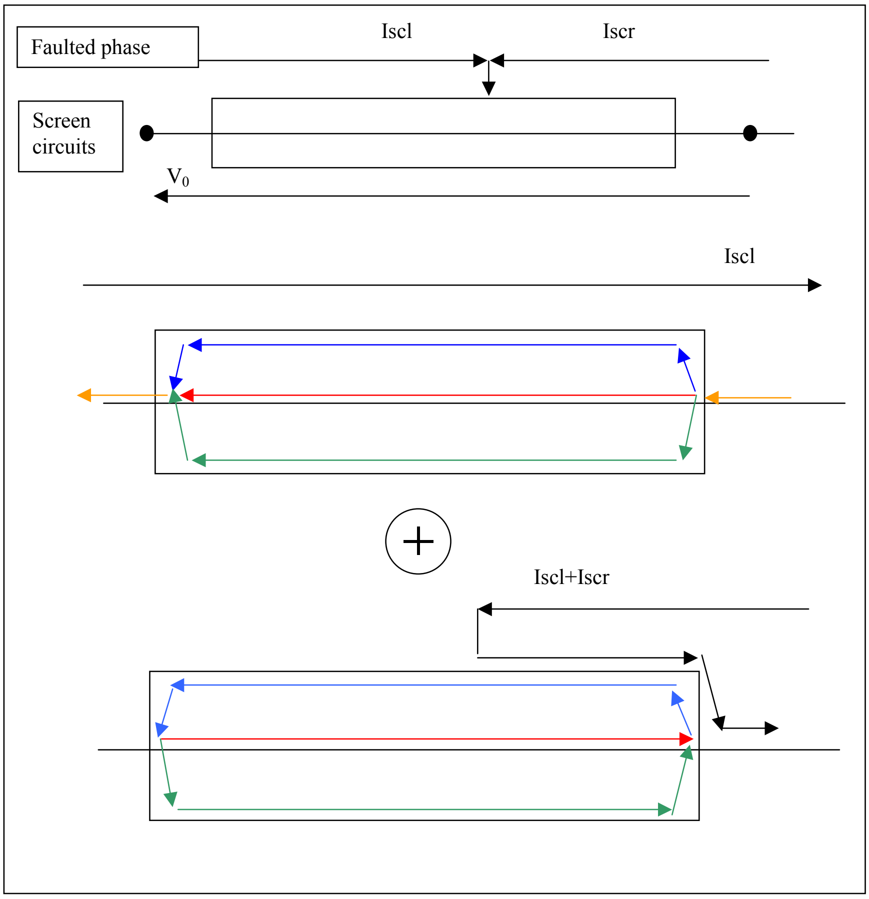


Figure 6.4: Internal Fault as a Superposition

6.2.2 Voltage Drop in the Major Section

The voltage drop in the major section is:

$$V_d = \left[Z_e^{'}.I_e + Z_m^{'}.I_{scl} + Z_0.\left(I_{scl} + I_{scr} \right) \right] L \qquad (6.2)$$

where Ie is the sum of the screen currents on the left side,
Z'e and Z'm are p.u.length self and mutual impedances of the screen circuits (see § 3.5)
Z0 depends on both the faulted circuit and the faulted minor section.

$$Z_e^{'} = \frac{1}{3}\left[Z_e + 2Z_c - \frac{2(Z_e - Z_c)(Z_c - Z_L)}{3Z_e - 4Z_c + Z_L)} \right] \qquad (6.3)$$

$$Z_m^{'} = \frac{1}{3}.\left[Z_m + 2.Z_c - 2.\frac{(Z_c - Z_e).(Z_L - Z_c)}{3Z_e - 4Z_c + Z_L} \right] \qquad (6.4)$$

$$Z_0 = \left[\frac{\beta_i.(Z_e - Z_c) + q.(Z_L - Z_c)}{3Z_e - 4Z_c + Z_L} \right] \bullet R_s \qquad (6.5)$$

Rs is the screen resistance (p.u. length)
β_i.L is the distance of the fault to the right end of the faulted major section i [1,2 or 3]

q	S1	S2	S3
Circuit 1	y/L	y/L	y/L
Circuit 2	$1/3$	$1/3$	0
Circuit 3	$1/3$	0	0

Table 6.1 : q coefficient

$$\beta_i = (\frac{y}{L} + \frac{3-i}{3}) \qquad (6.6)$$

Where y is the distance of the fault to the right end of the faulted minor section.

6.2.3 Voltage Drop Between Fault Location and Major Section End

The largest voltage drop in the third minor section, occurring in the faulted screen circuit, may be expressed as :

$$e = A.\left(I_{scr} + I_{scl}\right).\frac{L}{3} + e_{ext}(I_{scl}) \qquad (6.7)$$

where e_{ext} is the voltage drop in the event of an external fault.

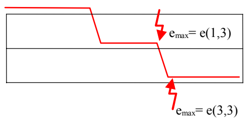
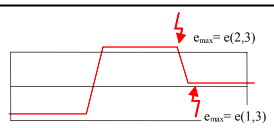
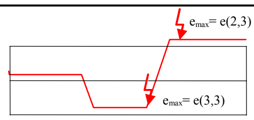
fault at 2° X-bonding point	in section 2	in section 3
	$\frac{7.R_S}{9} + \frac{R_S.(Z_c - Z_{out})}{9.\Delta} + \frac{2}{3}(Z_m - Z_c)$ (6.8)	$\frac{7.R_S}{9} + \frac{R_S.(Z_c - Z_{out})}{9.\Delta}$ (6.9)
	$\frac{7.R_S}{9} - 2.\frac{R_S.(Z_c - Z_{out})}{9.\Delta} + \frac{2}{3}(Z_m - Z_c)$ (6.10)	$\frac{7.R_S}{9} - 2.\frac{R_S.(Z_c - Z_{out})}{9.\Delta}$ (6.11)
	$\frac{7.R_S}{9} + \frac{R_S.(Z_c - Z_{out})}{9.\Delta} + \frac{2}{3}(Z_m - Z_{out})$ (6.12)	$\frac{7.R_S}{9} + \frac{R_S.(Z_c - Z_{out})}{9.\Delta}$ (6.13)

Table 6.2 : A Coefficient

Usually in systems, due to the order of magnitude of R_S , (Z_m-Z_c) et (Z_m-Z_{out}), the voltage rise is close to the EPR at the end of the section, the increase being :

$$e \approx \frac{7}{27} R_S.L.I_{cc} \qquad (6.14)$$

The following explanation may help with understanding this formula.

Assuming that the fault current flows in the faulted screen to the right end; there is no induced voltage in the sound screen circuits and there is zero current at the ends. Therefore, the current in the faulted screen is -2 x the current in the sound screens, for a laying in trefoil formation, as illustrated on figure 6.8.

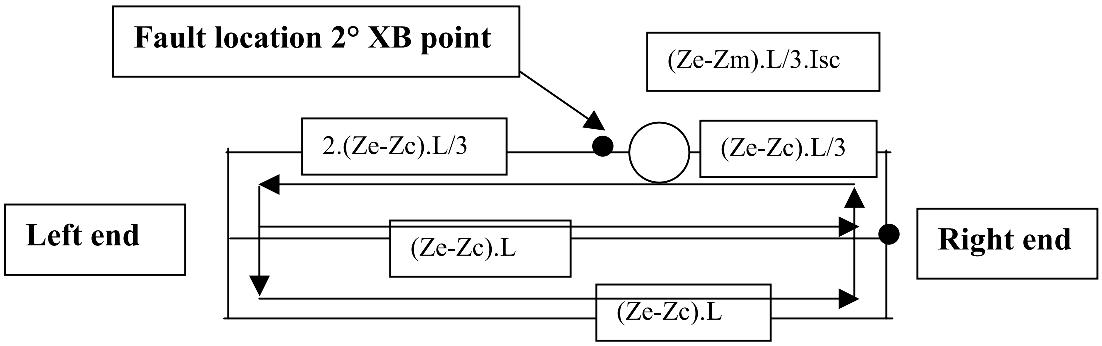


Figure 6.8: Model for Screen Circuits

Assuming zero current at the left end, the current due to the voltage induced in the faulted circuit flows in the screens, which may be represented by three impedances in series :

- First: for the faulted screen circuit between fault location and left end.
- Second: for the sound screen circuits, in parallel
- Third: for the faulted screen circuit between fault location and right end.

6.2.4 Maximum Screen Voltage

a) Connection Between Two Substations

The voltage drop in the major section Vd is expressed according to formula 6.1 in § 6.2.2 as:

$$V_d = \left[Z_e^{'}.I_e + Z_m^{'}.I_{scl} + Z_0.\left(I_{scl} + I_{scr}\right)\right]L \qquad (6.15)$$

Taking into account the end conditions:

$$V_d = -\left(R_r + R_l\right).\left[I_e + I_{scl}\right] \qquad (6.16)$$

The EPR being :

$$EPR = R_r.\left[I_e + I_{scl}\right] \qquad (6.17)$$

From the two expressions for V0, Ie+Iscl may be found, allowing the derivation of both the EPR and the voltage drop between the fault location and the right end.

Comparing with the maximum voltage rise during an external fault, it may be found for a trefoil formation :

$$V_{\max i} - V_{\max e} = \left[EPR + e\right]_i - \left[EPR + e\right]_e = \frac{Z_e - Z_m}{9}.L.\left(I_{scl} + I_{scr}\right).\left[\frac{7}{3} - \frac{R_r + \frac{Z_e^{'}}{3}}{R_r + R_l + Z_e^{'}}\right] \qquad (6.18)$$

When R_L and Z'e are small compared to Rr, (6.19) reduces to:

$$V_{\max i} \approx V_{\max e} + \frac{4}{27} R_s.L.(I_{scl} + I_{scr}) \qquad (6.19)$$

An overestimate of the voltage rise is :

$$V_{\max i} \approx V_{\max e} + \frac{7}{27} R_s.L.(I_{scl} + I_{scr}) \qquad (6.20)$$

The condition for safety is therefore :

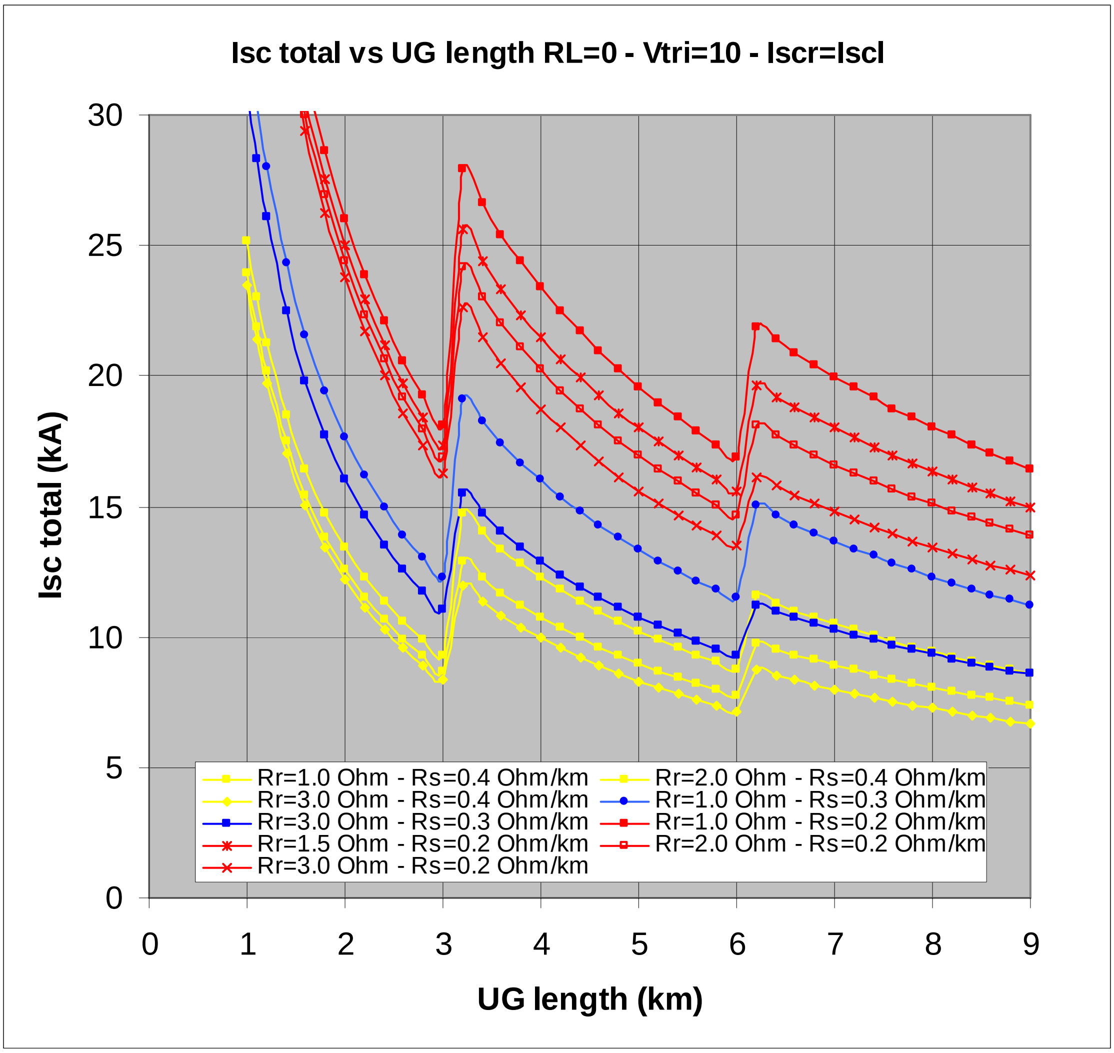
$$V_{\max e} \leq V_{tri} - \frac{7}{27} R_s.L.(I_{scl} + I_{scr}) \qquad (6.21)$$

This means that the rule given in section 5 may apply with a "corrected" value for Vtri.
Thus, the condition for safety is:

$$EPR < V_{\lim} \qquad V_{\lim} = \frac{3.N}{3.N-1}.\left[V_{tri}.\left(1 - \frac{2}{3}.\frac{I_{sc1}}{I_{sc3}}\right) - \frac{7}{27}.R_s.\frac{L}{N}.(I_{scr} + I_{scl})\right] \qquad (6.22)$$

where N is the number of major sections; Rl=0 being assumed (worst case)

Figure 6.9 gives the permissible maximum short-circuit current where maximum length of major section is assumed to be 3 km.



.

Figure 6.9: Maximum Permissible Short Circuit Current

b) UG link connected to a substation and an OH line

Same considerations apply
Relationships for the voltage drops in the screens for the major section and in the faulted screen from the fault location to the right end still hold.
This lead to the following condition for safety :

$$EPR < V_{\lim} \qquad V_{\lim} = \frac{3.N}{3.N-1}\cdot\left[V_{tri}\cdot\left(1-\frac{2}{3}\cdot\frac{I_{sc1}}{I_{sc3}}\right)-\frac{7}{27}.R_s\cdot\frac{L}{N}.(I_{scr}+I_{scl})\right] \qquad (6.23)$$

c) Siphon systems

$$EPR < V_{\lim} \qquad V_{\lim} = \left[V_{tri}\cdot\left(1-\frac{2}{3}\cdot\frac{I_{sc1}}{I_{sc3}}\right)-\frac{7}{27}.R_s\cdot\frac{L}{N}.(I_{scr}+I_{scl})\right] \qquad (6.24)$$

6.2.5 Sheath to Sheath Voltages.

These voltages do not depend on the short-circuit current return path. The highest sheath to sheath voltages at the cross-bonding points are obtained when the fault occurs at one of the ends of the 2nd elementary section.

Figure 6.10 and 6.11below give typical sheath to sheath voltages at the two cross-bonding points according to the position of the fault (the major section is assumed to be 3000 m in length – cables laid in flat formation).

Vij(k) is the sheath to sheath voltage between circuits i and j at cross-bonding point k
x is the ratio of the short-circuit current from left side to the overall short-circuit current.

Table 3 gives maximum sheath-to-sheath voltages (l is the length of the minor sections).

The highest voltage refers to the voltage between the faulted circuit and one of the sound circuits:

Either
- at 1st cross bonding position, $V_{12}[1]$ (fault on circuit 1) or $V_{23}[1]$ (fault on circuit 2)
- Where the fault occurs at the « left » end of the 2° minor section.
- Where the fault is fed by the « left » side (x=1).

Or
- at 2nd cross bonding position, $V_{12}[1]$ (fault on circuit 1) or $V_{23}[1]$ (fault on circuit 2)
- Where the fault occurs at the « right » end of the 2° minor section.
- Where the fault is fed by the « right » side (x=0).

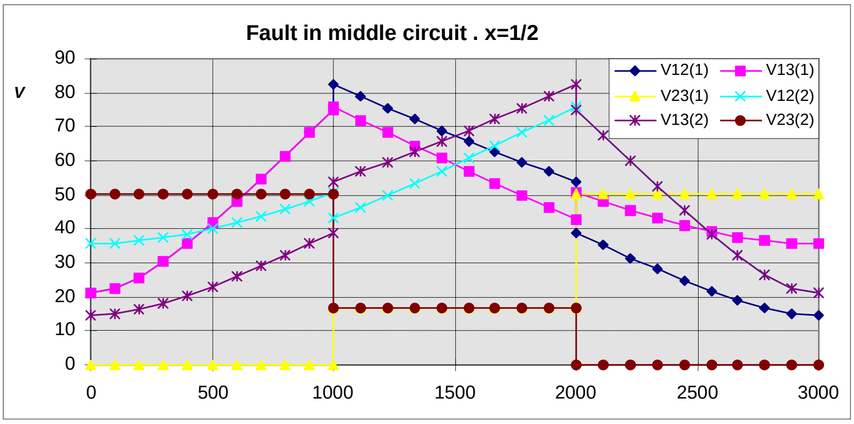


Figure 6.10: Sheath to Sheath Voltage – Middle Phase Faulted

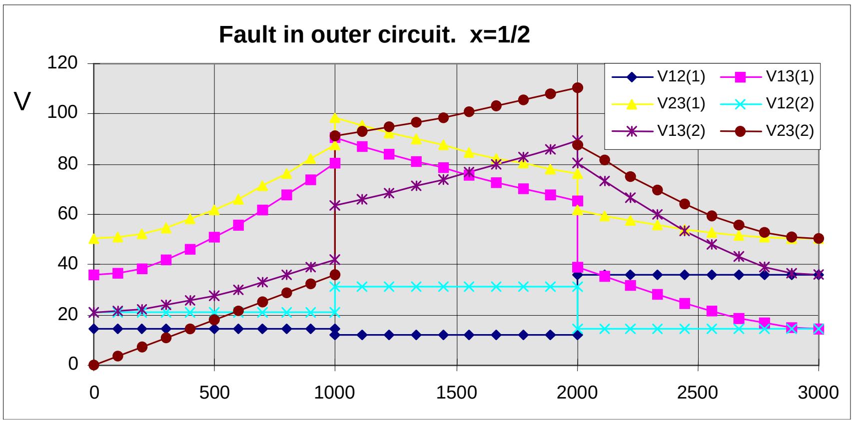


Figure 6.11: Sheath to Sheath Voltage – Outer Phase Faulted

	Trefoil	Flat formation
x ≤ ½	$\left[-\frac{2}{3}R_S + (x-\frac{4}{3}).(Z_m - Z_c)\right].\ell.I_{sc}$ (6.25)	$\left[-\frac{2}{3}R_S - (x-\frac{4}{3}).(Z_m - Z_{out})\right].\ell.I_{sc}$ (6.26)
x ≥ ½	$\left[-\frac{2}{3}R_S - (x+\frac{1}{3}).(Z_m - Z_c)\right].\ell.I_{sc}$ (6.27)	$\left[-\frac{2}{3}R_S - (x+\frac{1}{3}).(Z_m - Z_{out})\right].\ell.I_{sc}$ (6.28)
Maximum	$\left[-\frac{2}{3}R_S + \frac{4}{3}(Z_m - Z_c)\right].\ell.I_{sc}$ (6.29)	$\left[-\frac{2}{3}R_S \pm \frac{4}{3}(Z_m - Z_{out})\right].\ell.I_{sc}$ (6.30)

Table 6.3: Sheath to Sheath Voltages.

