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Application Guide
for Cable Sheath Bonding

FUNDAMENTALS OF CALCULATION OF EARTH POTENTIAL RISE IN THE UNDERGROUND POWER DISTRIBUTION CABLE NETWORK

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Foreword

This paper provides a detailed outline of how to calculate the fault currents and earth potential rise that will result when a high voltage cable between two substations has its sheath bonded to the substation earth mat at each end.

The author, Ashok Parsotam, presented this paper at the "Power and Telecommunications Systems Co-ordination Conference", Melbourne, on 19 March 1997. At the time he was an Engineer with Southpower.

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FUNDAMENTALS OF CALCULATION OF EARTH POTENTIAL RISE IN THE UNDERGROUND POWER DISTRIBUTION CABLE NETWORK

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SUMMARY

In this paper, the fundamentals of how to calculate earth potential rise (EPR) in an underground power distribution network are presented in some detail. The objective is to enable engineers with a basic knowledge of power system analysis to further develop their skills and understanding of EPR calculations in a typical distribution network.

The calculation of sequence impedances to model overhead lines and underground cables and calculate the Earth Potential Rise in the cable network, is presented in some detail, to enable a Power Systems Engineer to understand and design cost effective earthing systems.

This paper can be treated as a guide or a reference document for calculating the fault currents in a distribution network[1]. Several fault scenarios were modelled. For each model a numerical example outlining all steps required to calculate EPR is also provided.

The equations given in this document can also be used for calculating line and cable series impedance parameters required by PTI'S Power System Simulator (PSS/U) and most other load flow and short circuit analysis software packages

The methods and models presented in this paper are such that they can be readily applied to practical situations by a Power Systems Engineer using a basic scientific hand calculator.

[1]While the author has taken all reasonable care in compiling this paper, and satisfying himself as to the information in it, the author takes no responsibility whatsoever for any loss, expense, claim or damage suffered or incurred by any person who acts on reliance of any of the information contained in it. The author expressly disclaims all and any liability to any person, whether a purchaser of this paper or not, in respect of anything done or not done by that person in reliance either wholly or partly on the information contained in this paper.

For the 11kV cable network studied, the calculations show that even though 96% of the total fault current returns to the source via the cable sheath, the earth potential rise for a 10 Ohms

earthing system can still be as high as 3100 Volts. This indicates that careful consideration should be given to the design of all earthing systems.

1. INTRODUCTION

The author has observed young graduate engineers using available computer programs to model substation earth mats and calculate earth potential rise (EPR) without understanding the importance of the parameters involved.

In one instance, an engineer was calculating EPR for a 33/11kV zone substation earth mat. The calculated earth mat resistance was 3 Ohms, the source substation had an 11 Ohms neutral earthing resister and the length of the 33kV line to the zone substation was approximately 10km. This engineer used a 10kA fault current to simulate the substation earth potential rise and associated voltage contours. An engineer with some knowledge of power system fault analysis would have quickly worked out that the maximum phase to earth fault current (post transient steady state) at the source substation could not be greater than 33,000/(($\sqrt{3}$)(11 Ohm)) or 1732 amperes. Obviously, the EPR of a 3 Ohm earth mat with 1732 A fault current is only 5196 Volts compared to 30kV calculated by the earth mat analysis software.

The author, in early days of exposure to such calculations, also made similar mistakes. His mistakes were associated with calculation of EPR in an 11kV underground cable network. The author had fault analysis software (PSSU) which had the facility to calculate high impedance phase to earth fault currents. He used this facility and calculated earth fault currents and EPR in a cable network and it was a mistake. The fault current calculated by PSSU was equal to the current in the faulty phase conductor and there was no way of finding out the proportions that returned to the source via the cable sheath and the general mass of earth. It was during these calculations the author realised that special considerations are required to calculate EPR in a cable network.

The fundamental part of calculation of the earth potential rise is the calculation of the phase to earth fault current magnitude in a given network. This requires network impedance calculations, fault current analysis and then design of the earthing system to assess and control the hazardous EPR.

The fault current analysis of a 3-phase 3-wire overhead line distribution network is relatively simple compared to that of an underground cable network, or a combination of overhead and underground networks. In this paper, a method of calculating fault current split (between cable sheath and the general mass of earth), and the EPR and the transferred earth potential rise (TEPR) for the phase to earth faults in the overhead and the underground three core cable power distribution network will be presented.

2 EARTH POTENTIAL RISE

This paper models underground cable and overhead line systems to calculate phase to earth fault current splits and EPR. In these models, the earth mat will be represented as a single lumped impedance element in the fault circuit network. The touch and step voltages associated with EPR can not be calculated explicitly in such models. However, it is possible to calculate the transferred EPR.

The mathematical modelling of an earth mat for touch and step voltages inside and outside the confines of the earth mat is indeed a complex subject. The effective solution generally requires computer modelling. However, it is relatively easy to calculate EPR if the impedance of the earth mat is known.

3 CALCULATION OF SEQUENCE IMPEDANCES OF AN UNDERGROUND CABLE

In order to calculate the fault current in a network, one must first calculate the impedance of the network elements. In this paper, the symmetrical components method of analysis for current split during phase to earth faults will be developed and used.

To use the symmetrical components method of analysis, the network elements (transformers, lines, cables and generators) impedance should be calculated or obtained from measurements. For a typical distribution network system analysis, the elements are transformers, lines and cables. However, in this paper, to simplify calculations, transformers are not explicitly modelled. This enables us to carry out calculations without the additional complexity of transformer turns ratio and hence the use of the per-unit system.

The symmetrical components method of analysis is a convenient mathematical tool for the analysis of unbalanced network conditions. This method decomposes the unbalanced network parameters i.e. voltages and currents into three separate but balanced and symmetrical components, namely positive, negative and zero sequence components. Therefore, to calculate positive, negative and zero sequence voltages and currents, we must first calculate the corresponding positive, negative and zero sequence impedances which will generate and limit voltages and currents respectively. Extreme unbalances of voltages and currents in the network are caused by system faults such as phase to earth faults.

In the following sections, the equations for calculating the series positive and the zero sequence impedance values for a 3 core, insulated metallic sheath covered cables and 3-phase 3-wire short overhead lines are given and corresponding symmetrical components circuit models (for single phase to earth fault conditions) are developed.

The shunt admittance of the cables and the lines has been neglected from these calculations. In a later section, a comparison has been made between the results obtained using the models developed in this paper, and the models used in more sophisticated applications such as transient analysis.

The equations to calculate the cable and the line parameters were taken from the **Wagner & Evans** book (1). The derivation of these equations was shown in this book. And are in imperial units (inches, Ohm/mile) rather than metric units. The equations presented in this paper are an equivalent metric version of the original equations.

3.1 THE POSITIVE SEQUENCE IMPEDANCE OF THE 3-CORE INSULATED METALLIC SHEATH COVERED CABLES

In the following calculations, it is assumed that the cable sheath is insulated from the surrounding earth. Figure 3.1 below shows a cross section of a typical cable.