The maximum voltage may be larger than the voltage occurring in three -phase faults if:

- The screen resistance is “high”.
- The fault is fed mainly by one side.
- The magnitudes of the 3-phase and the phase to earth short-circuit currents are similar.

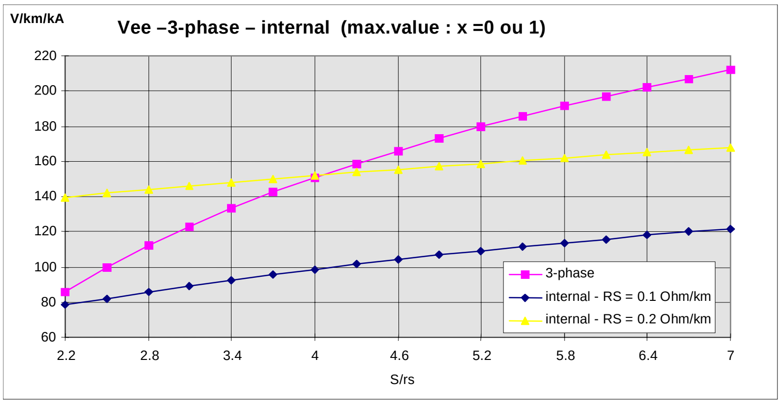


Figure 6.12 : Sheath to Sheath Voltages – Three--Phase and Internal Phase to Earth Faults

6.3 Conclusions

EPR due to internal faults is generally lower, compared to EPR occurring during external faults.
Conversely, the voltage drops in the faulted screen circuit between the fault and the nearest end are larger than voltage drops experienced during external faults, specially where high screen resistances are involved.
This turns into more stringent safety limits.

For cross-bonded systems, the maximum sheath to sheath voltage may be larger than the voltage occurring in 3-phase fault if:

- The screen resistance is “high”.
- The fault is fed mainly by one side.
- The magnitudes of the three-phase and the phase to earth short-circuit currents are similar.

7. WORKED EXAMPLES

7.1 General

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 (0.5Ω or less) due to multiple contributions such as buried interconnected metal structures. The EPR due to phase-to-earth faults rarely exceeds 1 or 2 kV in such cases.

If the cable system is fed by an overhead line, the situation is quite different. Due to lower magnetic coupling and higher resistance, the skywires used on overhead lines carry a much smaller 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 %. At the OH/UG transition, high EPRs occur due to the difference of the return current between the skywire and the cable sheaths.

A similar phenomenon can occur at the transition between a cross bonded cable section and a single point bonded section if the resistance of the ecc is significantly higher than that of the sheaths in parallel. This is illustrated in the following sections on simple examples and in Appendix B which deals with an actual situation, investigated using both EMTP and CIM to calculate EPR, which resulted in close agreement between the methods. .

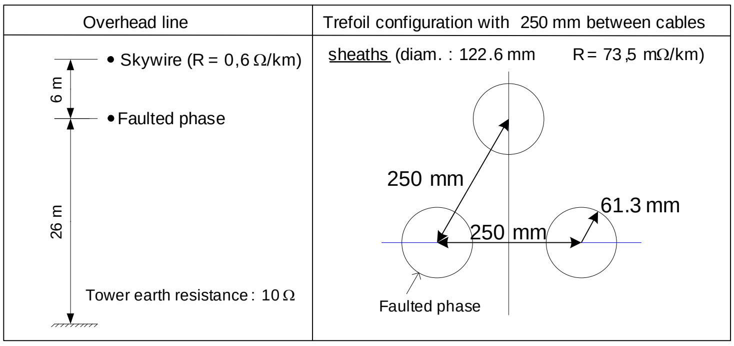
7.2 Calculation Example for a Cross-Bonded UGL Connected to a Substation and an OHL – Fault at the OH/UG Transition

7.2.1 General

A simple example illustrates the impact of the EPR due to OH/UG (overhead to underground) transitions on voltages appearing on the SVLs protecting the cable sheaths on cross-bonded links.

7.2.2 Description of the System

The underground link comprises two major 1.5-km sections. The link is fed directly by a substation on the left side and through a 10-km overhead line on the right side.
The main characteristics of the overhead and underground circuits are as follows:



Notes:
The circuit includes two major UG cable sections . To simplify the circuit , only the major section close to the transition is modeled in detail (3 minor sections). The 10-km long overhead line is modelled by one section only .
The earth resistance of substations at both ends is 0.2 Ω.
The earth resistance of towers is 10 Ω.
The earth resistance at the transition results from the local tower earth resistance in parallel with the equivalent earth impedance of the overhead line (the phase angle of the impedance is neglected ; it could be taken into account).
The earth resistance between the two major sections is set equal to the tower resistance .

Figure 7.1

7.2.3 Model of the Circuit in EMTP

EMTP is used to model the system. The "Exact Pi" line model is used both for overhead lines and cables. This model gives more precise results for steady state calculations. With a view to simplify the circuit, only one section is used to model the overhead line. The earth resistance at the OH/UG transition is equivalent to all the tower earth resistances as seen from the transition. A single phase-to-neutral fault is applied at the OH/UG transition or on the UG link at the closest joint of the transition.

7.2.4 Fault at the OH/UG Transition

If the fault is fed by the underground system only (left source), the EPRs are negligible. Neutral-to-earth voltages at transpositions are lower than 40 V/kA. If the fault is fed by the overhead line only (right source), the EPR at the OH/UG reaches 682 V/kA. This high EPR is transferred on the cable sheaths and the sheath or neutral-to-earth at the first transposition reaches 570 V/kA. Sheath-to-earth voltages at transpositions are dominated by the transferred EPR appearing at the fault location. If the fault is fed by both sources, the result is very similar to the previous one. Sheath-to-earth voltages at transpositions are dominated by the EPRs due to the contribution of the overhead line.

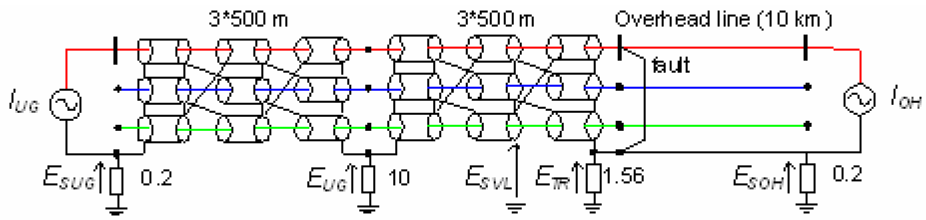


Figure.7.2 Circuit Diagram of the Simple System Example

Injected current		Neutral-to-earth voltages (V)				
I_{UG}	I_{OH}	E_{SUG}	E_{UG}	E_{SVL}	E_{TR}	E_{SOH}
1 kA	0	6	17	27	40	1
0	1 kA	80	350	570	682	136
1 kA	1 kA	74	359	597	700	136

Table 7.1 Results for a Fault at the OH/UG Transition

The EPR at the transition may be estimated using Figures 5.11and 5.12 of the report :

- *V0 is about 0.7 kV/kA for ZR=1.56 Ohm and a 3 km long link*
- *K is about 0.54 for an equal sharing of incoming short-circuit currents.*

This leads to :

$$EPR = 0.7 \cdot 2 \cdot 0.54 \approx 0.76\ kV \qquad (7.1)$$

The difference (760 V vs 700 V) is due to the approximation of infinite length for the OHL

7.2.5 Fault on the UG Link at the Joint Closest to the Transition

If the fault is fed by the underground system only (left source), the EPRs are negligible. Neutral-to-earth voltages at the transposition (fault location) reach 49 V/kA compared to 27 V/kA for the fault at the OH/UG transition. If the fault is fed by the overhead line only (right source), the EPRs along the system are very similar to those calculated for a fault 500 m away at the OH/UG transition. If the fault is fed by both sources, the results are again very similar to the previous case. Sheath-to-earth voltages at transpositions are dominated by the EPRs due to the contribution of the overhead line.

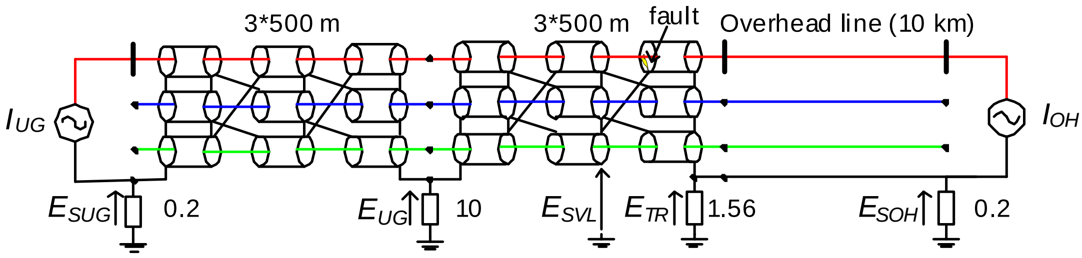


Figure 7.3

Injected current		**Neutral-to-earth voltages (V)**				
I_{UG}	I_{OH}	E_{SUG}	E_{UG}	E_{SVL}	E_{TR}	E_{SOH}
1 kA	0	5	19	49	33	1
0	1 kA	80	354	592	679	136
1 kA	1 kA	75	367	641	693	136

Table 7.2: Results for a fault at the closest transposition of the OH/UG transition

Compared with the previous case, the voltage stressing the SVL is increased by 44 V where the overall short-circuit current is 2000 A (the value is half when the short circuit current is 1000 A), i.e.

$$\frac{5.4}{27} \cdot R_S \cdot \frac{L}{N} \cdot (I_{scl} + I_{scr}) = \frac{5.4}{27} \cdot 73.5 \cdot 10^{-6} \cdot \frac{6500}{2} \cdot 2000 \qquad (7.2)$$

The coefficient 5.4 is a value lying between the maximum value (7) and the minimum (4) as mentioned in § 6.4

7.3 Calculation Example for a UGL Between Two Substations, Partly Cross-Bonded and Single-Point Bonded

7.3.1. Parameters of the modelled cable circuit

To demonstrate the node voltage analysis method the following 230 kV cable circuit consisting of a cross-bonded section and one single point bonded section shall be calculated.

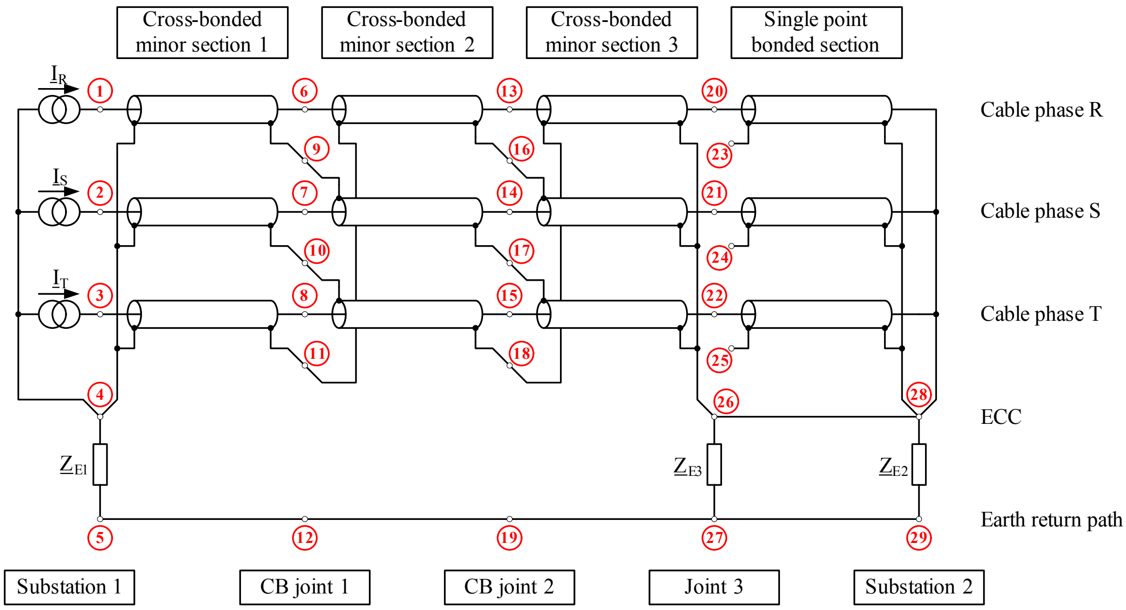


Fig. 7.4: Schematic of the cable circuit with node numbers for node voltage analysis

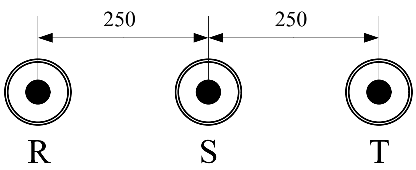


Fig. 7.5: Cable arrangement at cross-bonded section

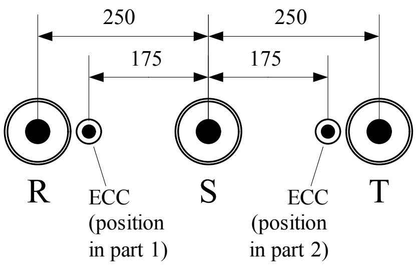


Fig. 7.6: Cable arrangement at single point bonded sections (ecc in optimal position)

The cables are single core XLPE insulated cables with 800 mm² copper conductor and a metallic screen, arranged in flat formation with 250 mm distance between cables. At the cross-bonding joints the cable positions are not transposed but the screens are connected as is typical for cross-bonded circuits. The single point bonded section is equipped with an ecc of 240 mm² (copper), which is located as usual at 70 % of the cable distance between the phases (175 mm to centre phase). The position of the ecc is transposed in the middle of the single point bonded section. The length of every section shall be 500 m.

The earthing impedances at both ends of the cable circuit (substation 1 and substation 2) are $\underline{Z}_{E1}$ and $\underline{Z}_{E2}$ as shown in figure 7.4. At the transition between the cross-bonded section and the single point bonded section (joint 3) the ecc of the single point bonded section as well as the screens of the cross-bonded section are earthed via the earthing impedance $\underline{Z}_{E3}$.

The parameters are as follows:

230 kV cable:

Conductor diameter:	34.6 mm
Screen diameter:	95.0 mm
Screen thickness:	3.5 mm
AC conductor resistance:	0.031 Ω/km
AC screen resistance:	0.150 Ω/km

ecc:

Conductor diameter:	18.4 mm	
AC conductor resistance:	0.0897 Ω/km	(assumed operating temperature 65 °C)

Earth impedances:

Substation 1:	0.5 Ω + j 0.0 Ω
Joint 3:	5.0 Ω + j 0.0 Ω
Substation 2:	0.2 Ω + j 0.0 Ω

General:

Length of minor CB sections:	500 m
Length of single point bonded section:	500 m
Frequency:	50 Hz
Electric soil resistivity:	100 Ω·m

For simplification the calculated example works with current sources in the 3 phase conductors. The real phase-to-earth voltages as well as any source or load impedances for the phase conductors are therefore not modelled. The following examples are calculated for normal operation with three-phase symmetrical operation at 1000 A and for single-phase short-circuit at substation 2 with 25 kA earth fault current in all three phases. All calculations were done for optimal ecc position in the single point bonded section (see above) as well as for two non-optimal positions (ecc outside of the cable circuit 250 mm and 1000 mm away from outer phase without transposition).

A detailed description of the solution steps for one particular case is given in appendix A1.

7.3.2. Calculated parameter combination

In the following, calculation results are given for both normal operation and single-phase-to-earth fault, making it possible to compare the influence of leading parameters in these two situations.

a) Variation of screen resistance

In order to demonstrate the influence of the screen resistance on EPR and screen-to-earth voltages a number of calculations were carried out with values for the screen resistance between 0.02 and 0.4 Ω/km. The results are as follows:

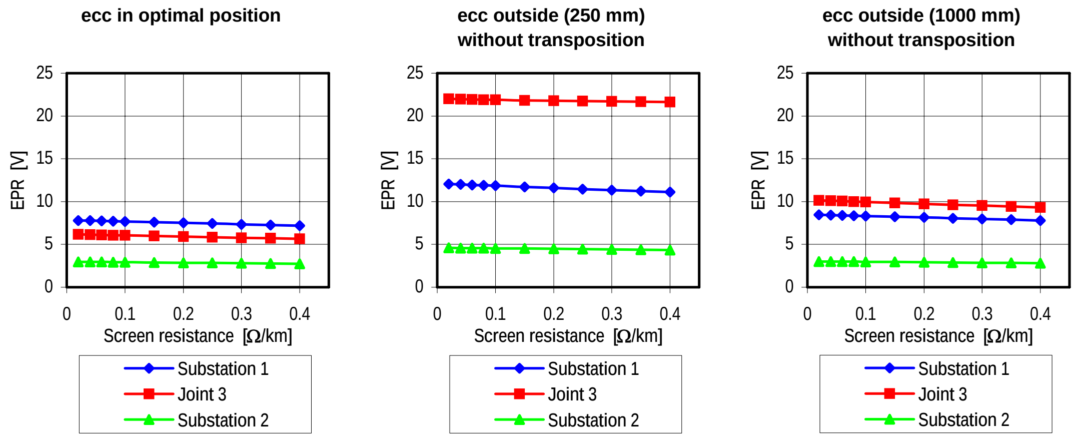


Fig. 7.7: Earth potential rise in substations 1 and 2 and at transition point between cross-bonded and single point bonded sections (joint 3) depending on screen resistance for 1000 A three-phase symmetrical current

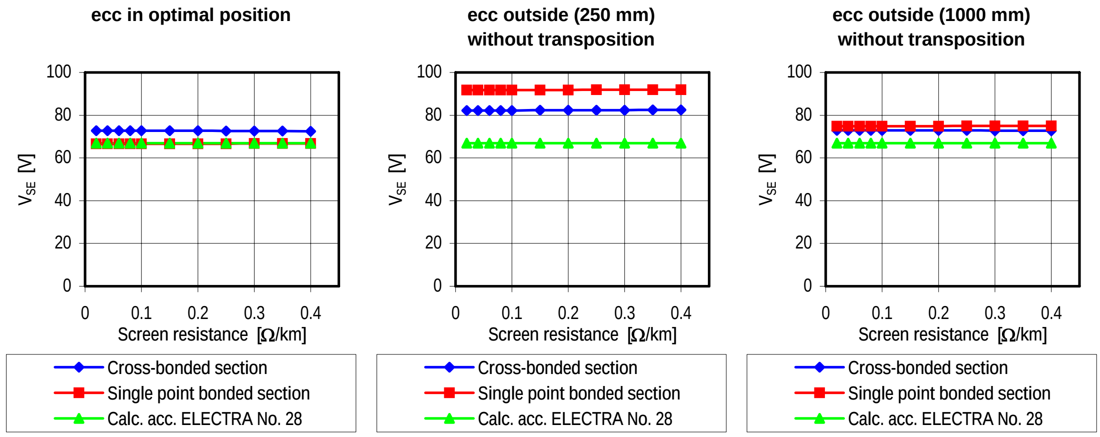


Fig. 7.8: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 (ref. [2]) depending on screen resistance for 1000 A three-phase symmetrical current

The calculations show that the influence of screen resistance on EPR and screen-to-earth voltages is generally low when the circuit carries a symmetrical three-phase current. If the ecc at the single point bonded section is located in the optimal position, the EPR at the substations as well as at the transition between cross-bonded and single point bonded section is low. The maximum screen-to-earth voltage for the single point bonded section is equal to the value calculated according to the simple formula from ELECTRA No. 28 (ref. [2]). On the other hand the screen-to-earth voltage in the cross-bonded section is higher. The difference is in the range of the calculated EPR. This result is in line with the general statement that the use of the simplified calculation formula for the screen-to-earth voltage is possible for single point bonded installations, if the ecc is in optimal position (i.e. does not carry significant current).

If the ecc in the single point section is located outside of the cable circuit and is not transposed, there will be a circulating current induced in the ecc. This leads to an increase of the EPR, in particular at the transition between cross-bonded and single point bonded section.

The effect tends to be larger if the ecc is located outside but still close to the cable circuit. This is due to the fact that the induced circulating current in the ecc is higher, if the ecc is located closer to the cable circuit (but still in non-optimal position). The calculation results for screen-to-earth voltages show consequently that all voltages are higher than the value calculated according to the simple formula from ELECTRA No. 28 [2].

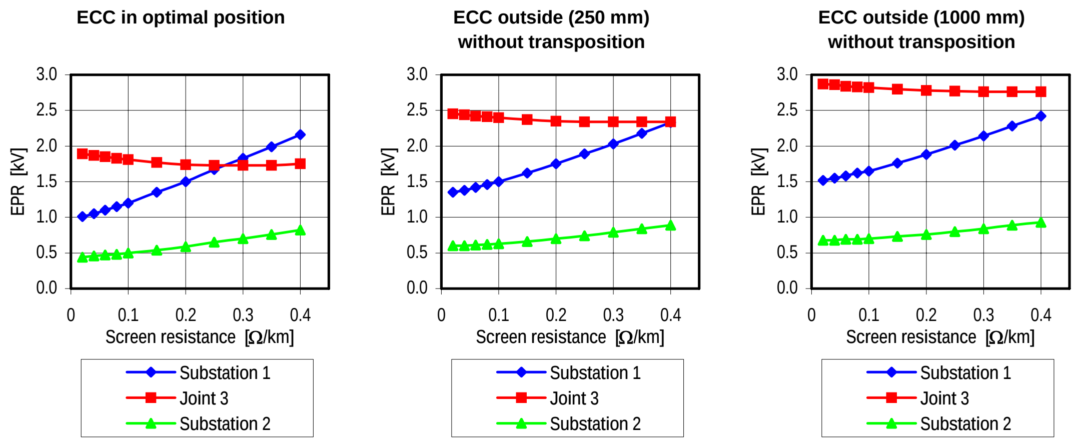


Fig. 7.9: Earth potential rise in substations 1 and 2 and at transition point between cross-bonded and single point bonded sections (joint 3) depending on screen resistance for 25 kA earth fault current

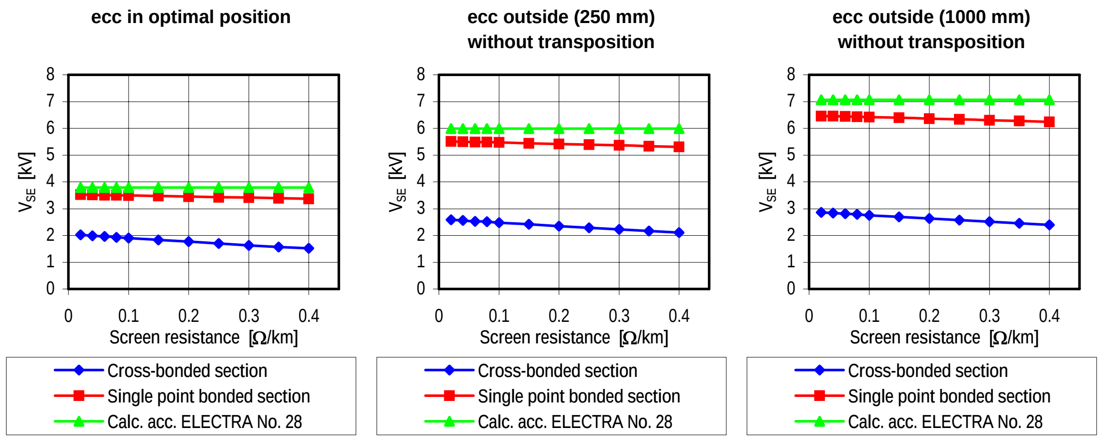


Fig. 7.10: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 [2] depending on screen resistance for 25 kA earth fault current

For single-phase-to-earth faults the calculation results show that EPR at the substations becomes generally higher with increasing screen resistance. This is due to the fact that at higher screen resistance an increasing fraction of the fault current flows via the earth path and therefore the EPR at both ends of the circuit is also increasing. In contrast the EPR at the transition point between cross-bonded and single point bonded section is only marginally influenced by the screen resistance. This is an indication that the current to earth at the transition point remains nearly constant. The calculated screen-to-earth voltages are as expected; they are significantly higher for the single point bonded section than for the cross-bonded section and they increase with increasing distance between the cable carrying the earth fault current and the ecc.

The simple formula for calculation of screen-to-earth voltages for single point bonded circuits from to ELECTRA No. 28 [2] leads to values slightly higher than those calculated here. This is mainly caused by the simplifying assumption in

ELECTRA No. 28 [2] that the whole earth fault current will return via the ecc. In general the dependency on screen resistance is relative small.

b) Variation of ecc size

The influence of ecc size in the single point bonded section was studied using ecc's from 95 mm² to 500 mm². The results are as follows:

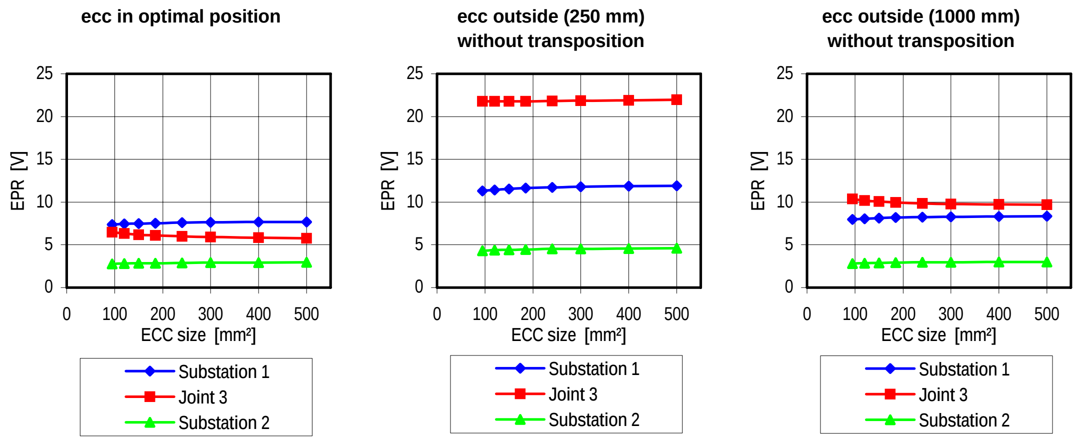


Fig. 7.11: Earth potential rise in substations 1 and 2 and at transition point between cross-bonded and single point bonded sections (joint 3) depending on ecc size for 1000 A three-phase symmetrical current

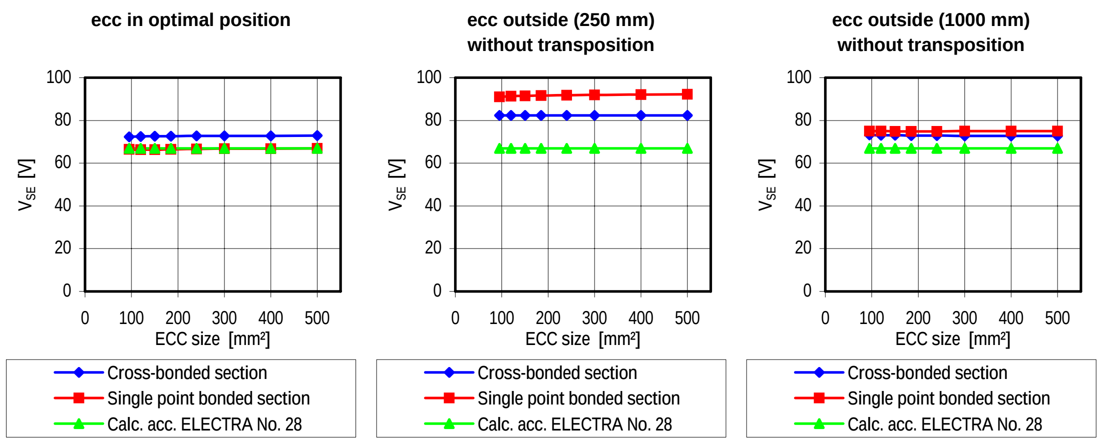


Fig. 7.12: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 (ref. [2]) depending on ecc size for 1000 A three-phase symmetrical current

The calculation results show behaviour very similar to the results obtained for the variation of screen resistance. For symmetrical three-phase current in the phase conductors there is nearly no influence of ecc size on the calculated EPR as well as on the calculated screen-to-earth-voltages. Again the calculations show that non-optimal positioning of the ecc at the single point bonded section may lead to significantly increased EPR values and as a consequence also to increased values of the screen-to-earth voltages in all sections.

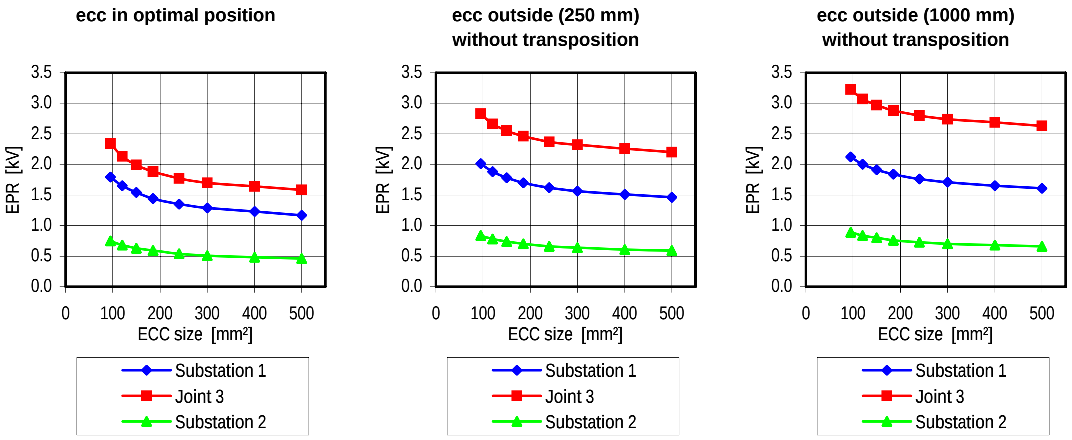


Fig. 7.13: Earth potential rise in substations 1 and 2 and at the transition point between cross-bonded and single point bonded sections (joint 3) depending on ecc size for 25 kA earth fault current

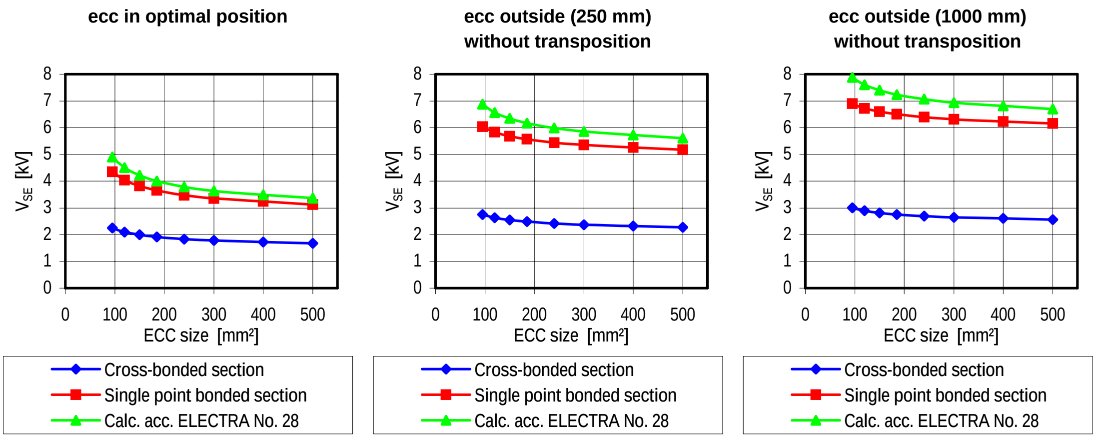


Fig. 7.14: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 (ref. [2]) depending on ecc size for 25 kA earth fault current

In case of a single-phase-to-earth fault the EPR as well as the maximum screen-to-earth voltages will become lower with increasing ecc size. Nevertheless the influence is not large within the range of parameters used for this calculation. This is in line with the common practice to select the ecc size mainly for earth fault current carrying capacity. If significant reduction of screen-to-earth voltages is required, it would not make much sense to increase the ecc size. In such a case it would be better to use more than one ecc per circuit (for details see ref. [1]). As already discussed in the example above, non-optimal positioning of the ecc significantly increases the screen-to-earth voltages. The simple formula according to ELECTRA No. 28 gives a good estimation of the maximum screen-to-earth voltage for the single point bonded section with a certain safety margin.

c) Variation of Earthing Impedance

The earthing impedance at the transition point between cross-bonded and single point bonded sections (joint 3) was varied between 0.1 Ω and 20 Ω. All other parameters, in particular also the earthing impedance at both substations, remained constant. The calculation results are as follows:

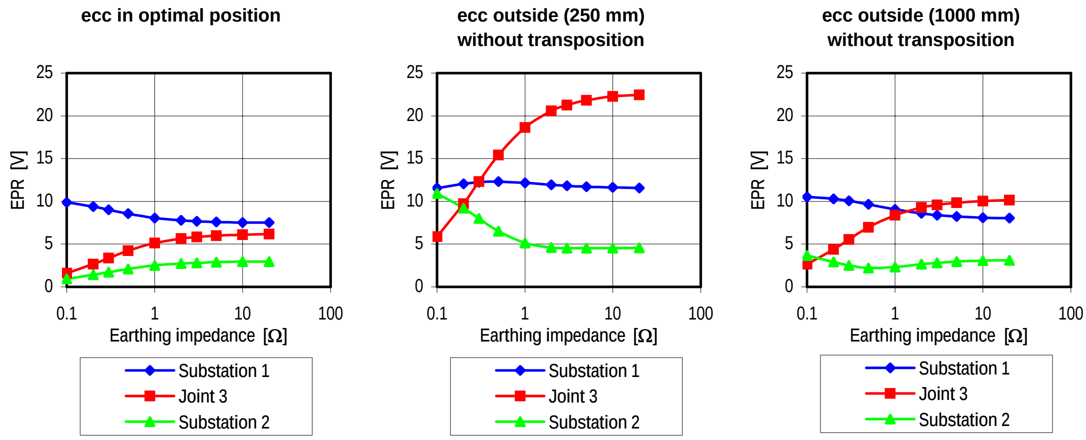


Fig. 7.15: Earth potential rise in substations 1 and 2 and at the transition point between cross-bonded and single point bonded sections (joint 3) depending on earthing impedance at transition point for 1000 A three-phase symmetrical current

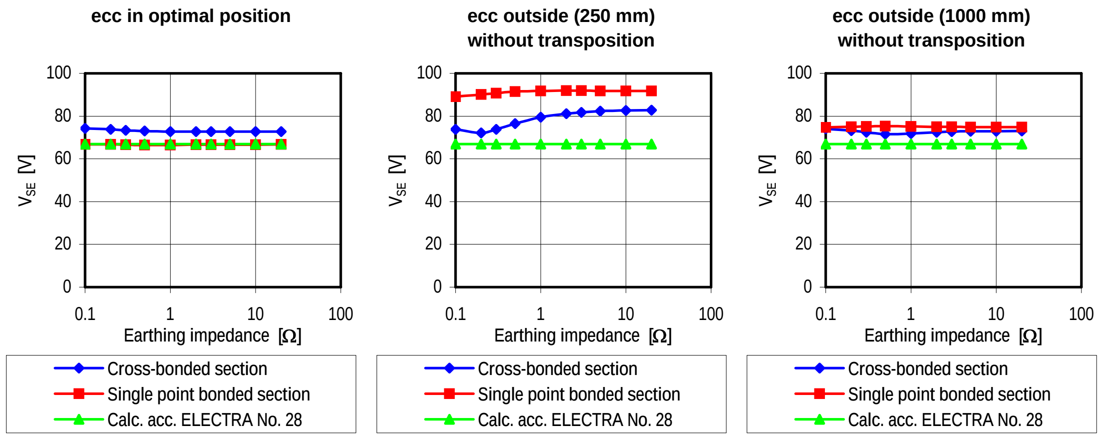


Fig. 7.16: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 (ref. [2]) depending on earthing impedance at transition point for 1000 A three-phase symmetrical current

The influence of the earthing impedance at the transition point on EPR is significant for symmetric three-phase load in particular for the EPR at that point. Nevertheless also the EPR at the substations is influenced because the current distribution between screens, ecc and the earth return path in the whole circuit is changing. On the other hand the calculated screen-to-earth voltages are much less dependent on the earthing impedance at the transition point than the EPR. The influence is particularly low, if the ecc in the single point bonded section is located in the optimal position.

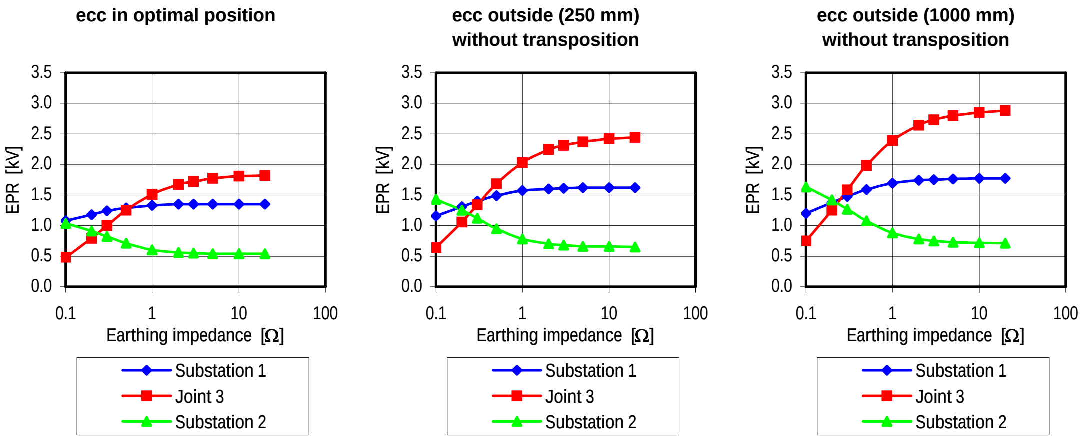


Fig. 7.17: Earth potential rise in substations 1 and 2 and at the transition point between cross-bonded and single point bonded sections (joint 3) depending on earthing impedance at transition point for 25 kA earth fault current

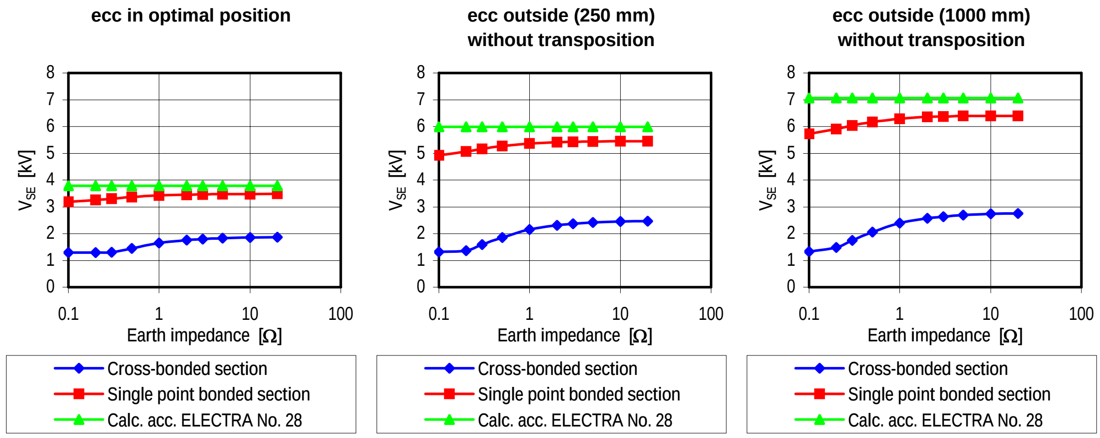


Fig. 7.18: Maximum voltage between screen and local earth in cross-bonded and single point bonded sections and voltage calculated according to formula from ELECTRA No. 28 (ref. [2]) depending on earthing impedance at transition point for 25 kA earth fault current

For single-phase-to-earth faults the influence of earthing impedance at the transition point on EPR is significant, in particular at the transition point itself. Nevertheless the calculated values of the screen-to-earth voltages show generally less dependency. As in the calculated examples above the simplified formula according to ELECTRA No. 28 gives a good conservative estimation for the maximum screen-to-earth voltage at the single point bonded section.