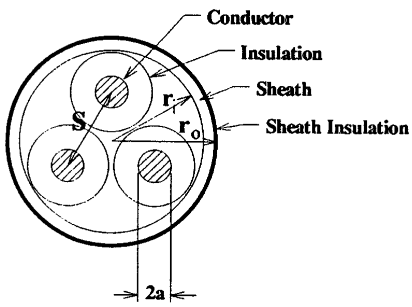


Fig. 3.1 Cross section of a typical underground cable. In this picture, the cable sheath is shown as electrically insulated from the ground.

3.1.1 Positive Sequence Resistance

For such analysis at power frequency (i.e. 50 HZ), it can be assumed that the positive sequence AC resistance of the conductors is equal to the DC resistance of the conductor.

$R_1=R_{cond}(DC)$ Ω/Ø/km eqn. 1

3.1.2 Positive Sequence Reactance

The positive sequence reactance of the cable can be calculated from the following equation:

$$X_1 = 2.893x10^{-3} f.\log_{10}\left(\frac{S}{GMR}\right) \quad \Omega/Ø/km \qquad \text{eqn.2}$$

where

f - frequency Hz

S - separation of the conductors (in an equilateral triangle disposition), or the Geometric Mean Distance (GMD) of conductors in mm. See figure 3.1.

GMR - is the Geometric Mean Radius of one conductor (mm) and is calculated by the following equation:

GMR = (k **a**) mm eqn. 3

a radius of the conductor mm. See figure 3.1

k factor to convert the conductor radius to the Geometric mean Radius (GMR) of the conductor (See Table 3.1)

Conductor type	K
Solid round conductor	0.779
Full Stranding	
7	0.726
19	0.758
37	0.768
61	0.772
91	0.774
127	0.776
Hollow stranded conductors and A.C.S.R. (Neglecting steel strands)	
6 one layer	0.768**
30 two layer	0.826
36 two layer	0.809
54 three layer	0.810
Single layer A.C.S.R.	0.35 - 0.70
Point within circle to circle	1
Point outside circle to circle	Distance to centre of circle
Rectangular section of sides α and β	0.2235 (α + β)

Table 3.1 Geometric Mean Radii (GMR) factors for different Conductors. This table is from the Wagner & Evans book "Symmetrical Components" pg. 138 **The 6 one layer ASCR k factor was calculated by the author. The calculation is shown in appendix A. More information on calculation of GMR can be found in [2].

Hence, the positive sequence impedance of a 3 core cable (figure 3.1) is given by:

$Z_1=R_1+jX_1$ Ω/Ø/km eqn. 4

3.2 THE NEGATIVE SEQUENCE IMPEDANCE OF THE CABLE

The negative sequence impedance of the cable is equal to the positive sequence impedance.

$Z_2 = Z_1 = R_1 + jX_1$ Ω/Ø/km

3.3 THE ZERO SEQUENCE IMPEDANCE OF THE CABLE

3.3.1 The Zero Sequence Self Impedance of the 3-Core Cable Conductors (Z_{sc0})

To calculate the zero sequence self impedance of the cable, the conductors in the cable must be considered as a group (see figure 3.2 below), and the equivalent GMR for the group of conductors must be calculated.

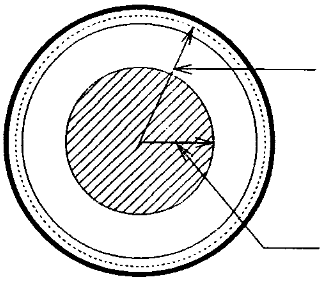


Figure 3.2 The 3 conductors of the cable replaced by a single conductor with an equivalent GMR and resistance of 3 parallel conductors considered as group.

The equation to calculate the zero sequence self impedance is given below.

$$Z_{sc0} = 3\left(\frac{R_{cond}}{3} + 988.2x10^{-6}\ f + j2.893x10^{-3}\ f\ \log_{10}\left(\frac{658368\sqrt{\frac{\rho}{f}}}{GMR_{3cond}}\right)\right) \quad \Omega/Ø/km \quad \text{eqn.5}$$

where
- R_{cond} - DC Resistance of one conductor (Ω/km)
- f - frequency (Hz)
- ρ - deep layer soil resistivity (Ω-m)
- GMR_{3cond} - $\sqrt[3]{kaS^2}$ mm eqn. 6
- k - factor to convert the conductor radius to the Geometric Mean Radius (GMR).
- **a** **-** radius of the conductor (mm). See fig. 3.1
- S - GMD of the conductors which in this case is also equal to the spacing between the centers of the conductors (mm). See fig. 3.1

The ($658368\sqrt{\frac{\rho}{f}}$) factor is known as an equivalent depth)D_e) of zero sequence earth return currents.

3.3.2 The Zero Sequence Self Impedance of the Sheath Z_{ss0})

The zero sequence self impedance of the sheath is calculated by equation 7 given below.

$$Z_{ss0}=3\left\{R_{sh}+988.2x10^{-6}f+2.893x10^{-3}f\log_{10}\left(\frac{658368\sqrt{\frac{\rho}{f}}}{GMR_{sh}}\right)\right\}\quad \Omega/Ø/\text{km} \qquad \text{eqn. 7}$$

where $R_{sh}=\dfrac{\rho_{sh}\,x10^{9}}{\pi\left(r_0^2-r_i^2\right)}$ Ω/km eqn. 8

ρ_{sh} - resistivity of the sheath material (Ω-m)
r_o - outer radius of the sheath mm
r_i - inner radius of the sheath mm
ρ - deep layer soil resistivity Ω-m
f - frequency Hz

Typical values at 20°C are:

Lead (Pb)	21.4 x 10^{-8} (Ω-m)
Aluminium (Al)	2.84 x 10^{-8} (Ω-m)

GMR_{sh} - GMR of the sheath = $\dfrac{ro+ri}{2}$ mm eqn. 9

3.3.3 The Zero Sequence Mutual Impedance (Z_{msc0})

The zero sequence mutual impedance between the group of 3 conductors and the sheath is calculated by equation 10:

$$Z_{msc0} = 3\left\{988.2x10^{-6}\,f + j2.893x10^{-3}f\log_{10}\left[\frac{658368\sqrt{\frac{\rho}{f}}}{d_{sc}}\right]\right\}\Omega/Ø/\text{km} \qquad \text{eqn.10}$$

where ρ - deep layer soil resistivity Ω-m
f - frequency Hz

dsc - Geometric mean spacing or distance (GMD) between the group of the 3 conductors and the sheath. It is the same as the GMR of the sheath.

$$d_{sc}=\frac{r_o+r_i}{2}\ \text{mm}$$

3.4 THE ZERO SEQUENCE IMPEDANCE CIRCUIT MODEL FOR THE 3 CORE, INSULATED METALLIC SHEATH CABLE

The equations 5, 7, and 9 given above can now be used to develop a zero sequence impedance circuit models that can be applied to calculate the fault current split between the cable sheath and the general mass of earth (through earth mats and electrodes) for all of the five cases described below in section 5. Figure 3.3 below shows a zero sequence model representation of a typical cable section, the two terminal substation earth mats, and the source substation neutral earthing impedance (resistor in this case - NER). The possible sheath terminal connections for a phase to earth fault scenario are also shown as switches in this figure.