8. CONCLUSIONS

EPR will occur in all underground cable systems when subject to single phase to earth faults. However, the level of EPR will only be significant for particular system arrangements.

EPR in cable systems is most influenced by the following key parameters:

- Magnitude of single phase to earth fault current
- Values of earth impedances at the cable terminals
- Cable screen resistance
- ecc resistance (where an ecc is included)
- Skywire resistance in connected overhead lines

Positions in a UG cable system where EPR will be higher are at the connections of dissimilar resistances at earthing positions, e.g. where the OH line skywire connects to the cable screens or where an ecc connects to cable screens at the junction of a cross bonded and single point bonded system.

Where an UG cable system terminates into substations at each end, with low earth impedances, EPR is unlikely to be significant. However, voltages stressing the SVL are likely to be severe in the case of internal fault

Where a UG cable system connects with an OHL having towers with high earth impedance, EPR will be generated at the interface and transferred to the cable screen. Skywire resistance will influence the level of EPR, which will be a maximum at the UG/OHL interface, decaying in value once into the cable screen system. The gradual reduction of EPR along the screen system will largely depend on screen resistance and the presence of any further discontinuities, e.g. connection to an ecc.

For a full assessment of EPR in cable screens it is necessary to use complex analysis such as EMTP, although the accuracy of the calculation depends heavily on key parameters such as earth impedances, which are not generally known. In most cases a simplified analysis may be used which may provide the order of magnitude of the EPR and indicate if a more detailed analysis is necessary. Methods detailed in sections 5 and 6 will provide design tools to enable such simplified analysis to be carried out and graphical results shown will help the user, by showing ranges of results for typical system and earthing conditions. As a worst case approach, complex systems can be broken down into smaller basic systems and the EPR result built up by superposition.

The use of a recognised calculation method is strongly recommended for the design of special bonding.
The responsibility for design data has to be clearly identified between utilities and cable system designers or suppliers.
Items such as the magnitude of the fault current, the earth electrode resistances, the grid structure are likely to be provided by utilities.
Other items, such as SVL rating, SVL connexion, ecc design … should be agreed.

Where it is necessary to protect SVLs against EPR, three measures may be considered:

- The star point earth may be removed. In this case it is necessary to ensure that clearances in the SVL enclosure are adequate for the EPR level.
- The SVLs may be arranged in a delta formation.
- For cross bonded systems an ecc may be included.

9. REFERENCES

Reference	Clauses	Title
[1]	1 4.1 4.3 6.1 A.1	Special bonding of high voltage power cables. Cigre WG B1-18 Technical Brochure, 2005.
[2]	1 7.3.2	The design of specially bonded systems. Paper presented by Working Group 07 of Study Committee 21. Electra No.28, 1973.
[3]	1	The design of specially bonded systems (part II). Paper presented by Working Group 07 of Study Committee 21. Electra No.47, 1976.
[4]	1	Guide to the protection of specially bonded systems against sheath overvoltages. Paper presented by Working Group 07 of Study Committee no.21. Electra No.128, 1990.
[5]	1	IEEE 80
[6]	3.3	Electromagnetic transients program reference manual (EMTP theory book). H.W.Dommel
[7]	4.5	Sheath overvoltages affecting specially bonded underground links during single-phase faults. : VO VAN HUY H. – DORISON E. Jicable 1999 – Report B 9 2.

A. APPENDIX A : APPLICATION OF THE NODE VOLTAGE (NV) METHOD

A.1 Worked Example using the Node Voltage Method

Parameters of the modelled cable circuit

The parameters of the calculated cable circuit are given in chapter 7.3. Using the formulas for the fictitious conductor representing the earth return path the following values are calculated (see ref. [1]):

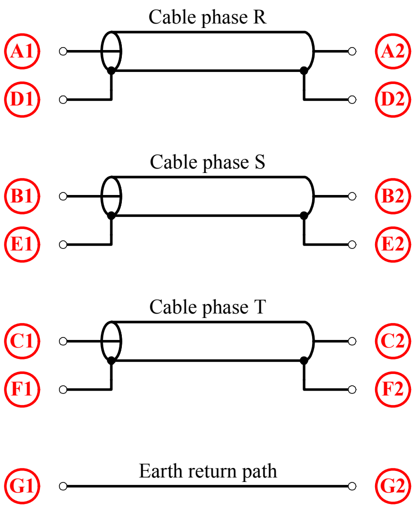
Depth of fictitious earth conductor: 931.1 m
Resistance of fictitious earth conductor: 4.9348E-05 Ω/m

The following equivalent radii were calculated for the conductors and screens using the formulae for compacted conductors (for cable conductors and ecc) and hollow conductors (for screens) accordingly (details see ref. [1]):

Equivalent radius for cable conductor: 13.47 mm
Equivalent radius for cable screen: 43.82 mm
Equivalent radius for ecc: 7.16 mm

The calculated example case shall be a single phase short circuit (25 kA) at substation 2 in phase R.

Partial node admittance matrices for cross-bonded minor sections



Node	
A1	Left side conductor R
B1	Left side conductor S
C1	Left side conductor T
D1	Left side screen R
E1	Left side screen S
F1	Left side screen T
G1	Left side earth return path

Node	
A2	Right side conductor R
B2	Right side conductor S
C2	Right side conductor T
D2	Right side screen R
E2	Right side screen S
F2	Right side screen T
G2	Right side earth return path

Fig. A.1: Schematic of single minor section of cross-bonded part of the cable circuit

First the impedance matrix of the particular cable circuit section has to be established. The real part of the impedance matrix contains the resistance of the branches at the main diagonal. In order to obtain the imaginary part first the mean geometric distances and finally the self and mutual reactances have to be calculated (details see ref. [1]). The reference radius for calculation of the reactances (i.e. the radius of the fictitious covering cylinder) has been chosen as equal to the depth of the earth return path.

Mean geometric distances (values in m):

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	Fict. EC
Cond. R	0.0135	0.2500	0.5000	0.0463	0.2500	0.5000	931.09
Cond. S	0.2500	0.0135	0.2500	0.2500	0.0463	0.2500	931.09
Cond. T	0.5000	0.2500	0.0135	0.5000	0.2500	0.0463	931.09
Screen R	0.0463	0.2500	0.5000	0.0463	0.2500	0.5000	931.09
Screen S	0.2500	0.0463	0.2500	0.2500	0.0463	0.2500	931.09
Screen T	0.5000	0.2500	0.0463	0.5000	0.2500	0.0463	931.09
Fict. EC	931.09	931.09	931.09	931.09	931.09	931.09	931.09

(Z_r) - Impedance matrix, real part (values in Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	Fict. EC
Cond. R	0.0155	0	0	0	0	0	0
Cond. S	0	0.0155	0	0	0	0	0
Cond. T	0	0	0.0155	0	0	0	0
Screen R	0	0	0	0.0750	0	0	0
Screen S	0	0	0	0	0.0750	0	0
Screen T	0	0	0	0	0	0.0750	0
Fict. EC	0	0	0	0	0	0	0.0247

(Z_i) - Impedance matrix, imaginary part (values in Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	Fict. EC
Cond. R	0.3501	0.2583	0.2365	0.3113	0.2583	0.2365	0
Cond. S	0.2583	0.3501	0.2583	0.2583	0.3113	0.2583	0
Cond. T	0.2365	0.2583	0.3501	0.2365	0.2583	0.3113	0
Screen R	0.3113	0.2583	0.2365	0.3113	0.2583	0.2365	0
Screen S	0.2583	0.3113	0.2583	0.2583	0.3113	0.2583	0
Screen T	0.2365	0.2583	0.3113	0.2365	0.2583	0.3113	0
Fict. EC	0	0	0	0	0	0	0

The impedance ($\underline{Z}$) matrix is inverted in order to get the admittance matrix ($\underline{Y}$):

(Y_r) - Admittance matrix, real part (values in 1/Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	Fict. EC
Cond. R	6.913	1.119	0.780	-7.855	-0.925	-0.372	0
Cond. S	1.119	6.668	1.119	-0.925	-7.381	-0.925	0
Cond. T	0.780	1.119	6.913	-0.372	-0.925	-7.855	0
Screen R	-7.855	-0.925	-0.372	10.695	-0.730	-0.396	0
Screen S	-0.925	-7.381	-0.925	-0.730	10.968	-0.730	0
Screen T	-0.372	-0.925	-7.855	-0.396	-0.730	10.695	0
Fict. EC	0	0	0	0	0	0	40.528

(Y_i) - Admittance matrix, imaginary part (values in 1/Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	Fict. EC
Cond. R	-7.824	2.235	1.031	1.961	1.041	0.616	0
Cond. S	2.235	-8.840	2.235	1.041	1.624	1.041	0
Cond. T	1.031	2.235	-7.824	0.616	1.041	1.961	0
Screen R	1.961	1.041	0.616	-3.660	-0.264	-0.065	0
Screen S	1.041	1.624	1.041	-0.264	-3.484	-0.264	0
Screen T	0.616	1.041	1.961	-0.065	-0.264	-3.660	0
Fict. EC	0	0	0	0	0	0	0

In the next step the partial node admittance matrix for the cable circuit section is established as follows:

Partial node admittance matrix, real part (values in 1/Ω)

	A1	B1	C1	D1	E1	F1	G1	A2	B2	C2	D2	E2	F2	G2
A1	6.913	1.119	0.780	-7.855	-0.925	-0.372	0	-6.913	-1.119	-0.780	7.855	0.925	0.372	0
B1	1.119	6.668	1.119	-0.925	-7.381	-0.925	0	-1.119	-6.668	-1.119	0.925	7.381	0.925	0
C1	0.780	1.119	6.913	-0.372	-0.925	-7.855	0	-0.780	-1.119	-6.913	0.372	0.925	7.855	0
D1	-7.855	-0.925	-0.372	10.695	-0.730	-0.396	0	7.855	0.925	0.372	-10.695	0.730	0.396	0
E1	-0.925	-7.381	-0.925	-0.730	10.968	-0.730	0	0.925	7.381	0.925	0.730	-10.968	0.730	0
F1	-0.372	-0.925	-7.855	-0.396	-0.730	10.695	0	0.372	0.925	7.855	0.396	0.730	-10.695	0
G1	0	0	0	0	0	0	40.528	0	0	0	0	0	0	-40.528
A2	-6.913	-1.119	-0.780	7.855	0.925	0.372	0	6.913	1.119	0.780	-7.855	-0.925	-0.372	0
B2	-1.119	-6.668	-1.119	0.925	7.381	0.925	0	1.119	6.668	1.119	-0.925	-7.381	-0.925	0
C2	-0.780	-1.119	-6.913	0.372	0.925	7.855	0	0.780	1.119	6.913	-0.372	-0.925	-7.855	0
D2	7.855	0.925	0.372	-10.695	0.730	0.396	0	-7.855	-0.925	-0.372	10.695	-0.730	-0.396	0
E2	0.925	7.381	0.925	0.730	-10.968	0.730	0	-0.925	-7.381	-0.925	-0.730	10.968	-0.730	0
F2	0.372	0.925	7.855	0.396	0.730	-10.695	0	-0.372	-0.925	-7.855	-0.396	-0.730	10.695	0
G2	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	40.528

Partial node admittance matrix, imaginary part (values in 1/Ω)

	A1	B1	C1	D1	E1	F1	G1	A2	B2	C2	D2	E2	F2	G2
A1	-7.824	2.235	1.031	1.961	1.041	0.616	0	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0
B1	2.235	-8.840	2.235	1.041	1.624	1.041	0	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0
C1	1.031	2.235	-7.824	0.616	1.041	1.961	0	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0
D1	1.961	1.041	0.616	-3.660	-0.264	-0.065	0	-1.961	-1.041	-0.616	3.660	0.264	0.065	0
E1	1.041	1.624	1.041	-0.264	-3.484	-0.264	0	-1.041	-1.624	-1.041	0.264	3.484	0.264	0
F1	0.616	1.041	1.961	-0.065	-0.264	-3.660	0	-0.616	-1.041	-1.961	0.065	0.264	3.660	0
G1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0	-7.824	2.235	1.031	1.961	1.041	0.616	0
B2	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0	2.235	-8.840	2.235	1.041	1.624	1.041	0
C2	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0	1.031	2.235	-7.824	0.616	1.041	1.961	0
D2	-1.961	-1.041	-0.616	3.660	0.264	0.065	0	1.961	1.041	0.616	-3.660	-0.264	-0.065	0
E2	-1.041	-1.624	-1.041	0.264	3.484	0.264	0	1.041	1.624	1.041	-0.264	-3.484	-0.264	0
F2	-0.616	-1.041	-1.961	0.065	0.264	3.660	0	0.616	1.041	1.961	-0.065	-0.264	-3.660	0
G2	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Furthermore the partial node admittance matrix of the cable circuit section has to be added to the total node admittance matrix of the whole cable circuit at the positions of the corresponding nodes as described in chapter 4.6.3. The partial node admittance matrices for all three cross-bonded minor sections are identical. The only difference is that they have to be added to different positions of the total node admittance matrix.

For instance in cross-bonded minor section 1, the left side of all three screens (nodes D1, E1 and F1 in partial node admittance matrix, see fig. A.1) is connected to the local earth potential of substation 1 (node 4 in the total node admittance matrix). Therefore the values to be added to the cells in row and column 4 of the total node admittance matrix are the sum of the corresponding cells in rows and columns D1, E1 and F1 of the partial node admittance matrix.

Cross-bonded minor section 1:

Values to be added to the real part of the total node admittance matrix (values in 1/Ω)

	1	2	3	4	5	6	7	8	9	10	11	12	…
1	6.913	1.119	0.780	-9.153	0	-6.913	-1.119	-0.780	7.855	0.925	0.372	0	
2	1.119	6.668	1.119	-9.231	0	-1.119	-6.668	-1.119	0.925	7.381	0.925	0	
3	0.780	1.119	6.913	-9.153	0	-0.780	-1.119	-6.913	0.372	0.925	7.855	0	
4	-9.153	-9.231	-9.153	28.646	0	9.153	9.231	9.153	-9.569	-9.508	-9.569	0	
5	0	0	0	0	40.528	0	0	0	0	0	0	-40.528	
6	-6.913	-1.119	-0.780	9.153	0	6.913	1.119	0.780	-7.855	-0.925	-0.372	0	
7	-1.119	-6.668	-1.119	9.231	0	1.119	6.668	1.119	-0.925	-7.381	-0.925	0	
8	-0.780	-1.119	-6.913	9.153	0	0.780	1.119	6.913	-0.372	-0.925	-7.855	0	
9	7.855	0.925	0.372	-9.569	0	-7.855	-0.925	-0.372	10.695	-0.730	-0.396	0	
10	0.925	7.381	0.925	-9.508	0	-0.925	-7.381	-0.925	-0.730	10.968	-0.730	0	
11	0.372	0.925	7.855	-9.569	0	-0.372	-0.925	-7.855	-0.396	-0.730	10.695	0	
12	0	0	0	0	-40.528	0	0	0	0	0	0	40.528	
…													

Cross-bonded minor section 1:

Values to be added to the imaginary part of the total node admittance matrix (values in 1/Ω)

	1	2	3	4	5	6	7	8	9	10	11	12	…
1	-7.824	2.235	1.031	3.618	0	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0	
2	2.235	-8.840	2.235	3.706	0	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0	
3	1.031	2.235	-7.824	3.618	0	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0	
4	3.618	3.706	3.618	-11.990	0	-3.618	-3.706	-3.618	3.989	4.012	3.989	0	
5	0	0	0	0	0	0	0	0	0	0	0	0	
6	7.824	-2.235	-1.031	-3.618	0	-7.824	2.235	1.031	1.961	1.041	0.616	0	
7	-2.235	8.840	-2.235	-3.706	0	2.235	-8.840	2.235	1.041	1.624	1.041	0	
8	-1.031	-2.235	7.824	-3.618	0	1.031	2.235	-7.824	0.616	1.041	1.961	0	
9	-1.961	-1.041	-0.616	3.989	0	1.961	1.041	0.616	-3.660	-0.264	-0.065	0	
10	-1.041	-1.624	-1.041	4.012	0	1.041	1.624	1.041	-0.264	-3.484	-0.264	0	
11	-0.616	-1.041	-1.961	3.989	0	0.616	1.041	1.961	-0.065	-0.264	-3.660	0	
12	0	0	0	0	0	0	0	0	0	0	0	0	
…													

<u>Cross-bonded minor section 2</u>:

Values to be added to the <u>real part</u> of the total node admittance matrix (values in 1/Ω)

	…	6	7	8	9	10	11	12	13	14	15	16	17	18	19	…
…																
6		6.913	1.119	0.780	-0.925	-0.372	-7.855	0	-6.913	-1.119	-0.780	7.855	0.925	0.372	0	
7		1.119	6.668	1.119	-7.381	-0.925	-0.925	0	-1.119	-6.668	-1.119	0.925	7.381	0.925	0	
8		0.780	1.119	6.913	-0.925	-7.855	-0.372	0	-0.780	-1.119	-6.913	0.372	0.925	7.855	0	
9		-0.925	-7.381	-0.925	10.968	-0.730	-0.730	0	0.925	7.381	0.925	0.730	-10.968	0.730	0	
10		-0.372	-0.925	-7.855	-0.730	10.695	-0.396	0	0.372	0.925	7.855	0.396	0.730	-10.695	0	
11		-7.855	-0.925	-0.372	-0.730	-0.396	10.695	0	7.855	0.925	0.372	-10.695	0.730	0.396	0	
12		0	0	0	0	0	0	40.528	0	0	0	0	0	0	-40.528	
13		-6.913	-1.119	-0.780	0.925	0.372	7.855	0	6.913	1.119	0.780	-7.855	-0.925	-0.372	0	
14		-1.119	-6.668	-1.119	7.381	0.925	0.925	0	1.119	6.668	1.119	-0.925	-7.381	-0.925	0	
15		-0.780	-1.119	-6.913	0.925	7.855	0.372	0	0.780	1.119	6.913	-0.372	-0.925	-7.855	0	
16		7.855	0.925	0.372	0.730	0.396	-10.695	0	-7.855	-0.925	-0.372	10.695	-0.730	-0.396	0	
17		0.925	7.381	0.925	-10.968	0.730	0.730	0	-0.925	-7.381	-0.925	-0.730	10.968	-0.730	0	
18		0.372	0.925	7.855	0.730	-10.695	0.396	0	-0.372	-0.925	-7.855	-0.396	-0.730	10.695	0	
19		0	0	0	0	0	0	-40.528	0	0	0	0	0	0	40.528	
…																

<u>Cross-bonded minor section 2</u>:

Values to be added to the <u>imaginary part</u> of the total node admittance matrix (values in 1/Ω)