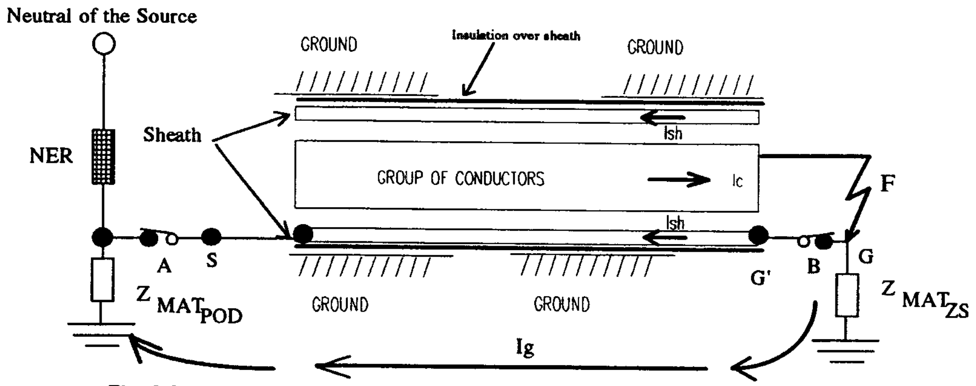


Fig. 3.3 An equivalent cable section. The cable is insulated from the ground. The conductors were grouped together to calculate equivalent GMR of 3 conductors.

The status of switches A and B (i.e. open or closed) indicate in the circuit whether the cable sheath terminals are bonded or not to the source (POD - point of delivery) substation and the zone substation earth mats. If switch A is shown as closed, the cable sheath is bonded at the source substation earth mat. If it is shown as open, then it is not bonded to that earth mat. Similarly if switch B is shown as closed, then the cable sheath is bonded to the Zone Substation (ZS) earth mat.

If the NER is not installed in the network, then it's impedance value will be equal to zero. It should be noted that in the zero sequence network, the measured impedance of the earth mat, the auxiliary earth connections (self impedance of other cable sheaths, overhead earth wire (OHEW), MEN impedance etc) and the NER should be multiplied by a factor of 3.

The equations given above are used to calculate the components of the zero sequence circuit shown in figure 3.4 below.

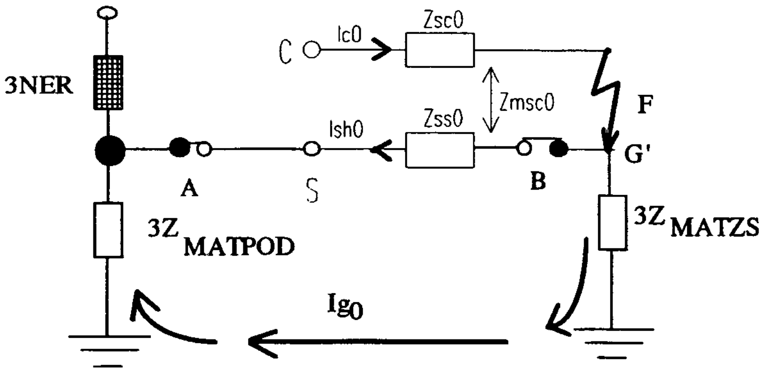


Fig. 3.4 A circuit to represent the zero sequence self and mutual impedances of the phase to earth fault in the cable. The switches are shown for modelling bonded and unbonded cable sheaths at POD and Zone substation earth mats

In above figure 3.4, Ic_0 is the zero sequence current in the cable conductors, Ish_0 is the zero sequence current in the cable sheath and Ig_0 is the zero sequence current in the general mass of earth. Ic_0=Ish_0Ig_0. It is a vector sum rather than an arithmetic sum.

The calculation of the zero sequence ϕ - E fault current with this type of representation is mathematically rather cumbersome since it requires a solution of a set of simultaneous equations.

The circuit in figure 3.4 can be further developed to represent the self and the mutual impedance in a mathematically equivalent circuit as shown in figure 3.5 below. In this configuration, the equivalent impedance are represented as uncoupled series and parallel impedance branches in the circuit and can be readily used for fault current splits and earth potential rise voltage calculations.

Z_{msc0} in the figure 3.5 is the effective impedance to the flow of current in the general mass of earth, and therefore referred as Z_{g0}.

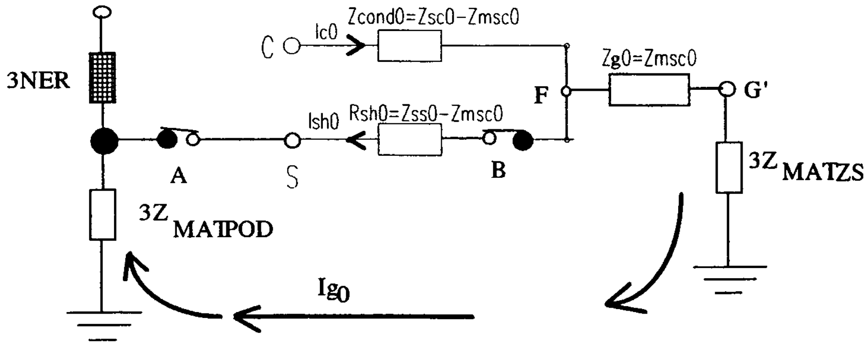


Fig. 3.5 An equivalent circuit for zero sequence impedance of the cable including the termination impedances

A closer look at the above circuit diagram reveals that at the fault point F, for the cable sheath bonded at both ends (switches A & B closed), the total fault current splits between the cable sheath (R_{sh0}) path and the general mass of earth path Z_{g0}). The zero sequence current in the cable sheath is impeded only by the cable sheath resistance where as the portion returning via the general mass of earth is impeded by both, the zone substation earth mat ($Z_{MAT\ ZS}$) and the POD earth mat (Z_{MATPOD}) impedance.

The zero sequence fault current split between the sheath and the general mass of earth is shown in the figure 3.6 below. From this figure it can be seen that if the cable sheath was not bonded to the zone substation earth mat but only bonded to the POD substation earth mat, then switch B will be open and consequently no current will flow through the cable sheath. On the other hand if the cable sheath was only bonded to the zone substation earth mat, then switch A will be open and switch B closed. In this situation, the isolated sheath terminal will develop a high voltage during fault and if it was not insulated properly, it could be hazardous to personnel working near that terminal.

The zero sequence impedance circuit for a continuous piece of cable between the source (Point of Delivery, POD) and the receiving substation (Zone substation, ZS) with the cable sheath bonded at both substation earth mats, and the neutral earthing resistor impedance is shown in the figure 3.6 below.

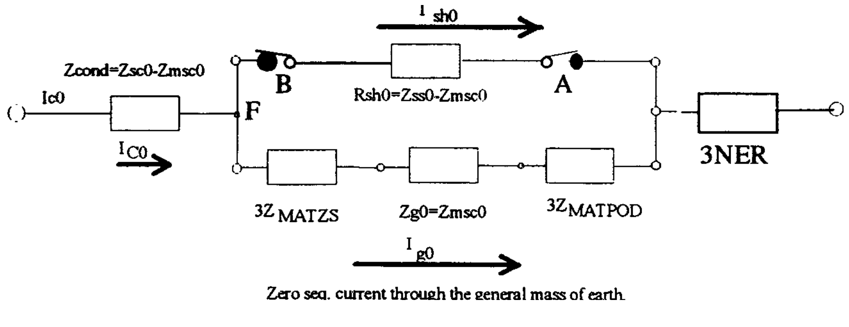


Figure 3.6 An equivalent zero sequence circuit ready for connection to a zero sequence network for fault current calculation

4. CALCULTION OF SEQUENCE IMPEDANCES OF AN OVERHEAD LINE

4.1 The Positive Sequence Impedance of 3-Phase 3-Wire Short Transmission Lines (i.e. Without Overhead Earth Wires)

Figure 4.1 below shows a general arrangement of 3-phase 3-wire overhead line conductors. The insulators, cross arm and the pole supporting the conductors are not shown.

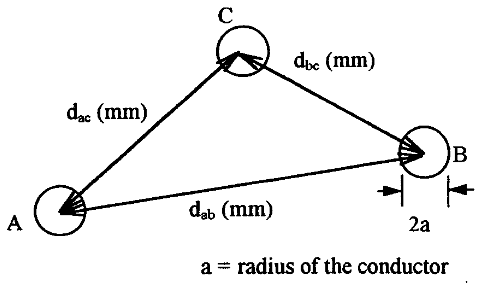


Fig. 4.1 General arrangement of a 3 phase 3 wire transmission line

4.1.1 Positive Sequence Resistance

For an overhead line it can be assumed that the positive sequence AC resistance of the conductor is equal to the DC resistance of the conductor. This is similar to the cable analysis at power frequency (i.e. 50Hz).

$R_1 = R_{cond}(DC)\ \ \Omega/\phi/km$ eqn 11

4.1.2 Positive Sequence Reactance

The positive sequence reactance of the 3 phase 3 wire line can be calculated from the following equation:

$X_1 = 2.893\text{x}10^{-3}\, f.\log_{10}\left(\frac{GMD}{GMR}\right)\Omega/\phi/km$ eqn. 12

where:

f - frequency Hz

GMD - Geometric Mean (mm). For an equilateral triangle disposition of the conductors, GMD = S - or the separation of the conductors. For any other arrangements of the 3-phase 3-wire line, it can be calculated with the following equation:

GMD = $\sqrt[3]{d_{ab}d_{bc}d_{ca}}$ mm eqn. 13

d_{ab}, d_{bc} and d_{ca} are the spacing (mm) between the phase conductors as shown in the figure 4.1 above.

GMR - Geometric Mean Radius of one conductor (mm). It is calculated by equation 3.

We get the positive sequence impedance of a 3-phase 3-wire short transmission line combining R_1 and X_1 as follows:

$Z_1 = R_1 + jX_1\ \ \Omega/\phi/km$ eqn. 14

4.2 The Negative Sequence Impedance of a Short 3-Phase 3-Wire Transmission Line

The negative sequence impedance of the line is equal to the positive sequence impedance.

$Z_2 = Z_1 = R_1 + jX_1\ \ \Omega/\phi/km$

4.3 The Zero Sequence Impedance of a Short 3-Phase 3-Wire Transmission Line

To calculate the zero sequence impedance of a short 3-Phase 3-Wire transmission line, the 3 conductors must be considered as a group and therefore the equivalent GMR for the group of conductors must be calculated. The equation to calculate the zero sequence impedance is given below.

$$Z_0 = 3\left\{\frac{R_{cond}}{3} + 988.2x10^{-6}.f + j2.893x10^{-3}.f.\log_{10}\left(\frac{658368\sqrt{\frac{\rho}{f}}}{GMR_{3cond}}\right)\right\}\ \Omega/\phi/km \qquad \text{eqn. 15}$$

where R_{cond} - Resistance of one conductor Ω/km
f - frequency Hz
ρ - deep layer soil resistivity Ω-m
GMR_{1cond} - Geometric Mean radius of one conductor (mm)

$$GMR_{3cond} = \sqrt[9]{(GMR_{1cond})^3\, d^2{}_{ab} d^2{}_{bc} d^2{}_{ca}}\ mm \qquad \text{eqn. 16}$$

d_{ab}, d_{bc}, and d_{ca} are the spacing (mm) between the phase conductors as shown in the figure 4.1 above.

5 THE ZERO SEQUENCE IMPEDANCE CIRCUIT MODELS FOR THE 3 CORE, INSULATED METALLIC SHEATH CABLES IN FIVE DIFFERENT CIRCUIT LOCATIONS

In a distribution network, there are five different locations within a network where a 3 core, insulated metallic sheath cable can be installed with its cable sheath bonded to earth mats at both ends. These are:

(i) A continuous length of cable laid between the source substation and a receiving substation. The cable sheath is bonded to earth at both substation earth mats. See figure 5.1 below.

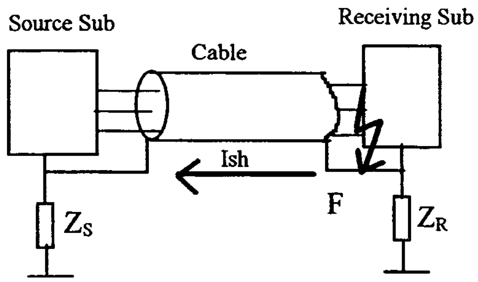


Fig. 5.1 A continuous length of cable between the source and the receiving substations. Phase to earth fault at the receiving substation earth mat. The fault current returns to the source via the cable sheath and the general mass of earth

The zero sequence impedance circuit for the cable installation in figure 5.1 above is identical to the one shown in figure 3.6 above. The Z_S and the Z_R are the source and the receiving substation earth mat impedance respectively.

(ii) A piece of cable laid from the source substation and terminated on a riser pole outside the substation earth mat confines. The cable sheath is bonded to earth at the source substation earth mat and at the riser pole. See figure 5.2 below.

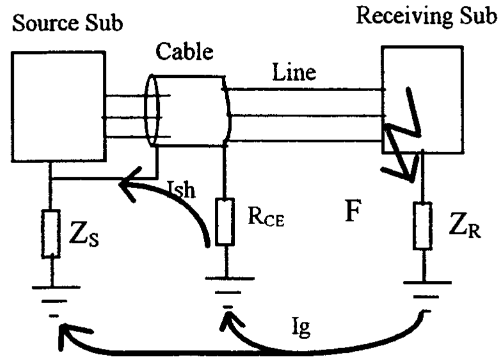


Figure 5.2 A cable and a line combination between the source and the receiving substations. Phase to earth fault at the receiving substation earth mat. The fault current returns to the source via the general mass of earth and the cable sheath

The zero sequence impedance circuit for the cable installation as shown in figure 5.2 above is shown in figure 5.3 below. R_{CE} is the cable sheath bonding electrode resistance.