	…	6	7	8	9	10	11	12	13	14	15	16	17	18	19	…
…																
6		-7.824	2.235	1.031	1.041	0.616	1.961	0	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0	
7		2.235	-8.840	2.235	1.624	1.041	1.041	0	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0	
8		1.031	2.235	-7.824	1.041	1.961	0.616	0	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0	
9		1.041	1.624	1.041	-3.484	-0.264	-0.264	0	-1.041	-1.624	-1.041	0.264	3.484	0.264	0	
10		0.616	1.041	1.961	-0.264	-3.660	-0.065	0	-0.616	-1.041	-1.961	0.065	0.264	3.660	0	
11		1.961	1.041	0.616	-0.264	-0.065	-3.660	0	-1.961	-1.041	-0.616	3.660	0.264	0.065	0	
12		0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13		7.824	-2.235	-1.031	-1.041	-0.616	-1.961	0	-7.824	2.235	1.031	1.961	1.041	0.616	0	
14		-2.235	8.840	-2.235	-1.624	-1.041	-1.041	0	2.235	-8.840	2.235	1.041	1.624	1.041	0	
15		-1.031	-2.235	7.824	-1.041	-1.961	-0.616	0	1.031	2.235	-7.824	0.616	1.041	1.961	0	
16		-1.961	-1.041	-0.616	0.264	0.065	3.660	0	1.961	1.041	0.616	-3.660	-0.264	-0.065	0	
17		-1.041	-1.624	-1.041	3.484	0.264	0.264	0	1.041	1.624	1.041	-0.264	-3.484	-0.264	0	
18		-0.616	-1.041	-1.961	0.264	3.660	0.065	0	0.616	1.041	1.961	-0.065	-0.264	-3.660	0	
19		0	0	0	0	0	0	0	0	0	0	0	0	0	0	
…																

Cross-bonded minor section 3:

Values to be added to the real part of the total node admittance matrix (values in 1/Ω)

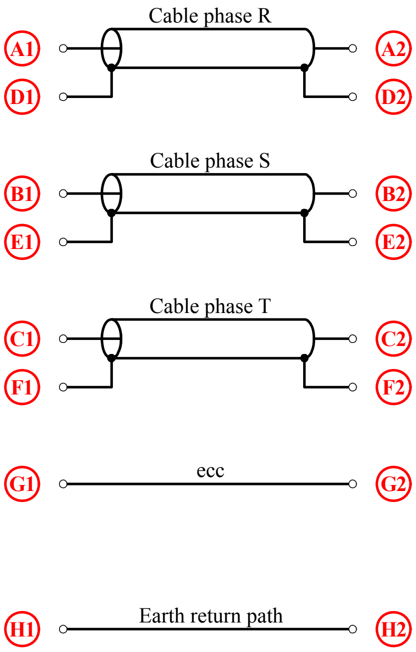
	…	13	14	15	16	17	18	19	20	21	22	…	26	27	…
…															
13		6.913	1.119	0.780	-0.925	-0.372	-7.855	0	-6.913	-1.119	-0.780		9.153	0	
14		1.119	6.668	1.119	-7.381	-0.925	-0.925	0	-1.119	-6.668	-1.119		9.231	0	
15		0.780	1.119	6.913	-0.925	-7.855	-0.372	0	-0.780	-1.119	-6.913		9.153	0	
16		-0.925	-7.381	-0.925	10.968	-0.730	-0.730	0	0.925	7.381	0.925		-9.508	0	
17		-0.372	-0.925	-7.855	-0.730	10.695	-0.396	0	0.372	0.925	7.855		-9.569	0	
18		-7.855	-0.925	-0.372	-0.730	-0.396	10.695	0	7.855	0.925	0.372		-9.569	0	
19		0	0	0	0	0	0	40.528	0	0	0		0	-40.528	
20		-6.913	-1.119	-0.780	0.925	0.372	7.855	0	6.913	1.119	0.780		-9.153	0	
21		-1.119	-6.668	-1.119	7.381	0.925	0.925	0	1.119	6.668	1.119		-9.231	0	
22		-0.780	-1.119	-6.913	0.925	7.855	0.372	0	0.780	1.119	6.913		-9.153	0	
…															
26		9.153	9.231	9.153	-9.508	-9.569	-9.569	0	-9.153	-9.231	-9.153		28.646	0	
27		0	0	0	0	0	0	-40.528	0	0	0		0	40.528	
…															

Cross-bonded minor section 3:

Values to be added to the imaginary part of the total node admittance matrix (values in 1/Ω)

	…	13	14	15	16	17	18	19	20	21	22	…	26	27	…
…															
13		-7.824	2.235	1.031	1.041	0.616	1.961	0	7.824	-2.235	-1.031		-3.618	0	
14		2.235	-8.840	2.235	1.624	1.041	1.041	0	-2.235	8.840	-2.235		-3.706	0	
15		1.031	2.235	-7.824	1.041	1.961	0.616	0	-1.031	-2.235	7.824		-3.618	0	
16		1.041	1.624	1.041	-3.484	-0.264	-0.264	0	-1.041	-1.624	-1.041		4.012	0	
17		0.616	1.041	1.961	-0.264	-3.660	-0.065	0	-0.616	-1.041	-1.961		3.989	0	
18		1.961	1.041	0.616	-0.264	-0.065	-3.660	0	-1.961	-1.041	-0.616		3.989	0	
19		0	0	0	0	0	0	0	0	0	0		0	0	
20		7.824	-2.235	-1.031	-1.041	-0.616	-1.961	0	-7.824	2.235	1.031		3.618	0	
21		-2.235	8.840	-2.235	-1.624	-1.041	-1.041	0	2.235	-8.840	2.235		3.706	0	
22		-1.031	-2.235	7.824	-1.041	-1.961	-0.616	0	1.031	2.235	-7.824		3.618	0	
…															
26		-3.618	-3.706	-3.618	4.012	3.989	3.989	0	3.618	3.706	3.618		-11.990	0	
27		0	0	0	0	0	0	0	0	0	0		0	0	
…															

Partial node admittance matrix for single point bonded section



Node	
A1	Left side conductor R
B1	Left side conductor S
C1	Left side conductor T
D1	Left side screen R
E1	Left side screen S
F1	Left side screen T
G1	Left side ecc
H1	Left side earth return path

Node	
A2	Right side conductor R
B2	Right side conductor S
C2	Right side conductor T
D2	Right side screen R
E2	Right side screen S
F2	Right side screen T
G2	Right side ecc
H2	Right side earth return path

Fig. A.2: Schematic of single point bonded section of the cable circuit

The matrices are built up in the same way as demonstrated above for the cross-bonded sections. Because the position of the ecc changes within both parts of that section, the reactances have to be calculated as the sum of the separately calculated reactances of both parts.

Mean geometric distances part 1 (values in m):

	Cond. R	**Cond. S**	**Cond. T**	**Screen R**	**Screen S**	**Screen T**	**ecc**	**Fict. EC**
Cond. R	0.0135	0.2500	0.5000	0.0463	0.2500	0.5000	0.0750	931.09
Cond. S	0.2500	0.0135	0.2500	0.2500	0.0463	0.2500	0.1750	931.09
Cond. T	0.5000	0.2500	0.0135	0.5000	0.2500	0.0463	0.4250	931.09
Screen R	0.0463	0.2500	0.5000	0.0463	0.2500	0.5000	0.0750	931.09
Screen S	0.2500	0.0463	0.2500	0.2500	0.0463	0.2500	0.1750	931.09
Screen T	0.5000	0.2500	0.0463	0.5000	0.2500	0.0463	0.4250	931.09
ecc	0.0750	0.1750	0.4250	0.0750	0.1750	0.4250	0.0072	931.09
Fict. EC	931.09	931.09	931.09	931.09	931.09	931.09	931.09	931.09

Mean geometric distances part 2 (values in m):

	Cond. R	**Cond. S**	**Cond. T**	**Screen R**	**Screen S**	**Screen T**	**ecc**	**Fict. EC**
Cond. R	0.0135	0.2500	0.5000	0.0463	0.2500	0.5000	0.4250	931.09
Cond. S	0.2500	0.0135	0.2500	0.2500	0.0463	0.2500	0.1750	931.09
Cond. T	0.5000	0.2500	0.0135	0.5000	0.2500	0.0463	0.0750	931.09
Screen R	0.0463	0.2500	0.5000	0.0463	0.2500	0.5000	0.4250	931.09
Screen S	0.2500	0.0463	0.2500	0.2500	0.0463	0.2500	0.1750	931.09
Screen T	0.5000	0.2500	0.0463	0.5000	0.2500	0.0463	0.0750	931.09
ecc	0.4250	0.1750	0.0750	0.4250	0.1750	0.0750	0.0072	931.09
Fict. EC	931.09	931.09	931.09	931.09	931.09	931.09	931.09	931.09

(Z_r) - Impedance matrix (whole single point bonded section), real part (values in Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	ecc	Fict. EC
Cond. R	0.0155	0	0	0	0	0	0	0
Cond. S	0	0.0155	0	0	0	0	0	0
Cond. T	0	0	0.0155	0	0	0	0	0
Screen R	0	0	0	0.0750	0	0	0	0
Screen S	0	0	0	0	0.0750	0	0	0
Screen T	0	0	0	0	0	0.0750	0	0
ecc	0	0	0	0	0	0	0.0449	0
Fict. EC	0	0	0	0	0	0	0	0.0247

(Z_i) - Impedance matrix (whole single point bonded section), imaginary part (values in Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	ecc	Fict. EC
Cond. R	0.3501	0.2583	0.2365	0.3113	0.2583	0.2365	0.2689	0
Cond. S	0.2583	0.3501	0.2583	0.2583	0.3113	0.2583	0.2695	0
Cond. T	0.2365	0.2583	0.3501	0.2365	0.2583	0.3113	0.2689	0
Screen R	0.3113	0.2583	0.2365	0.3113	0.2583	0.2365	0.2689	0
Screen S	0.2583	0.3113	0.2583	0.2583	0.3113	0.2583	0.2695	0
Screen T	0.2365	0.2583	0.3113	0.2365	0.2583	0.3113	0.2689	0
ecc	0.2689	0.2695	0.2689	0.2689	0.2695	0.2689	0.3699	0
Fict. EC	0	0	0	0	0	0	0	0

The impedance (Z) matrix is inverted in order to get the admittance matrix (Y):

(Y_r) - Admittance matrix, real part (values in 1/Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	ecc	Fict. EC
Cond. R	6.7625	0.9628	0.6287	-7.5932	-0.7413	-0.1102	-0.1997	0
Cond. S	0.9628	6.5194	0.9628	-0.7413	-7.2534	-0.7413	0.0101	0
Cond. T	0.6287	0.9628	6.7625	-0.1102	-0.7413	-7.5932	-0.1997	0
Screen R	-7.5932	-0.7413	-0.1102	10.8504	-0.6054	-0.2408	-1.1736	0
Screen S	-0.7413	-7.2534	-0.7413	-0.6054	11.0663	-0.6054	-0.8628	0
Screen T	-0.1102	-0.7413	-7.5932	-0.2408	-0.6054	10.8504	-1.1736	0
ecc	-0.1997	0.0101	-0.1997	-1.1736	-0.8628	-1.1736	3.5196	0
Fict. EC	0	0	0	0	0	0	0	40.5285

(Y_i) - Admittance matrix, imaginary part (values in 1/Ω)

	Cond. R	Cond. S	Cond. T	Screen R	Screen S	Screen T	ecc	Fict. EC
Cond. R	-8.3911	1.8169	0.4641	1.7655	0.8738	0.4213	2.1880	0
Cond. S	1.8169	-9.1448	1.8169	0.8738	1.4840	0.8738	1.6713	0
Cond. T	0.4641	1.8169	-8.3911	0.4213	0.8738	1.7655	2.1880	0
Screen R	1.7655	0.8738	0.4213	-3.5647	-0.2030	0.0300	0.3488	0
Screen S	0.8738	1.4840	0.8738	-0.2030	-3.4471	-0.2030	0.3506	0
Screen T	0.4213	0.8738	1.7655	0.0300	-0.2030	-3.5647	0.3488	0
ecc	2.1880	1.6713	2.1880	0.3488	0.3506	0.3488	-7.4379	0
Fict. EC	0	0	0	0	0	0	0	0

The partial node admittance matrix for the single point bonded cable circuit section therefore is

Partial node admittance matrix, real part (values in 1/Ω)

	A1	B1	C1	D1	E1	F1	G1	H1	A2	B2	C2	D2	E2	F2	G2	H2
A1	6.762	0.963	0.629	-7.593	-0.741	-0.110	-0.200	0	-6.762	-0.963	-0.629	7.593	0.741	0.110	0.200	0
B1	0.963	6.519	0.963	-0.741	-7.253	-0.741	0.010	0	-0.963	-6.519	-0.963	0.741	7.253	0.741	-0.010	0
C1	0.629	0.963	6.762	-0.110	-0.741	-7.593	-0.200	0	-0.629	-0.963	-6.762	0.110	0.741	7.593	0.200	0
D1	-7.593	-0.741	-0.110	10.850	-0.605	-0.241	-1.174	0	7.593	0.741	0.110	-10.850	0.605	0.241	1.174	0
E1	-0.741	-7.253	-0.741	-0.605	11.066	-0.605	-0.863	0	0.741	7.253	0.741	0.605	-11.066	0.605	0.863	0
F1	-0.110	-0.741	-7.593	-0.241	-0.605	10.850	-1.174	0	0.110	0.741	7.593	0.241	0.605	-10.850	1.174	0
G1	-0.200	0.010	-0.200	-1.174	-0.863	-1.174	3.520	0	0.200	-0.010	0.200	1.174	0.863	1.174	-3.520	0
H1	0	0	0	0	0	0	0	40.528	0	0	0	0	0	0	0	-40.528
A2	-6.762	-0.963	-0.629	7.593	0.741	0.110	0.200	0	6.762	0.963	0.629	-7.593	-0.741	-0.110	-0.200	0
B2	-0.963	-6.519	-0.963	0.741	7.253	0.741	-0.010	0	0.963	6.519	0.963	-0.741	-7.253	-0.741	0.010	0
C2	-0.629	-0.963	-6.762	0.110	0.741	7.593	0.200	0	0.629	0.963	6.762	-0.110	-0.741	-7.593	-0.200	0
D2	7.593	0.741	0.110	-10.850	0.605	0.241	1.174	0	-7.593	-0.741	-0.110	10.850	-0.605	-0.241	-1.174	0
E2	0.741	7.253	0.741	0.605	-11.066	0.605	0.863	0	-0.741	-7.253	-0.741	-0.605	11.066	-0.605	-0.863	0
F2	0.110	0.741	7.593	0.241	0.605	-10.850	1.174	0	-0.110	-0.741	-7.593	-0.241	-0.605	10.850	-1.174	0
G2	0.200	-0.010	0.200	1.174	0.863	1.174	-3.520	0	-0.200	0.010	-0.200	-1.174	-0.863	-1.174	3.520	0
H2	0	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	0	40.528

Partial node admittance matrix, imaginary part (values in 1/Ω)

	A1	B1	C1	D1	E1	F1	G1	H1	A2	B2	C2	D2	E2	F2	G2	H2
A1	-8.391	1.817	0.464	1.766	0.874	0.421	2.188	0	8.391	-1.817	-0.464	-1.766	-0.874	-0.421	-2.188	0
B1	1.817	-9.145	1.817	0.874	1.484	0.874	1.671	0	-1.817	9.145	-1.817	-0.874	-1.484	-0.874	-1.671	0
C1	0.464	1.817	-8.391	0.421	0.874	1.766	2.188	0	-0.464	-1.817	8.391	-0.421	-0.874	-1.766	-2.188	0
D1	1.766	0.874	0.421	-3.565	-0.203	0.030	0.349	0	-1.766	-0.874	-0.421	3.565	0.203	-0.030	-0.349	0
E1	0.874	1.484	0.874	-0.203	-3.447	-0.203	0.351	0	-0.874	-1.484	-0.874	0.203	3.447	0.203	-0.351	0
F1	0.421	0.874	1.766	0.030	-0.203	-3.565	0.349	0	-0.421	-0.874	-1.766	-0.030	0.203	3.565	-0.349	0
G1	2.188	1.671	2.188	0.349	0.351	0.349	-7.438	0	-2.188	-1.671	-2.188	-0.349	-0.351	-0.349	7.438	0
H1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	8.391	-1.817	-0.464	-1.766	-0.874	-0.421	-2.188	0	-8.391	1.817	0.464	1.766	0.874	0.421	2.188	0
B2	-1.817	9.145	-1.817	-0.874	-1.484	-0.874	-1.671	0	1.817	-9.145	1.817	0.874	1.484	0.874	1.671	0
C2	-0.464	-1.817	8.391	-0.421	-0.874	-1.766	-2.188	0	0.464	1.817	-8.391	0.421	0.874	1.766	2.188	0
D2	-1.766	-0.874	-0.421	3.565	0.203	-0.030	-0.349	0	1.766	0.874	0.421	-3.565	-0.203	0.030	0.349	0
E2	-0.874	-1.484	-0.874	0.203	3.447	0.203	-0.351	0	0.874	1.484	0.874	-0.203	-3.447	-0.203	0.351	0
F2	-0.421	-0.874	-1.766	-0.030	0.203	3.565	-0.349	0	0.421	0.874	1.766	0.030	-0.203	-3.565	0.349	0
G2	-2.188	-1.671	-2.188	-0.349	-0.351	-0.349	7.438	0	2.188	1.671	2.188	0.349	0.351	0.349	-7.438	0
H2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Analogous to the procedure for cross-bonded sections, the partial node admittance matrix of the single point bonded section has to be added to the total node admittance matrix of the whole cable circuit at the positions of the corresponding nodes:

Single point bonded section:

Values to be added to the real part of the total node admittance matrix (values in 1/Ω)

	…	20	21	22	23	24	25	26	27	28	29
…											
20		6.762	0.963	0.629	-7.593	-0.741	-0.110	-0.200	0	0.290	0
21		0.963	6.519	0.963	-0.741	-7.253	-0.741	0.010	0	0.281	0
22		0.629	0.963	6.762	-0.110	-0.741	-7.593	-0.200	0	0.290	0
23		-7.593	-0.741	-0.110	10.850	-0.605	-0.241	-1.174	0	-0.386	0
24		-0.741	-7.253	-0.741	-0.605	11.066	-0.605	-0.863	0	-0.257	0
25		-0.110	-0.741	-7.593	-0.241	-0.605	10.850	-1.174	0	-0.386	0
26		-0.200	0.010	-0.200	-1.174	-0.863	-1.174	3.520	0	0.080	0
27		0	0	0	0	0	0	0	40.528	0	-40.528
28		0.290	0.281	0.290	-0.386	-0.257	-0.386	0.080	0	0.087	0
29		0	0	0	0	0	0	0	-40.528	0	40.528

Single point bonded section:

Values to be added to the imaginary part of the total node admittance matrix (values in 1/Ω)

	…	20	21	22	23	24	25	26	27	28	29
…											
20		-8.391	1.817	0.464	1.766	0.874	0.421	2.188	0	0.862	0
21		1.817	-9.145	1.817	0.874	1.484	0.874	1.671	0	0.608	0
22		0.464	1.817	-8.391	0.421	0.874	1.766	2.188	0	0.862	0
23		1.766	0.874	0.421	-3.565	-0.203	0.030	0.349	0	0.328	0
24		0.874	1.484	0.874	-0.203	-3.447	-0.203	0.351	0	0.271	0
25		0.421	0.874	1.766	0.030	-0.203	-3.565	0.349	0	0.328	0
26		2.188	1.671	2.188	0.349	0.351	0.349	-7.438	0	0.342	0
27		0	0	0	0	0	0	0	0	0	0
28		0.862	0.608	0.862	0.328	0.271	0.328	0.342	0	-3.602	0
29		0	0	0	0	0	0	0	0	0	0

Partial node admittance matrix for earthing impedances

The remaining passive elements of the circuit are the three earthing impedances $\underline{Z}_{E1}$, $\underline{Z}_{E2}$ and $\underline{Z}_{E3}$. They are added to the total node admittance matrix in form of their reciprocals to the appropriate nodes as follows:

$\underline{Z}_{E1} = (0.5 + j\ 0.0)\ \Omega$ $\underline{Y}_{E1} = (2.0 + j\ 0.0)\ \Omega^{-1}$ between nodes 4 and 5
$\underline{Z}_{E2} = (0.2 + j\ 0.0)\ \Omega$ $\underline{Y}_{E2} = (5.0 + j\ 0.0)\ \Omega^{-1}$ between nodes 28 and 29
$\underline{Z}_{E3} = (5.0 + j\ 0.0)\ \Omega$ $\underline{Y}_{E3} = (0.2 + j\ 0.0)\ \Omega^{-1}$ between nodes 26 and 27

Since in the particular example the imaginary part of all earthing impedances is equal to zero, no values have to be added to the imaginary part of the total node admittance matrix.