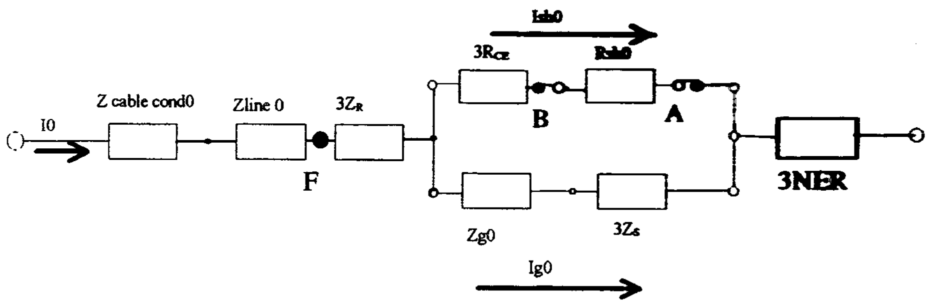


Figure 5.3 The zero sequence impedance circuit for the cable and line combination shown in figure 5.2 above

(iii) A piece of cable laid from the riser pole (out side the confines of the receiving substation earth mat) and terminated at the receiving substation. The cable sheath is bonded to earth at the riser pole and at the receiving substation earth mat. See figure 5.4 below.

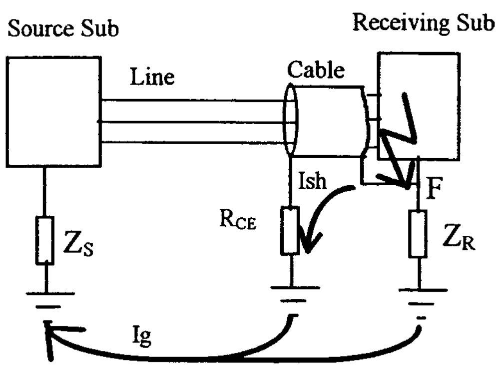


Figure 5.4 A line and cable combination between the source and the receiving substations. Phase to earth fault at the receiving substation earth mat. The

fault current returns to the source via the cable sheath and the general mass of earth

The zero sequence impedance for the cable installation in figure 5.4 above is shown in figure 5.5 below.

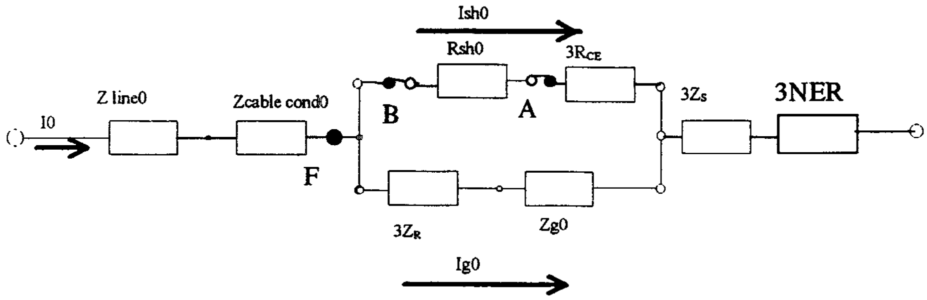


Figure 5.5 The zero sequence impedance circuit for the line and the cable combination shown in figure 5.4 above

(iv) A length of cable laid from the source substation to a riser pole and from another riser pole to the receiving substation with a line in between. Both ends of both cable sheaths are bonded to earth. See figure 5.6 below.

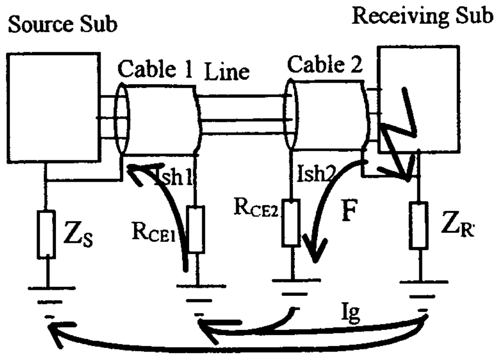


Figure 5.6 A cable, line and cable combination between the source and the receiving substations. Phase to earth fault at the receiving substation earth mat. The fault current returns to the source via both cable sheaths and the general mass of earth

The zero sequence impedance for the cable installation in figure 5.6 above is shown in figure 5.7 below.

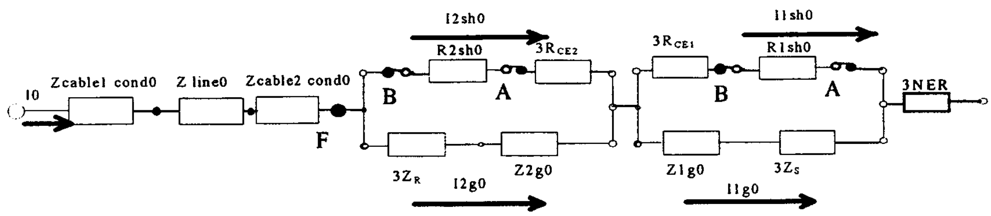


Figure 5.7 The zero sequence impedance circuit for a cable, line and cable combination shown in figure 5.6 above

(v) A piece of cable laid from a riser pole to another riser pole, between the source substation and the receiving substation. See figure 5.8 below.

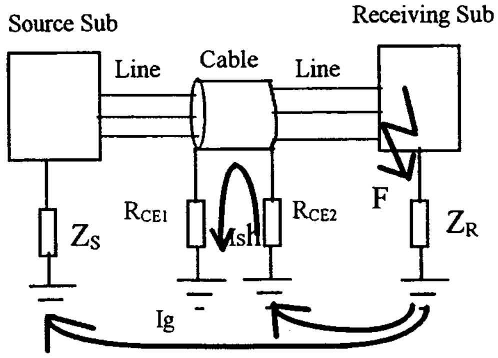


Figure 5.8 A line, cable, and line combination between the source and the receiving substations. Phase to earth fault at the receiving substation earth mat. The fault current returns to the source via both the general mass of earth and the cable sheath

The zero sequence impedance for the cable installation in figure 5.8 above is shown in figure 5.9 below.

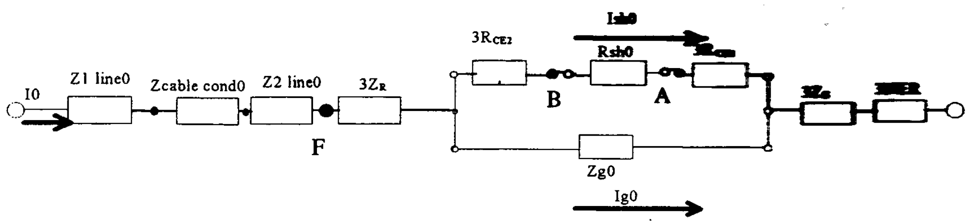


Figure 5.9 The zero sequence impedance circuit for a line, a cable and a line combination shown in figure 5.9 above

6 VALIDATION OF THE CABLE POSITIVE AND ZERO SEQUENCE MODELS

A separate study was carried out for a hypothetical cable to compare results from models developed here with results obtained using a very sophisticated cable model (Alternate Transients Program model) to ensure that these models were appropriate and correct for studying EPR and current splits in the cable network.

The Alternate Transients Program (ATP) is a very powerful and sophisticated computer software program developed to study electromagnetic transients in an electrical network. In addition to performing transient simulations for a given network, it also calculates parameters for cables, lines, transformers, etc. The parameters are calculated using very accurate models for cables, lines and other equipment. The ATP not only calculates the series self and mutual impedance but also calculates the shunt (capacitance) admittance for cables and lines of any given configuration.

It can be seen from the following figures 6.1 and table 6.1 that for the hypothetical cable, as the source voltage increases, the influence of the shunt admittance on the fault current splits and therefore the difference in results between the two models becomes noticeable. However, if the shunt admittance was neglected in the ATP model, the results becomes comparable. This shows that models presented in this paper are accurate for the type of analysis being performed. The ATP cable model parameter calculations are very difficult to perform without a computer. In contrast the models in this paper can be readily and easily used with a very basic scientific calculator.

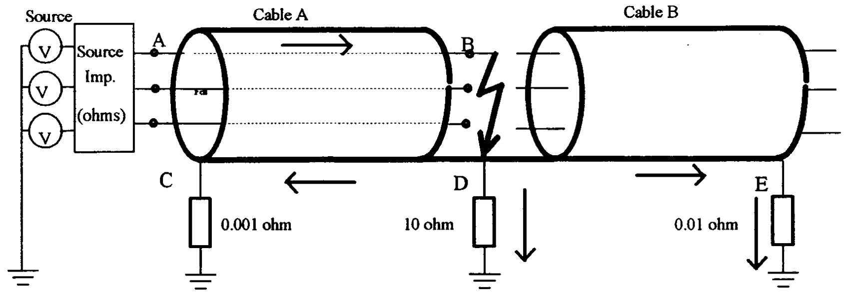


Figure 6.1 Comparison of models for a hypothetical cable - fault current splits

Source Voltage 415V	**Current (A)**				
	A to B	**D to earth**	**D to C**	**D to E**	**E to earth**
ATP Model Including Shunt Capacitance	36.513 +j153.72	0.014-j2.37	56.65 - j137.3	-20.16 - j13.84	-31.22 - j13.76
ATP Model Excluding Shunt Capacitance	36.202 j152.19	0.32-j1.67	56.014 - j136.55	-20.14 - j13.97	-20.14 - j13.97
Model Developed in this paper	34.737 - j151.247	032-j1.66	54.45 - j135.84	-20.02 - j13.74	-20.02 - j13.74

Source Voltage 11000V	**Current (A)**				
	A to B	**D to earth**	**D to C**	**D to E**	**E to earth**
ATP Model Including Shunt Capacitance	966.2 - j4067	0.37 - j62.81	1499 - j3639	-533.5 - j366	-826.17 j364
ATP Model Excluding Shunt Capacitance	957.97 - j4027	8.64 - j44.29	1482 - j3613	-532.93 - j369	-532.9 - j369
Model Developed in this paper	920.75 - j4008	8.37 - j44.04	1443 - j3600	530.9 - k364.2	-530.9 - j364.2

Source Voltage 33000V	**Current (A)**				
	A to B	**D to earth**	**D to C**	**D to E**	**E to earth**
ATP Model Including Shunt Capacitance	2898.6 - j12203	1.11 - j188.46	4497.87 - j10917	-1600 - j1094	-2478 j1092
ATP Model Excluding Shunt Capacitance	2873.9 - j12082	25.94 - j132.89	4446.77 - j10840	-1598.79 - j1109.10	-1598 - j1109
Model Developed in this paper	2762.3 -j12026	25.09 - j132.12	4329.79 -j10802	-1592.6 -j1092.17	-1592.6 -j1109

Source Voltage 66000V	**Current (A)**				
	A to B	**D to earth**	**D to C**	**D to E**	**E to earth**
ATP Model Including Shunt Capacitance	5797 - j24407	2.22 - j376	8995 - j21835	-3201 - j2196	-4957 - j2184
ATP Model Excluding Shunt Capacitance	5747 - j24164	51.8 - j265.79	8893 - j21680	-3197 j2218	-3197 j2218
Model Developed in this paper	5524 - j24053	50.2 - j264.24	8659 - j21604	-3185 - j2185	-3185 - j2185

Table 6.1 Current split as calculated by different cable models. It can be seen that if the shunt admittance was to be neglected from the ATP model, then model developed in this paper is accurate

7 SYMMETRICAL COMPONENT MODEL FOR A PHASE TO EARTH FAULT IN A TYPICAL SUB-TRANSMISSION AND A DISTRIBUTION NETWORK

The symmetrical components circuit models for a single phase-to-earth faults in a typical 33kV sub-transmission and a 11kV distribution network where a 220/33kV Point of Delivery substation is connected to a 33/11kV zone substation by an overhead line and a cable for the following five fault locations will be developed in this section (see Fig. 7.1).

a) Fault at Point of Delivery (POD) substation on 220kV side inside POD earth mat confines.
b) Fault at POD substation on 33kV side inside POD earth mat confines
c) Faults on a 33kV sub-transmission overhead line to zone substation, outside POD and zone substation earth mat confines.
d) Fault on a 33kV sub-transmission cable to zone substation, inside zone substation earth mat confines.
e) Fault on a 11kV feeder from zone substation outside zone sub-earth mat confines - at a distribution substation earth mat.

7.1 Analysis of a Typical Sub-Transmission and Distribution Network

Point of Delivery substation (POD) connected to a Zone substation by a 33kV sub-transmission 3-phase 3-wire overhead line and a 3 core cable with an insulated metallic sheath. The Zone substation is connected to a 11,000/415V distribution substations by a 11kV 3 core cables with insulated metallic sheaths.

In the following analysis, unless otherwise stated, it has been assumed that the cable sheath is insulated from the surrounding earth and both terminal ends are solidly bonded to the earth of known impedance.

The figure 7.1 below shows the fault scenarios for this case.