The real part of the values to be added to the total node admittance matrix is therefore:

Earthing impedances:

Values to be added to the real part of the total node admittance matrix (values in 1/Ω)

	…	4	5	…	26	27	28	29
…								
4		2.000	-2.000					
5		-2.000	2.000					
…								
26					0.200	-0.200		
27					-0.200	0.200		
28							5.000	-5.000
29							-5.000	5.000

Total node admittance matrix for the whole cable circuit

Real part of the total node admittance matrix (values in 1/Ω)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	6.913	1.119	0.780	-9.153	0	-6.913	-1.119	-0.780	7.855	0.925	0.372	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1.119	6.668	1.119	-9.231	0	-1.119	-6.668	-1.119	0.925	7.381	0.925	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.780	1.119	6.913	-9.153	0	-0.780	-1.119	-6.913	0.372	0.925	7.855	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	-9.153	-9.231	-9.153	30.646	-2.000	9.153	9.231	9.153	-9.569	-9.508	-9.569	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	-2.000	42.528	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	-6.913	-1.119	-0.780	9.153	0	13.826	2.238	1.559	-8.781	-1.298	-8.228	0	-6.913	-1.119	-0.780	7.855	0.925	0.372	0	0	0	0	0	0	0	0	0	0	0
7	-1.119	-6.668	-1.119	9.231	0	2.238	13.337	2.238	-8.306	-8.306	-1.851	0	-1.119	-6.668	-1.119	0.925	7.381	0.925	0	0	0	0	0	0	0	0	0	0	0
8	-0.780	-1.119	-6.913	9.153	0	1.559	2.238	13.826	-1.298	-8.781	-8.228	0	-0.780	-1.119	-6.913	0.372	0.925	7.855	0	0	0	0	0	0	0	0	0	0	0
9	7.855	0.925	0.372	-9.569	0	-8.781	-8.306	-1.298	21.663	-1.460	-1.126	0	0.925	7.381	0.925	0.730	-10.968	0.730	0	0	0	0	0	0	0	0	0	0	0
10	0.925	7.381	0.925	-9.508	0	-1.298	-8.306	-8.781	-1.460	21.663	-1.126	0	0.372	0.925	7.855	0.396	0.730	-10.695	0	0	0	0	0	0	0	0	0	0	0
11	0.372	0.925	7.855	-9.569	0	-8.228	-1.851	-8.228	-1.126	-1.126	21.390	0	7.855	0.925	0.372	-10.695	0.730	0.396	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	-40.528	0	0	0	0	0	0	81.057	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	-6.913	-1.119	-0.780	0.925	0.372	7.855	0	13.826	2.238	1.559	-8.781	-1.298	-8.228	0	-6.913	-1.119	-0.780	0	0	0	9.153	0	0	0
14	0	0	0	0	0	-1.119	-6.668	-1.119	7.381	0.925	0.925	0	2.238	13.337	2.238	-8.306	-8.306	-1.851	0	-1.119	-6.668	-1.119	0	0	0	9.231	0	0	0
15	0	0	0	0	0	-0.780	-1.119	-6.913	0.925	7.855	0.372	0	1.559	2.238	13.826	-1.298	-8.781	-8.228	0	-0.780	-1.119	-6.913	0	0	0	9.153	0	0	0
16	0	0	0	0	0	7.855	0.925	0.372	0.730	0.396	-10.695	0	-8.781	-8.306	-1.298	21.663	-1.460	-1.126	0	0.925	7.381	0.925	0	0	0	-9.508	0	0	0
17	0	0	0	0	0	0.925	7.381	0.925	-10.968	0.730	0.730	0	-1.298	-8.306	-8.781	-1.460	21.663	-1.126	0	0.372	0.925	7.855	0	0	0	-9.569	0	0	0
18	0	0	0	0	0	0.372	0.925	7.855	0.730	-10.695	0.396	0	-8.228	-1.851	-8.228	-1.126	-1.126	21.390	0	7.855	0.925	0.372	0	0	0	-9.569	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	81.057	0	0	0	0	0	0	0	-40.528	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	-6.913	-1.119	-0.780	0.925	0.372	7.855	0	13.676	2.082	1.408	-7.593	-0.741	-0.110	-9.353	0	0.290	0
21	0	0	0	0	0	0	0	0	0	0	0	0	-1.119	-6.668	-1.119	7.381	0.925	0.925	0	2.082	13.188	2.082	-0.741	-7.253	-0.741	-9.221	0	0.281	0
22	0	0	0	0	0	0	0	0	0	0	0	0	-0.780	-1.119	-6.913	0.925	7.855	0.372	0	1.408	2.082	13.676	-0.110	-0.741	-7.593	-9.353	0	0.290	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-7.593	-0.741	-0.110	10.850	-0.605	-0.241	-1.174	0	-0.386	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.741	-7.253	-0.741	-0.605	11.066	-0.605	-0.863	0	-0.257	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.110	-0.741	-7.593	-0.241	-0.605	10.850	-1.174	0	-0.386	0
26	0	0	0	0	0	0	0	0	0	0	0	0	9.153	9.231	9.153	-9.508	-9.569	-9.569	0	-9.353	-9.221	-9.353	-1.174	-0.863	-1.174	32.366	-0.200	0.080	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-40.528	0	0	0	0	0	0	-0.200	81.257	0	-40.528
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.290	0.281	0.290	-0.386	-0.257	-0.386	0.080	0	5.087	-5.000
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-40.528	-5.000	45.528

Imaginary part of the total node admittance matrix (values in 1/Ω)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	-7.824	2.235	1.031	3.618	0	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2.235	-8.840	2.235	3.706	0	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1.031	2.235	-7.824	3.618	0	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	3.618	3.706	3.618	-11.990	0	-3.618	-3.706	-3.618	3.989	4.012	3.989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	7.824	-2.235	-1.031	-3.618	0	-15.648	4.470	2.062	3.002	1.657	2.577	0	7.824	-2.235	-1.031	-1.961	-1.041	-0.616	0	0	0	0	0	0	0	0	0	0	0
7	-2.235	8.840	-2.235	-3.706	0	4.470	-17.679	4.470	2.665	2.665	2.082	0	-2.235	8.840	-2.235	-1.041	-1.624	-1.041	0	0	0	0	0	0	0	0	0	0	0
8	-1.031	-2.235	7.824	-3.618	0	2.062	4.470	-15.648	1.657	3.002	2.577	0	-1.031	-2.235	7.824	-0.616	-1.041	-1.961	0	0	0	0	0	0	0	0	0	0	0
9	-1.961	-1.041	-0.616	3.989	0	3.002	2.665	1.657	-7.144	-0.528	-0.329	0	-1.041	-1.624	-1.041	0.264	3.484	0.264	0	0	0	0	0	0	0	0	0	0	0
10	-1.041	-1.624	-1.041	4.012	0	1.657	2.665	3.002	-0.528	-7.144	-0.329	0	-0.616	-1.041	-1.961	0.065	0.264	3.660	0	0	0	0	0	0	0	0	0	0	0
11	-0.616	-1.041	-1.961	3.989	0	2.577	2.082	2.577	-0.329	-0.329	-7.320	0	-1.961	-1.041	-0.616	3.660	0.264	0.065	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	7.824	-2.235	-1.031	-1.041	-0.616	-1.961	0	-15.648	4.470	2.062	3.002	1.657	2.577	0	7.824	-2.235	-1.031	0	0	0	-3.618	0	0	0
14	0	0	0	0	0	-2.235	8.840	-2.235	-1.624	-1.041	-1.041	0	4.470	-17.679	4.470	2.665	2.665	2.082	0	-2.235	8.840	-2.235	0	0	0	-3.706	0	0	0
15	0	0	0	0	0	-1.031	-2.235	7.824	-1.041	-1.961	-0.616	0	2.062	4.470	-15.648	1.657	3.002	2.577	0	-1.031	-2.235	7.824	0	0	0	-3.618	0	0	0
16	0	0	0	0	0	-1.961	-1.041	-0.616	0.264	0.065	3.660	0	3.002	2.665	1.657	-7.144	-0.528	-0.329	0	-1.041	-1.624	-1.041	0	0	0	4.012	0	0	0
17	0	0	0	0	0	-1.041	-1.624	-1.041	3.484	0.264	0.264	0	1.657	2.665	3.002	-0.528	-7.144	-0.329	0	-0.616	-1.041	-1.961	0	0	0	3.989	0	0	0
18	0	0	0	0	0	-0.616	-1.041	-1.961	0.264	3.660	0.065	0	2.577	2.082	2.577	-0.329	-0.329	-7.320	0	-1.961	-1.041	-0.616	0	0	0	3.989	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	7.824	-2.235	-1.031	-1.041	-0.616	-1.961	0	-16.215	4.052	1.495	1.766	0.874	0.421	5.806	0	0.862	0
21	0	0	0	0	0	0	0	0	0	0	0	0	-2.235	8.840	-2.235	-1.624	-1.041	-1.041	0	4.052	-17.984	4.052	0.874	1.484	0.874	5.377	0	0.608	0
22	0	0	0	0	0	0	0	0	0	0	0	0	-1.031	-2.235	7.824	-1.041	-1.961	-0.616	0	1.495	4.052	-16.215	0.421	0.874	1.766	5.806	0	0.862	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.766	0.874	0.421	-3.565	-0.203	0.030	0.349	0	0.328	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.874	1.484	0.874	-0.203	-3.447	-0.203	0.351	0	0.271	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.421	0.874	1.766	0.030	-0.203	-3.565	0.349	0	0.328	0
26	0	0	0	0	0	0	0	0	0	0	0	0	-3.618	-3.706	-3.618	4.012	3.989	3.989	0	5.806	5.377	5.806	0.349	0.351	0.349	-19.428	0	0.342	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.862	0.608	0.862	0.328	0.271	0.328	0.342	0	-3.602	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Total vector of current sources for the whole circuit

For the particular example there is only one current source to be taken into account; the current source representing the injected short circuit current in phase R. The current source has to be placed in the vector of current sources at positions corresponding to node 1 (conductor of phase R in substation 1) and node 4 (local earth of substation 1). The short-circuit current is assumed to be (25.0 + j 0.0) kA.

The total vector of current sources for the whole circuit is therefore (values in kA):

Node	Current [kA]
1	25.0 + j 0.0
2	0.0 + j 0.0
3	0.0 + j 0.0
4	-25.0 + j 0.0
5	0.0 + j 0.0
6	0.0 + j 0.0
7	0.0 + j 0.0
8	0.0 + j 0.0
9	0.0 + j 0.0
10	0.0 + j 0.0
11	0.0 + j 0.0
12	0.0 + j 0.0
13	0.0 + j 0.0
14	0.0 + j 0.0
15	0.0 + j 0.0
16	0.0 + j 0.0
17	0.0 + j 0.0
18	0.0 + j 0.0
19	0.0 + j 0.0
20	0.0 + j 0.0
21	0.0 + j 0.0
22	0.0 + j 0.0
23	0.0 + j 0.0
24	0.0 + j 0.0
25	0.0 + j 0.0
26	0.0 + j 0.0
27	0.0 + j 0.0
28	0.0 + j 0.0
29	0.0 + j 0.0

Solution of the equation system

Prior to the solution of the equation system, one of the nodes has to be selected as reference node. The corresponding row and column then has to be deleted from the total node admittance matrix and from the total vector of the current sources. In the present example, node 4 (representing the local earth potential in substation 1) is selected as the reference node. All subsequently calculated voltages are therefore related to the local earth potential in substation 1.

The calculated vector of node voltages for the present example is (related to node 4, values in kV):

Node	Node voltage [kV]
1	4.198 + j 10.601
2	2.660 + j 0.925
3	2.648 - j 0.752
5	1.319 - j 0.285
6	3.657 + j 7.858
7	2.503 + j 0.638
8	2.495 - j 0.657
9	0.406 - j 1.759
10	0.402 - j 0.273
11	0.406 + j 0.109
12	1.384 - j 0.299
13	3.117 + j 5.115
14	2.346 + j 0.351
15	2.342 - j 0.562
16	0.812 - j 1.649
17	0.808 - j 2.031
18	0.808 - j 0.163
19	1.449 - j 0.313
20	2.576 + j 2.372
21	2.189 + j 0.064
22	2.188 - j 0.467
23	2.188 + j 1.401
24	2.189 + j 0.064
25	2.188 - j 0.467
26	1.214 - j 1.922
27	1.515 - j 0.327
28	2.121 - j 0.384
29	1.581 - j 0.333

From these calculation results all required voltages may be derived as shown in the following table:

	Calculated as:	Voltage [kV]
Earth potential rise		
Substation 1	$\underline{V}_4 - \underline{V}_5$	-1.319 + j 0.285
Substation 2	$\underline{V}_{28} - \underline{V}_{29}$	0.540 - j 0.050
Joint 3	$\underline{V}_{26} - \underline{V}_{27}$	-0.301 - j 1.595
Sheath-to-local-earth-voltages		
CB joint 1, screen R -> S	$\underline{V}_9 - \underline{V}_{12}$	-0.978 - j 1.460
CB joint 1, screen S -> T	$\underline{V}_{10} - \underline{V}_{12}$	-0.983 + j 0.026
CB joint 1, screen T -> R	$\underline{V}_{11} - \underline{V}_{12}$	-0.978 + j 0.408
CB joint 2, screen R -> S	$\underline{V}_{16} - \underline{V}_{19}$	-0.638 - j 1.336
CB joint 2, screen S -> T	$\underline{V}_{17} - \underline{V}_{19}$	-0.642 - j 1.718
CB joint 2, screen T -> R	$\underline{V}_{18} - \underline{V}_{19}$	-0.642 + j 0.150
Joint 3 (single point bonded section), screen R	$\underline{V}_{23} - \underline{V}_{26}$	0.975 + j 3.323
Joint 3 (single point bonded section), screen S	$\underline{V}_{24} - \underline{V}_{26}$	0.975 + j 1.986
Joint 3 (single point bonded section), screen T	$\underline{V}_{25} - \underline{V}_{26}$	0.975 + j 1.455

Note: At cross-bonding joints local earth potential is equal to remote earth potential, because no current is flowing to earth.

A.2 Practical Hints for Handling a Complex Equation System

Electric network calculations often require the inversion of a complex matrix. In the following a method is described which allows to calculate the real and imaginary part of the inverse without the need of complex arithmetic operations. The method is illustrated using the inversion of a complex impedance matrix as an example.

The voltages and currents in an electrical network are linked together via the matrix of impedances. For calculations in the frequency domain all values are complex i.e. they consist of a real part and an imaginary part.

$$(\underline{V}) = (\underline{Z}) \cdot (\underline{I}) \qquad \text{(A.1)}$$

with
- $(\underline{V})$ voltage vector
- $(\underline{I})$ current vector
- $(\underline{Z})$ impedance matrix

The complex values may be expressed as a combination of real and imaginary part as

$$\begin{aligned} (\underline{V}) &= (V_r) + j(V_i) \\ (\underline{Z}) &= (Z_r) + j(Z_i) \\ (\underline{I}) &= (I_r) + j(I_i) \end{aligned} \qquad \text{(A.2), (A3), (A.4)}$$

Therefore

$$(V_r) + j(V_i) = [(Z_r) + j(Z_i)] \cdot [(I_r) + j(I_i)] \qquad \text{(A.5)}$$

$$(V_r) + j(V_i) = (Z_r) \cdot (I_r) - (Z_i) \cdot (I_i) + j[(Z_i) \cdot (I_r) + (Z_r) \cdot (I_i)] \qquad \text{(A.6)}$$

The complex equation system may therefore be transformed into a real one by separation of real and imaginary part.

$$\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} Z_r & -Z_i \\ Z_i & Z_r \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix} \qquad \text{(A.7)}$$

Instead of an equation system with n complex unknowns one gets an equation system with 2n real unknowns. The real vectors (V_r), (V_i), (I_r) and (I_i) are partial vectors of dimension n. The real matrices (Z_r) and (Z_i) are partial matrices of dimension n x n.

Due to its special structure the inversion of that real matrix of dimension 2n can be done by a number of operations with partial matrices of dimension n:

$$\begin{pmatrix} Z_r & -Z_i \\ Z_i & Z_r \end{pmatrix}^{-1} = \begin{pmatrix} Y_r & -Y_i \\ Y_i & Y_r \end{pmatrix} \qquad \text{(A.8)}$$

with

$$(Y_r) = \left[(Z_r) + (Z_i)\cdot(Z_r)^{-1}\cdot(Z_i)\right]^{-1}$$

(A.9), (A10)

$$(Y_i) = -\left[(Z_r) + (Z_i)\cdot(Z_r)^{-1}\cdot(Z_i)\right]^{-1}\cdot(Z_i)\cdot(Z_r)^{-1}$$

For practical reasons it is recommended to calculate first an auxiliary matrix *(A)*:

$$(A) = (Z_i)\cdot(Z_r)^{-1} \qquad \text{(A.11)}$$

The final matrices (Y_r) and (Y_i) are then calculated as

$$(Y_r) = \left[(Z_r) + (A)\cdot(Z_i)\right]^{-1}$$

(A.12), (A.13)

$$(Y_i) = -(Y_r)\cdot(A)$$

B. APPENDIX B : EPR ANALYSIS OF AN ACTUAL CABLE SYSTEM

B.1 General

At the OH/UG (overhead to underground) transition, high EPRs occur due to the difference of the return current between the skywire and the cable sheaths. A similar phenomenon can occur at the transition between a cross bonded cable section and a single point bonded section if the resistance of the ecc is significantly higher than that of the sheaths in parallel. This example looks at the impact of the EPR due to these transitions on voltages appearing on the SVLs protecting the cable sheaths.

B.2 Description of the System

Figure B.1 presents the simplified circuit diagram of the 220 kV system under study. Substations A and E feed the underground system through double circuit overhead lines. The underground system comprises three substations (B, C and D). A single phase to earth fault occurs at substation C which is located 31.8 and 15.8 km respectively from substation A and E.

Figure B.2 presents the main characteristics of the overhead and underground circuits. The skywire on the double circuit overhead line has a resistance of 0.6 Ω/km. The underground cable system uses a cross bonded scheme for all sections except for a 1.2 km single point bounded section connected to substation C. A trefoil configuration with 250 mm between cables is used for all sections except two using a touching trefoil configuration. The ecc on the single point bonded section has a resistance of 0.093 Ω/km.

B.3 Model of the Circuit in EMTP

EMTP is used to model the system. Figure B.3 presents the detailed circuit. A frequency dependant distributed line model is used both for overhead lines and cables. In order to simplify the circuit, only one section is used to model each of the two overhead lines ; the earth resistance at the OH/UG transitions is equivalent to all the tower earth resistances as seen from the transition. A single phase-to-neutral fault is applied on both circuits at substation C.