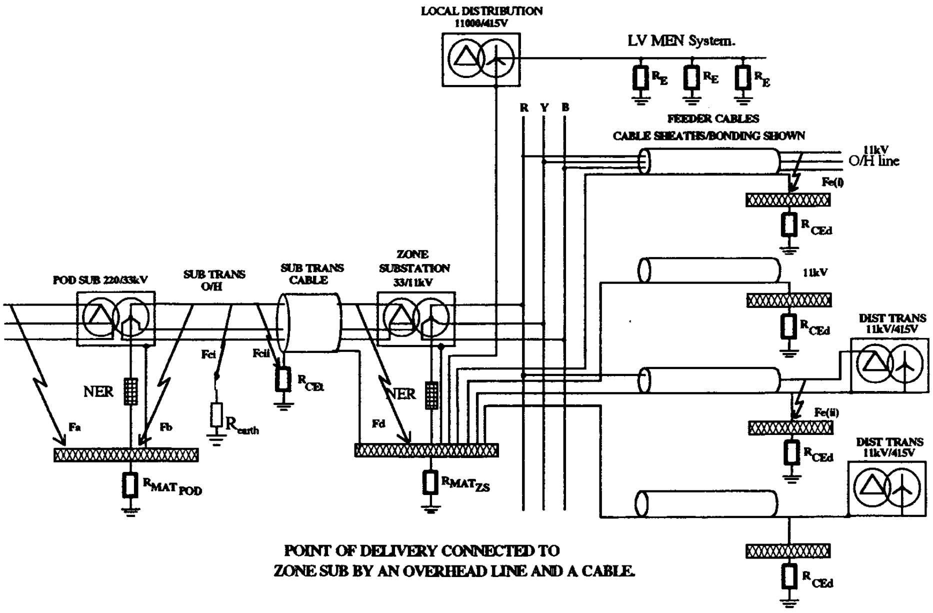


Figure 7.1 Network fault scenarios

7.1a One Phase to Earth Fault at Point of Delivery (POD) substation on 220kV Side Inside the POD Earth Mat Confines (Fa)

Assume a solid (zero impedance) fault.

7.1 A1 The EPR at the POD station

$EPR_{POD} = 1_f R_{MATPOD}$ Volts

where:

I_f is the fault current

R_{MATPOD} is the Point of Delivery substation earth mat resistance

Although in this example it is not necessary, if there are any auxiliary earth connections to this earth mat which contributes in lowering the total impedance, then the total impedance Z_{MATPOD} should be calculated first to calculate the substation EPR. The Z_{MATPOD} which is equal to R_{MATPOD} in parallel with all other auxiliary earths such as sub-transmission cable sheaths earthing is calculated by the following equation:

$$Z_{MATPOD} = \left[\frac{1}{R_{MATPOD}} + \frac{1}{\frac{Z_{ss0}}{3} + R_{CEt}} + \ldots + \frac{1}{Z_n} \right] \Omega$$

where: R_{MATPOD} - is the Point of Delivery substation earth mat resistance Ω.

$\frac{Z_{ss0}}{3} + R_{CEt}$ - the sub-transmission cable sheath self impedance and its earth bonding electrode resistance (Ω). The cable sheath self impedance is its zero sequence self impedance divided by 3.

Z_n - is the auxiliary earth impedance - this may be the self impedance of an overhead earth wire plus the pole footing resistance (outside the confines the substation earth mat) or other cable sheaths self impedance plus their bonding earth electrode resistance (Ω).

7.1B One Phase to Earth Fault at Point of Delivery (POD) substation on 33kV Side Inside the POD Earth Mat Confines (Fb)

Assume a solid (zero impedance) fault to the earth mat.

For such a fault on the earth mat, no current will flow through the earth mat to the general mass of earth, therefore the Earth Potential Rise (EPR) of the station earth mat (R_{MATPOD}) is equal to **zero**.

7.1C One Phase to Earth Fault On the 33kV Overhead Feeder to Zone Substation outside the POD Earth Mat Confines.

Assume a solid (zero impedance) fault.

7.1 C1 Fault at the 33kV Sub-transmission line pole F_{ci})

With reference to figure 7.1 and 7.3.

7.1 C1.1 The Earth Potential Rise (EPR) of the sub-transmission pole

$EPR_{pole} = 3I_0R_{earth}V$

I_0 - zero sequence current. A

R_{earth} - the resistance of the pole with respect to a remote earth Ω

7.1 C1.2 The EPR at the POD station

$EPR_{POD} = 3I_0R_{MATPOD}$ V

I_0 - zero sequence current. A

R_{MATPOD} - the resistance of the POD earth mat Ω

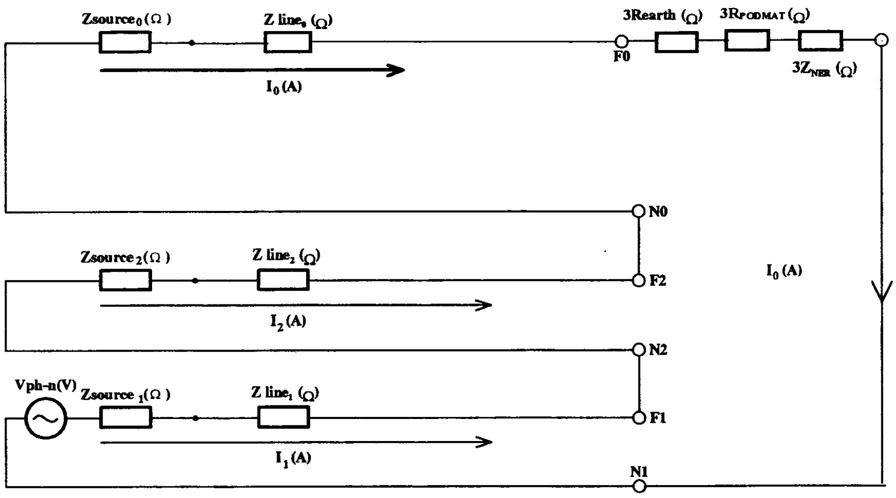


Figure 7.3 The sequence network for fault Fc_i. In this figure, Z_{source} and $3Z_{NER}$ are 33 kV system impedances.

7.1 C2 Fault at the sub-transmission cable to overhead line termination joint (Fc_{ii})

Assume a solid (zero impedance) fault.

With reference to figures 7.1 and 7.4:

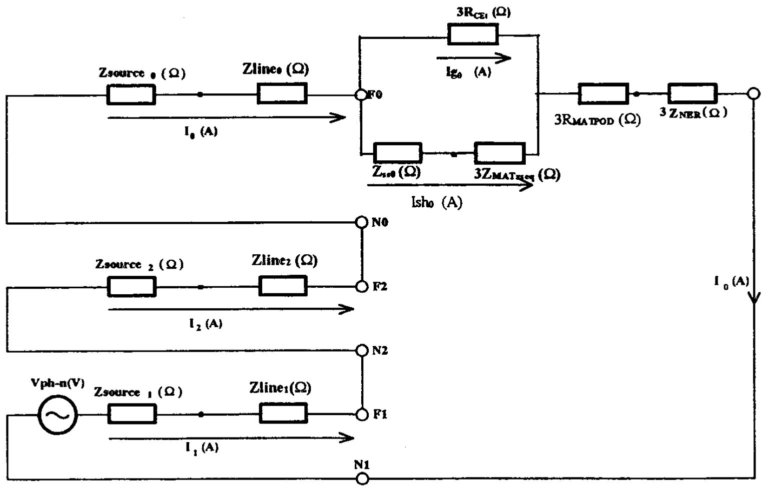


Figure 7.4. The sequence network for fault Fc_{ij}. In this figure, Z_{source} and $3Z_{NER}$ are 33 kV system impedance.