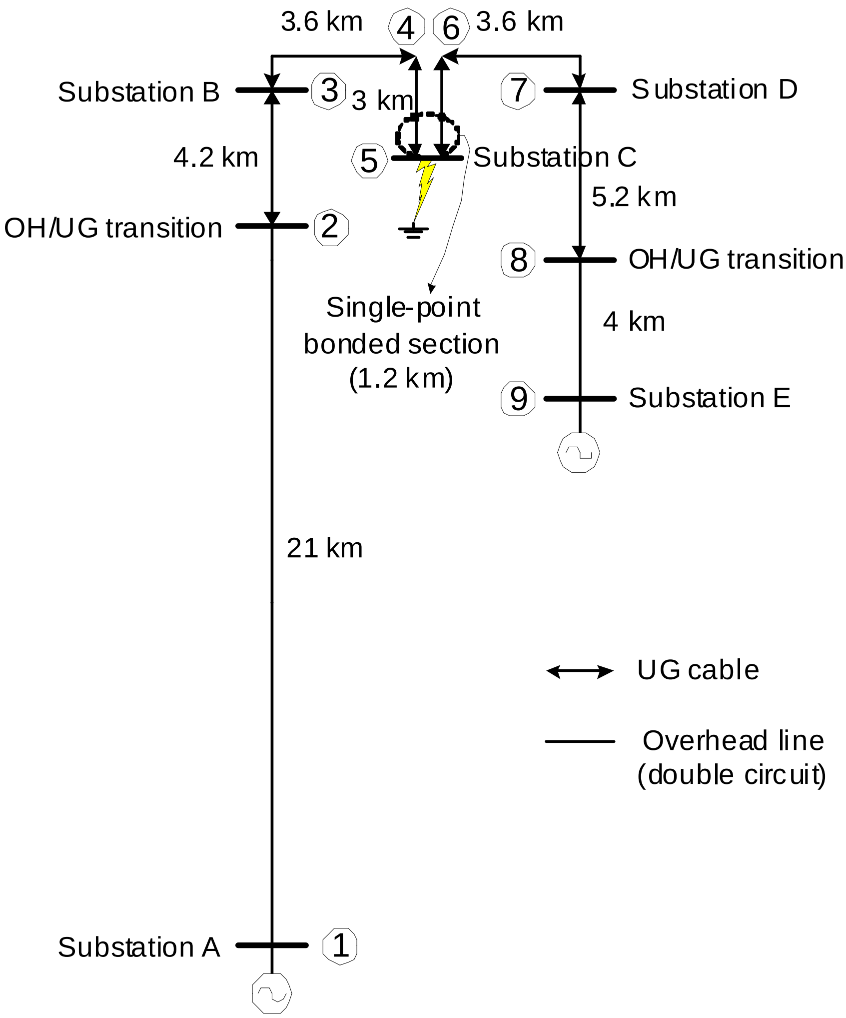


Figure B.1 Simplified Diagram of the 220 kV System Under Study

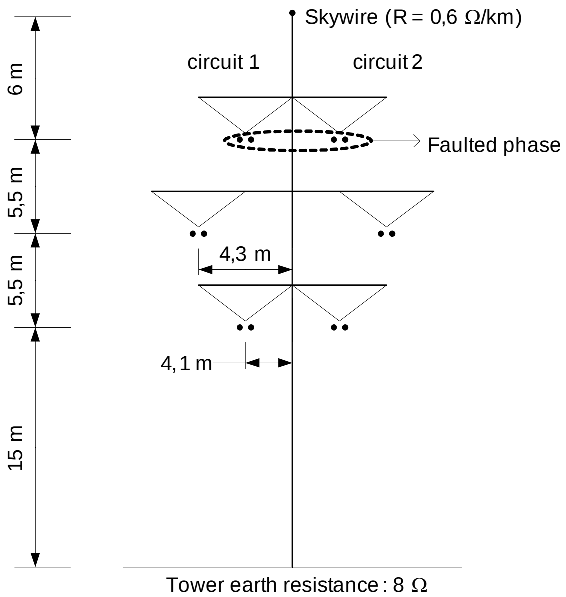
B.4 Analysis of the results

The most significant results are given in figure B.3. The total fault current exceeds 33 kA; the contribution from substations A and E is 8.4 and 25.3 kA respectively.
Figure B.4 presents the EPR along the system. For the reasons given before, the maximum values occur at the OH/UG transitions. The EPR reaches 7 and 16.9 kV at those two transitions. A high EPR value (4.9 kV) is also seen at the transition between cross bonded and single point bonded sections close to substation A on the circuit carrying the highest contribution to the fault current (25.3 kA).

The high EPR values at the transition points are transferred by the cable sheaths to the cross bonding joints. Figure B.5 shows the sheath-to-earth voltages seen at the first cross bonding joint after the UG/OH transition close to substation E. They reach 15 kV, a value very close to the EPR of 16.9 kV at the transition. If the SVL's are connected in a grounded star arrangement, the voltage across each SVL reaches 15 kV at this joint. The following joints also experience high voltages. For example, the sheath-to-earth voltages are 13 kV at the second joint.

SVL's do not have the capability to limit power frequency overvoltages. Their voltage rating should therefore be higher than the 50-Hz voltage during a fault. If this voltage is considered too high, a delta or floating neutral star arrangement can be used.

220 kV double circuit transmission line



220 kV underground cable system

section	Sheath connections
② → ③	3x600 m crossbonded , 2.4 km earthed at both ends
③ → ④	3x600 m crossbonded , 3x600 m crossbonded
④ → ⑤	3x600 m crossbonded , 1200 m single point bonded(1)
⑥ → ⑤	3x600 m crossbonded , 1200 m single point bonded
⑥ → ⑦	3x600 m crossbonded , 3x600 m crossbonded (2)
⑦ → ⑧	3.4 km earthed at both ends , 3x600 m crossbonded

The trefoil configuration with 250 mm between cables is used for all sections except :
(1) for the last 600 m, a touching trefoil configuration is used
(2) for the second 3x600 m section, a touching trefoil configuration is used

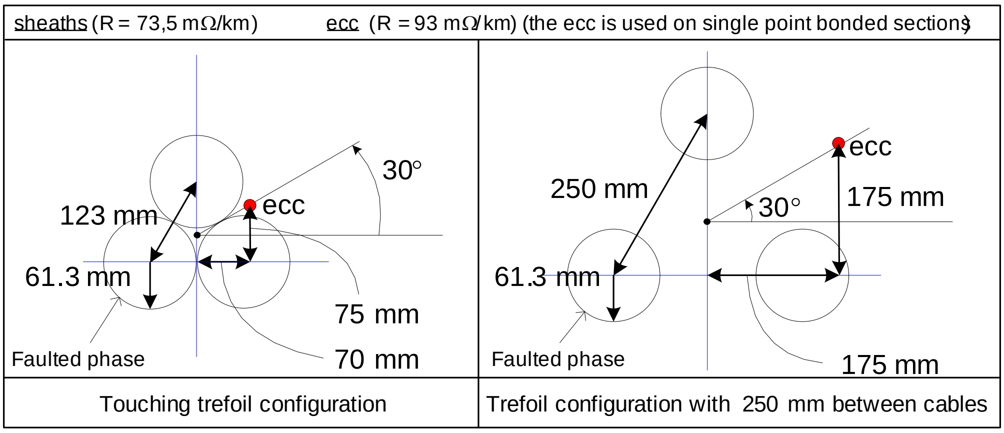


Figure B.2 Characteristics of the Overhead and Underground Circuits

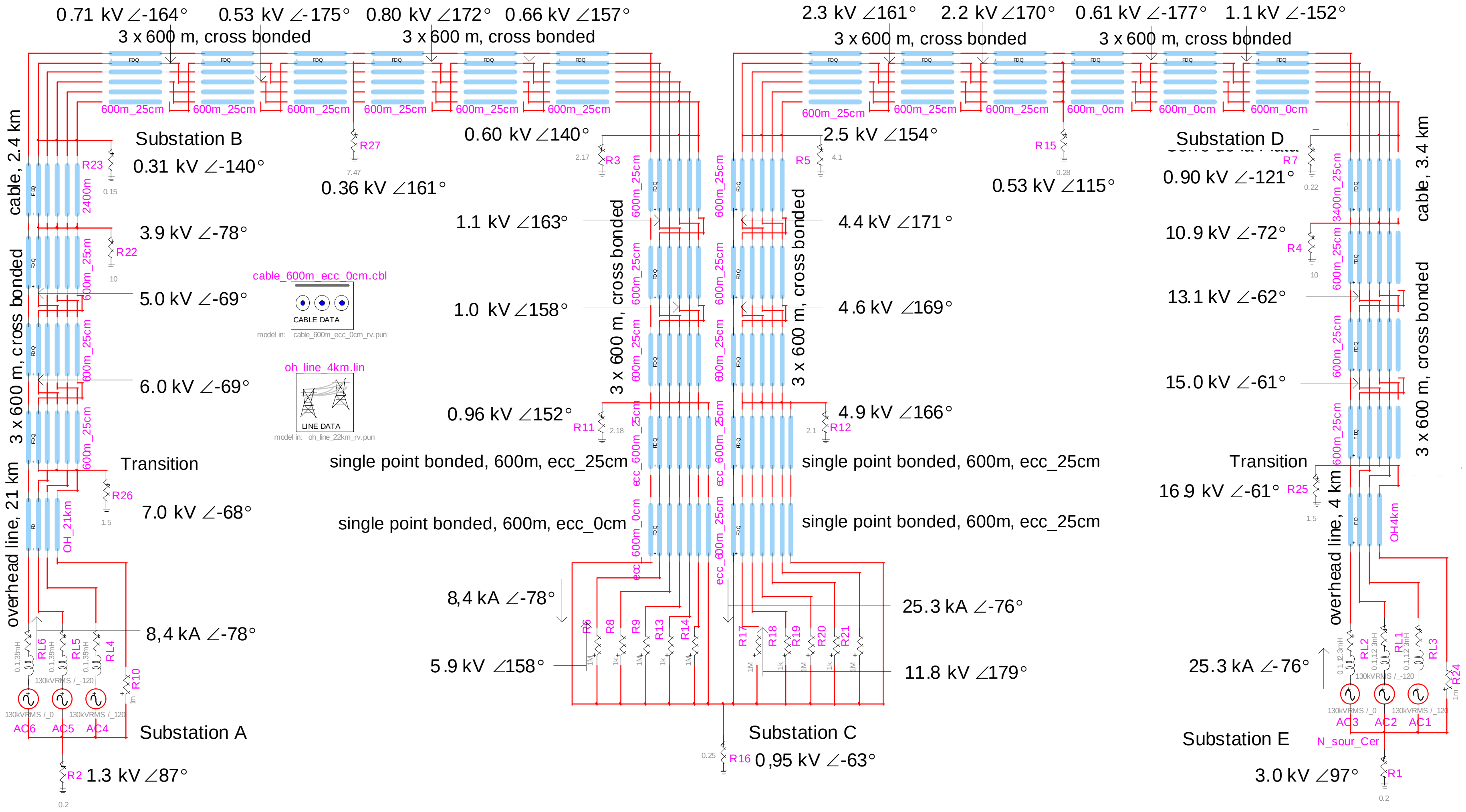


Figure B.3 EMTP circuit and results : EPRs and sheath-to-earth voltages during a phase-to-earth fault at substation C

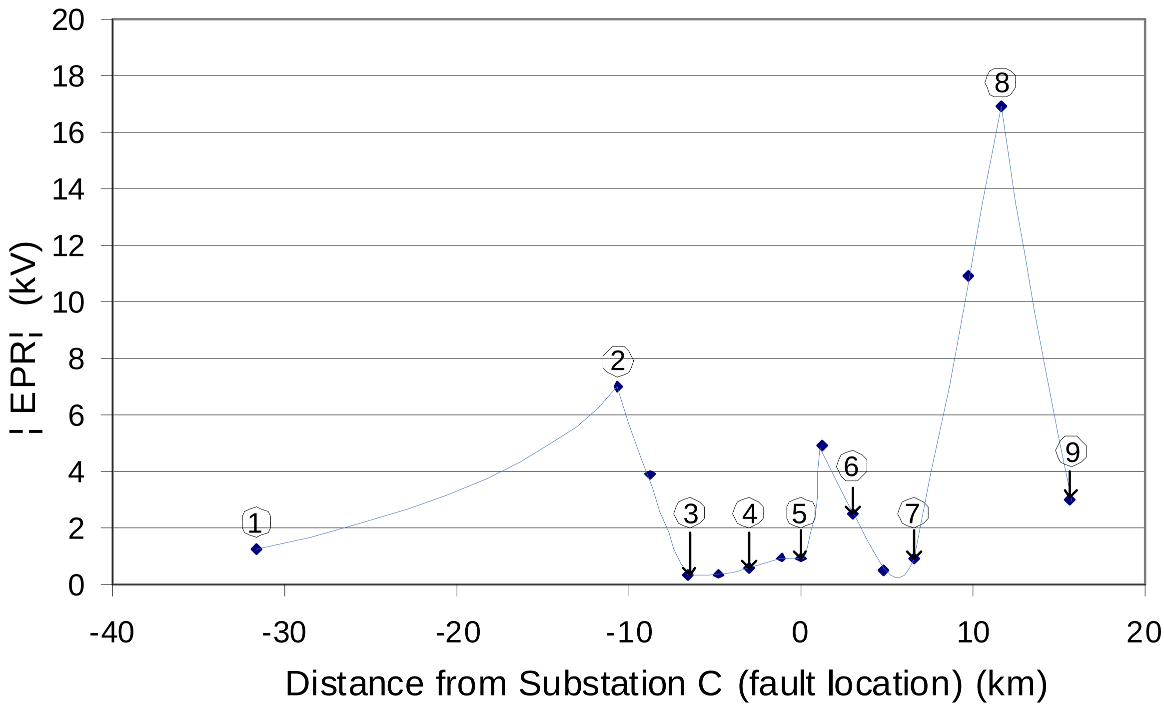


Figure B.4 EPR along the circuit during a phase-to-neutral fault at Substation C

Another option is possible. The use of an ecc can reduce significantly the voltage across the SVL's. Figure B.6 gives an example. The sheath-to-earth voltage is reduced from 15 to 2 kV. A high sheath-to-neutral voltage (11.8 kV) is also seen on the single-point bonded section at substation C. This voltage is proportional to the length of the section and increases with the resistance of the ecc.

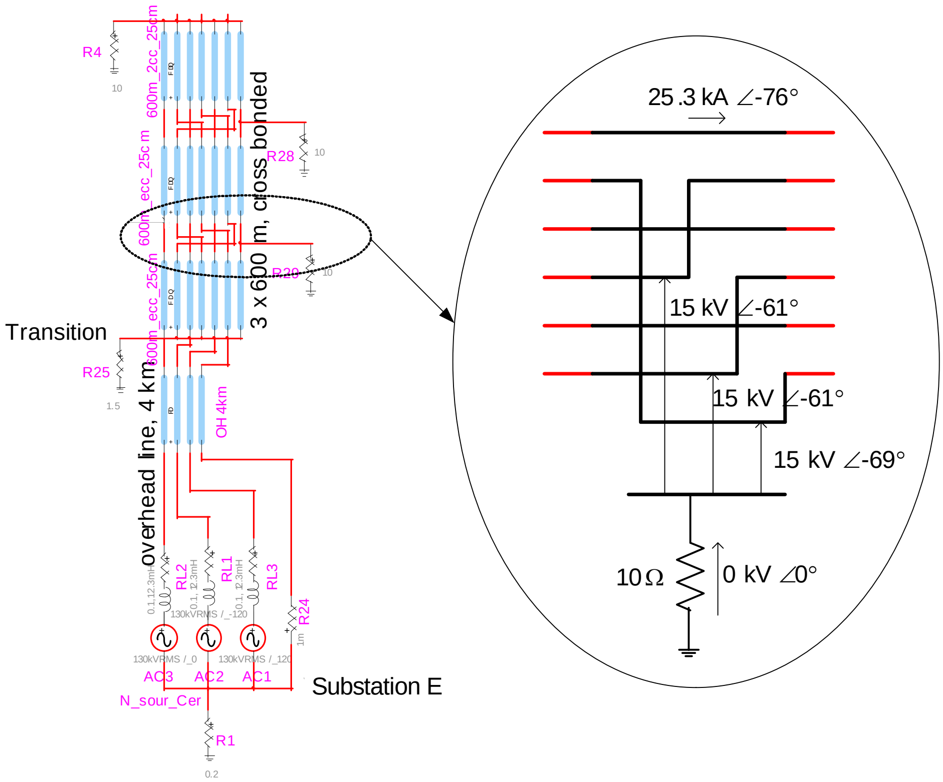


Figure B.5 Sheath-to-Earth Voltages at the First Cross Bonding Joint After the UG/OH Transition Close to Substation E

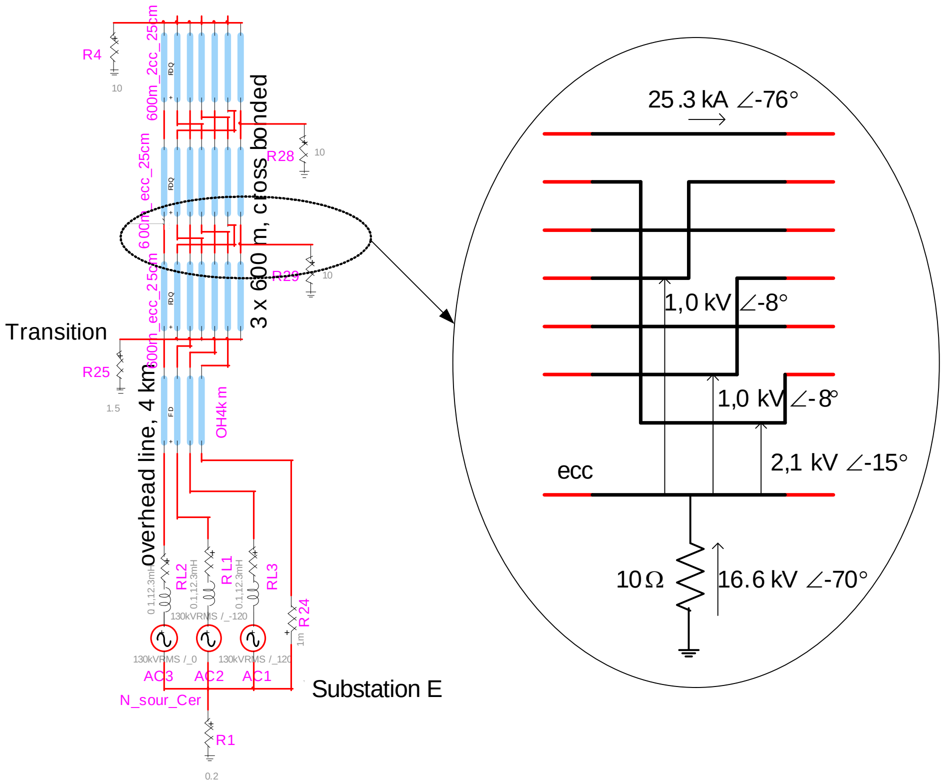


Figure B.6 Sheath-to-ecc Voltages at the First Cross Bonding Joint After the UG/OH Transition Close to Substation E (with an ecc)

B.5 Fault at The OH/UG Transition

The following figures show high EPR.

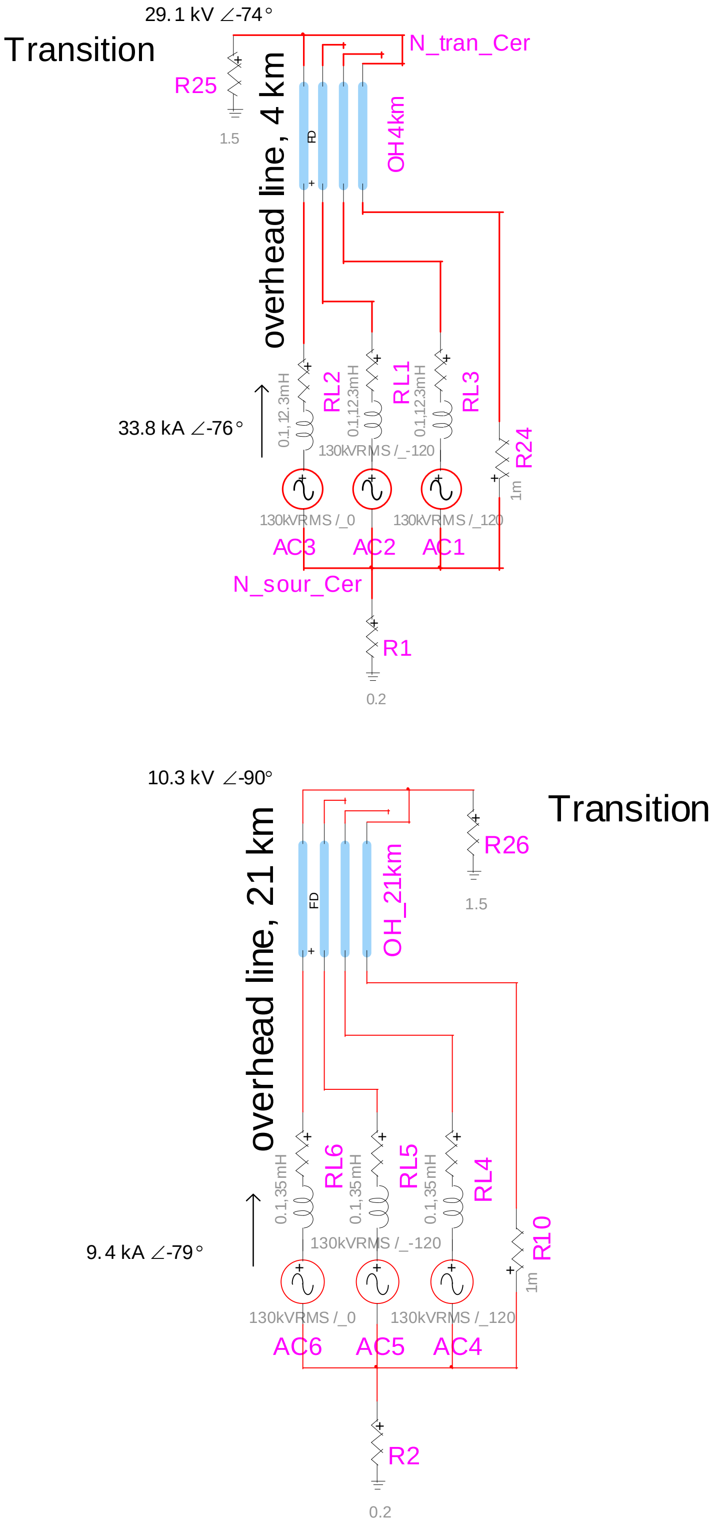


Figure B.7: Single phase fault at the OH/UG transitions

B.6 Model of the Circuit with CIM

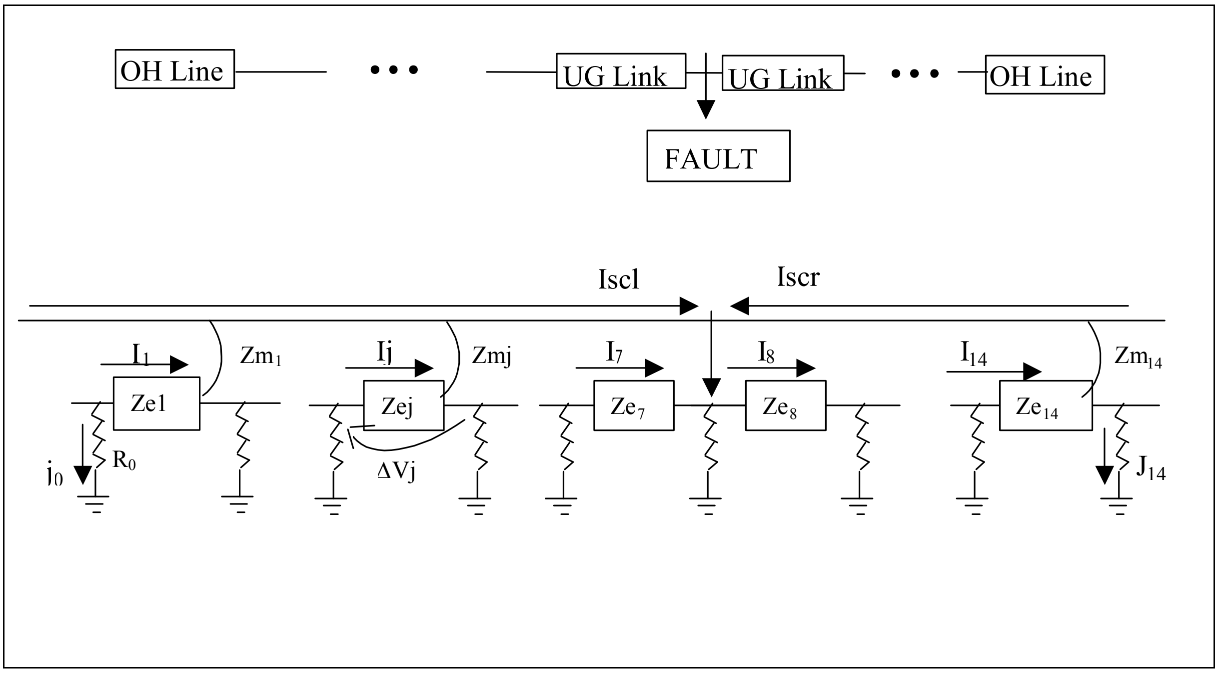


Figure B7 : Circuit Model for CIM Computations

The short-circuit return currents may be derived from a set of equations, expressing Ohm's law in every loop :

$$-R_{j-1}.\lfloor I_{j-1} - I_j \rfloor + \Delta V_j + R_j.\lfloor I_j - I_{j+1} \rfloor = 0 \qquad \text{(B.1)}$$

$$-R_{j-1}.I_{j-1} + \lfloor R_{j-1} + Z_{ej} + R_j \rfloor I_j - R_j.I_{j+1} = -Z_{mj}.I_{sc} \qquad \text{(B.2)}$$

Using matrix form :

$$[MZ].[I] = [CI] \qquad \text{(B.3)}$$

Introducing real and imaginary components :

$$[MZ_r + j.MZ_i].[I_r + j.I_i] = [CI_r + j.CI_i] \qquad \text{(B.3)}$$

NZ being the matrix inverse to MZ:

$$[I_r + j.I_i] = [NZ_r + j.NZ_i].[CI_r + j.CI_i]$$

$$[NZ_r + j.NZ_i] = [MZ_r + j.MZ_i]^{-1}. \qquad \text{(B.4), (B.5)}$$

EPR are computed using :

$$EPR_j = R_j.j_j = R_j.\lfloor I_j - I_{j+1} \rfloor \qquad \text{(B.6)}$$

Cable 2000 mm2 Cu			ecc 185 mm² Cu		
Core diameter (mm)	56.3		ecc diameter (mm)	15.9	
a.c. Core resistance (ohm/km)	1.10E-02		Resistance (Ohm/km)	0.093	
Metallic screen type	Al sheath				
Screen resistivity at 50 °C (Ohm.m)	3.18E-08		ecc location	Xecc (mm)	Yecc (mm)
Screen mean diameter (mm)	114.7		Trefoil - spacing : 250 mm	175	175
Screen thickness (mm)	1.2		Trefoil - touching	70	75
Screen a.c. resistance. (Ohm/km)	7.35E-02				
Cable diameter (mm)	122.6				

OHL: 1circuit 4 wires 280 mm² - gap 200 mm		
Phase conductor resistance (Ohm/km)	0.025	
diameter (mm)	24	
Skywire 50 mm² Al - Resistance (Ohm/km)	0.6	
diameter (mm)	20	
Span length (m)	**350**	
Earth footing rsistance (Ohm)	**8**	
	X1(m)	Y1(m)
Phase 0	-4.1	26
Phase 4	-4.3	20.5
Phase 8	-4.1	15
SkyWire	0	31.9

	p.u. length	Ze	Zm
OHL	Real	6.4935E-04	4.9348E-05
	Imaginary	7.3466E-04	3.0564E-04
UG XB 250	Real	7.3848E-05	4.9348E-05
	Imaginary	5.4748E-04	5.4748E-04
UG XB 123	Real	7.3848E-05	4.9348E-05
	Imaginary	5.7733E-04	5.7733E-04
UG SP 250	Real	1.4235E-04	4.9348E-05
	Imaginary	7.4908E-04	5.3734E-04
UG SP 123	Real	1.4235E-04	4.9348E-05
	Imaginary	7.4908E-04	5.9187E-04

Link	Length (m)	Ze - Real	Zm - Real	Ze - Im	Zm - Im	Earth. R. (Ohm)
OHL	4000	2.5974	0.1974	2.9387	1.2226	1.5
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	10
UG XB 250	3400	0.2511	0.1678	1.8614	1.8614	0.22
UG XB 123	1800	0.1329	0.0888	1.0392	1.0392	0.28
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	4.1
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	2.1
UG SP 250	1200	0.1708	0.0592	0.8989	0.6448	0.25
UG SP 250/123	1200	0.1708	0.0592	0.8989	0.6749	2.18
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	2.17
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	7.47
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	0.15
UG XB 250	2400	0.1772	0.1184	1.3140	1.3140	10
UG XB 250	1800	0.1329	0.0888	0.9855	0.9855	1.5
OHL	21000	13.6363	1.0363	15.4280	6.4184	

MZ and CI matrices

	Real	2	3	4	5	6	7	8	9	10	11	12	13	14
1	4.0974	-1.5000	0	0	0	0	0	0	0	0	0	0	0	0
2	-1.5000	11.6329	-10.0000	0	0	0	0	0	0	0	0	0	0	0
3	0	-10.0000	10.4711	-0.2200	0	0	0	0	0	0	0	0	0	0
4	0	0	-0.2200	0.6329	-0.2800	0	0	0	0	0	0	0	0	0
5	0	0	0	-0.2800	4.5129	-4.1000	0	0	0	0	0	0	0	0
6	0	0	0	0	-4.1000	6.3329	-2.1000	0	0	0	0	0	0	0
7	0	0	0	0	0	-2.1000	2.5208	-0.2500	0	0	0	0	0	0
8	0	0	0	0	0	0	-0.2500	2.6008	-2.1800	0	0	0	0	0
9	0	0	0	0	0	0	0	-2.1800	4.4829	-2.1700	0	0	0	0
10	0	0	0	0	0	0	0	0	-2.1700	9.7729	-7.4700	0	0	0
11	0	0	0	0	0	0	0	0	0	-7.4700	7.7529	-0.1500	0	0
12	0	0	0	0	0	0	0	0	0	0	-0.1500	10.3272	-10.0000	0
13	0	0	0	0	0	0	0	0	0	0	0	-10.0000	11.6329	-1.5000
14	0	0	0	0	0	0	0	0	0	0	0	0	-1.5000	15.1363

Real
-4994.0
-2247.3
-4244.9
-2247.3
-2247.3
-2247.3
-9923.2
8922.4
746.1
746.1
746.1
994.9
746.1
8705.0

	Imaginary													
1	2.9387	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0.9855	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1.8614	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1.0392	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0.9855	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0.9855	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0.8989	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0.8989	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0.9855	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0.9855	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0.9855	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1.3140	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0.9855	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	15.4280

Imaginary
-30930.7
-24932.2
-47094.2
-26291.4
-24932.2
-24932.2
-16313.5
5669.0
8277.9
8277.9
8277.9
11037.2
8277.9
53914.8

NZ matrix

	Real	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.46E-01	-1.75E-03	-1.57E-02	-1.34E-02	-1.28E-03	-7.42E-04	-2.48E-04	6.46E-05	6.20E-05	4.70E-05	4.40E-05	1.13E-06	7.97E-07	-5.93E-08
2	-1.75E-03	1.59E-01	1.09E-01	-2.78E-02	-5.48E-03	-4.19E-03	-2.67E-03	-3.03E-05	9.95E-05	1.37E-04	1.40E-04	7.40E-06	6.05E-06	1.04E-07
3	-1.57E-02	1.09E-01	1.53E-01	-2.65E-02	-6.20E-03	-4.92E-03	-3.30E-03	-8.58E-05	8.50E-05	1.44E-04	1.50E-04	8.82E-06	7.30E-06	1.78E-07
4	-1.34E-02	-2.78E-02	-2.65E-02	3.96E-01	-4.27E-02	-5.41E-02	-5.46E-02	-6.63E-03	-2.67E-03	-2.63E-04	7.70E-05	1.12E-04	1.03E-04	8.27E-06
5	-1.28E-03	-5.48E-03	-6.20E-03	-4.27E-02	2.17E-01	8.06E-02	-2.83E-02	-2.42E-02	-1.76E-02	-1.07E-02	-9.52E-03	-7.91E-05	-1.95E-05	2.55E-05
6	-7.42E-04	-4.19E-03	-4.92E-03	-5.41E-02	8.06E-02	1.70E-01	3.53E-02	-2.15E-02	-1.84E-02	-1.29E-02	-1.19E-02	-2.42E-04	-1.57E-04	2.10E-05
7	-2.48E-04	-2.67E-03	-3.30E-03	-5.46E-02	-2.83E-02	3.53E-02	2.99E-01	-4.85E-03	-1.76E-02	-1.95E-02	-1.94E-02	-8.82E-04	-7.05E-04	-3.19E-06
8	6.46E-05	-3.03E-05	-8.58E-05	-6.63E-03	-2.42E-02	-2.15E-02	-4.85E-03	3.28E-01	7.23E-02	-6.07E-02	-7.81E-02	-9.20E-03	-8.05E-03	-4.44E-04
9	6.20E-05	9.95E-05	8.50E-05	-2.67E-03	-1.76E-02	-1.84E-02	-1.76E-02	7.23E-02	1.96E-01	-4.51E-04	-2.79E-02	-1.00E-02	-9.09E-03	-6.73E-04
10	4.70E-05	1.37E-04	1.44E-04	-2.63E-04	-1.07E-02	-1.29E-02	-1.95E-02	-6.07E-02	-4.51E-04	1.63E-01	1.18E-01	-8.56E-03	-8.57E-03	-1.05E-03
11	4.40E-05	1.40E-04	1.50E-04	7.70E-05	-9.52E-03	-1.19E-02	-1.94E-02	-7.81E-02	-2.79E-02	1.18E-01	2.03E-01	-6.24E-03	-6.90E-03	-1.15E-03
12	1.13E-06	7.40E-06	8.82E-06	1.12E-04	-7.91E-05	-2.42E-04	-8.82E-04	-9.20E-03	-1.00E-02	-8.56E-03	-6.24E-03	2.33E-01	1.78E-01	-4.23E-03
13	7.97E-07	6.05E-06	7.30E-06	1.03E-04	-1.95E-05	-1.57E-04	-7.05E-04	-8.05E-03	-9.09E-03	-8.57E-03	-6.90E-03	1.78E-01	2.18E-01	-1.54E-03
14	-5.93E-08	1.04E-07	1.78E-07	8.27E-06	2.55E-05	2.10E-05	-3.19E-06	-4.44E-04	-6.73E-04	-1.05E-03	-1.15E-03	-4.23E-03	-1.54E-03	3.12E-02

	Imaginary													
1	-1.36E-01	-8.38E-02	-7.74E-02	-4.48E-03	1.01E-03	1.11E-03	1.02E-03	1.05E-04	3.56E-05	-4.36E-06	-9.84E-06	-2.20E-06	-1.98E-06	-1.36E-07
2	-8.38E-02	-2.32E-01	-2.42E-01	-3.84E-02	2.34E-04	1.57E-03	2.30E-03	4.15E-04	2.19E-04	8.01E-05	5.94E-05	-3.80E-06	-3.84E-06	-4.87E-07
3	-7.74E-02	-2.42E-01	-2.59E-01	-4.68E-02	-4.19E-04	1.24E-03	2.26E-03	4.64E-04	2.59E-04	1.07E-04	8.43E-05	-3.36E-06	-3.58E-06	-5.35E-07
4	-4.48E-03	-3.84E-02	-4.68E-02	-7.04E-01	-8.31E-02	-5.36E-02	-2.50E-02	2.49E-03	3.10E-03	2.69E-03	2.58E-03	8.74E-05	6.62E-05	-1.86E-06
5	1.01E-03	2.34E-04	-4.19E-04	-8.31E-02	-3.46E-01	-3.23E-01	-2.61E-01	-1.93E-02	-3.11E-03	5.02E-03	6.05E-03	6.14E-04	5.33E-04	2.69E-05
6	1.11E-03	1.57E-03	1.24E-03	-5.36E-02	-3.23E-01	-3.33E-01	-2.92E-01	-2.73E-02	-7.86E-03	2.77E-03	4.20E-03	6.51E-04	5.78E-04	3.58E-05
7	1.02E-03	2.30E-03	2.26E-03	-2.50E-02	-2.61E-01	-2.92E-01	-3.55E-01	-5.45E-02	-2.63E-02	-7.51E-03	-4.76E-03	6.51E-04	6.28E-04	6.54E-05
8	1.05E-04	4.15E-04	4.64E-04	2.49E-03	-1.93E-02	-2.73E-02	-5.45E-02	-3.38E-01	-2.62E-01	-1.69E-01	-1.53E-01	-2.08E-03	-1.06E-03	3.47E-04
9	3.56E-05	2.19E-04	2.59E-04	3.10E-03	-3.11E-03	-7.86E-03	-2.63E-02	-2.62E-01	-2.80E-01	-2.26E-01	-2.14E-01	-6.35E-03	-4.66E-03	2.24E-04
10	-4.36E-06	8.01E-05	1.07E-04	2.69E-03	5.02E-03	2.77E-03	-7.51E-03	-1.69E-01	-2.26E-01	-2.97E-01	-3.01E-01	-1.56E-02	-1.27E-02	-1.92E-04
11	-9.84E-06	5.94E-05	8.43E-05	2.58E-03	6.05E-03	4.20E-03	-4.76E-03	-1.53E-01	-2.14E-01	-3.01E-01	-3.17E-01	-1.97E-02	-1.64E-02	-4.54E-04
12	-2.20E-06	-3.80E-06	-3.36E-06	8.74E-05	6.14E-04	6.51E-04	6.51E-04	-2.08E-03	-6.35E-03	-1.56E-02	-1.97E-02	-2.82E-01	-2.60E-01	-2.14E-02
13	-1.98E-06	-3.84E-06	-3.58E-06	6.62E-05	5.33E-04	5.78E-04	6.28E-04	-1.06E-03	-4.66E-03	-1.27E-02	-1.64E-02	-2.60E-01	-2.45E-01	-2.27E-02
14	-1.36E-07	-4.87E-07	-5.35E-07	-1.86E-06	2.69E-05	3.58E-05	6.54E-05	3.47E-04	2.24E-04	-1.92E-04	-4.54E-04	-2.14E-02	-2.27E-02	-3.41E-02

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Short-circuit return current							Currents flowing to earth				
Real	NZr.Ir	Nzi.Ii		Imaginary	Nzr.Ii	Nzi.Ir			Real	Imaginary	Modulus
-621.7	9975.2	-10597.0		-3330.7	1189.9	-2140.8		J1	10826.2	3847.2	11489.5
-700.1	20723.1	-21423.2		-8020.2	2032.2	-5988.0		J2	1093.9	274.6	1127.8
-696.7	21820.4	-22517.1		-8379.2	2116.6	-6262.6		J3	3136.6	-3915.5	5016.9
49.7	25703.4	-25653.7		-4819.4	2472.3	-2347.1		J4	-2093.9	-649.6	2192.4
-489.8	23069.9	-23559.8		-5807.5	4110.0	-1697.5		J5	-335.3	-407.6	527.8
-982.3	22242.2	-23224.5		-5527.2	4237.4	-1289.9		J6	-860.0	-1688.1	1894.6
-2924.3	19440.2	-22364.5		-3895.0	4293.3	398.3		J7	3496.3	706.7	3567.0
3021.0	-4818.2	7839.3		2509.5	-2817.9	-308.4		J8	-112.3	-526.7	538.6
1008.6	-6942.9	7951.6		2826.9	-2608.6	218.3		J9	-156.9	-338.9	373.5
-110.5	-8219.0	8108.5		2657.2	-2100.0	557.2		J10	-16.5	-69.9	71.8
-260.4	-8385.3	8125.0		2631.3	-2004.2	627.1		J11	1073.2	-2230.2	2474.9
236.2	-6815.6	7051.8		3577.0	-719.8	2857.3		J12	366.0	93.1	377.7
243.0	-6442.8	6685.8		3446.4	-682.2	2764.2		J13	4161.2	1501.6	4423.8
260.1	-2264.5	2524.6		1595.3	-332.7	1262.6					

EPR in various locations – from EMTP and CIM