For this particular type of fault, the zero sequence fault current will split between the cable sheath bonding earth electrode and the cable sheath. The zero sequence current flowing through the sheath will further split between the zone substation earth mat, 11kV feeder cable sheaths and the connected LV MEN system.

The EPR due to this fault will be transferred to the zone substation earth mat, the distribution substation earth mats, and the LV MEN connected to these distribution substations.

7.1 C2.1 The Earth Potential Rise (EPR) of the sub-transmission cable sheath bonding electrode

$EPR_{RCEt} = 3I_{go}R_{CEt}$ V

I_{go} - zero sequence current returning to the source through this electrode and the general mass of earth. A

R_{CEt} - the resistance of the sub-transmission cable sheath bonding electrode Ω

7.1 C2.2 The EPR at the POD station

$EPR_{POD} = 3I_0Z_{MATPOD}$ V

I_0 - zero sequence current A

R_{MATPOD} - the resistance of the POD earth mat Ω

7.1 C2.3 The Transferred EPR to the Zone substation earthing system

$EPR_{zs} = 3Ish_0\ Z_{MATseq}$ V

Ish_0 - zero sequence current returning to the source via the sub-transmission cable and the zone substation earthing system. A

$Z_{MATZSeq}$ - the zone substation earthing system impedance (Ω). It is the zone substation earthing system impedance measured with respect to a remote earth. The measurement should include the influence of the connected MEN system and the auxiliary earthing (e.g. cable sheaths bonded to earth outside the substation earth mat) which contribute to this earthing system. The influence of the connected MEN system and the cable sheaths to the earth mat can be estimated by the following equations. From these equations, TEPR to remote points can also be assessed.

$$Z_{MATZSeq} \quad \frac{1}{\dfrac{1}{Z_{MATZS}} + \displaystyle\sum_{i=1}^{m}\left(\dfrac{1}{\dfrac{Z_{ss0di}}{3} + R_{CEdi}}\right) + \dfrac{1}{Z_{MEN}}}\,\Omega$$

m - number of 11kV distribution cable sheaths connected to the zone substation earth mat

Z_{MATZS} - the impedance of the earth mat with respect to the remote earth. This value should preferably be obtained before installation of the 11kV cables and the LV MEN Ω

Z_{ss0d} - the zero sequence self impedance of the 11kV distribution feeder cable sheath Ω

R_{CEd} - the Distribution substation earthing system resistance measured with respect to a remote earth (Ω). This value may include the impedance of the MEN system connected to this distribution substation earth mat.

Z_{MEN} - the impedance of the MEN connected to the zone substation earth mat. This value can be approximated by the following equation Ω

$$Z_{MEN} = \frac{1}{\displaystyle\sum_{i=1}^{n}\frac{1}{R_n}}\,\Omega$$

R_n - customer earth electrode resistance Ω

Note that the self impedance of the neutral conductor has been omitted from the above equation. If the impedance of the neutral conductor is required in the above calculation, then a ladder network equation should be used to calculate the Z_{MEN}.

7.1 C2.4 The Transferred EPR to the distribution substation earthing system

With reference to figures 7.1 and 7.5:

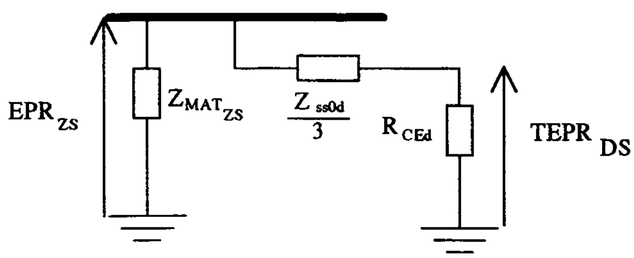


Figure 7.5 In this figure, the circuit diagram of the transferred EPR through cable sheath is shown. All impedance are in ohms

The transferred EPR at a distribution substation is calculated by the following equation:

$$TEPR_{DS} = EPR_{ZS}\left(\frac{R_{CEd}}{\frac{Z_{ss0d}}{3}+R_{CEd}}\right)V$$

where:

R_{CEd} - a Distribution substation earthing system resistance measured with respect to a remote earth Ω

Z_{ss0d} - the zero sequence self impedance of a 11kV distribution cable sheath Ω

7.1D One Phase to Earth Fault On the Feeder to Zone Substation Inside the Zone Substation Earth Mat Confines (Fd)

Assume a solid (zero impedance) fault to the earth mat

With reference to figures 7.1 and 7.6:

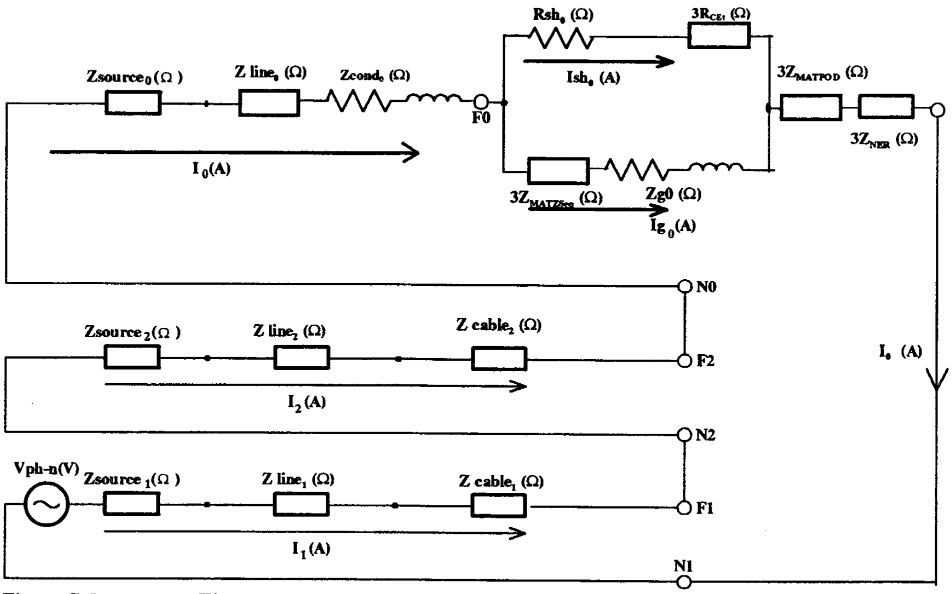


Figure 7.5 The sequence network for fault Fd. In this figure, Z_{source} and $3Z_{NER}$ are 33 kV system impedance.

7.1 D1 The Earth Potential Rise (EPR) of the POD station earth mat ($R_{(MATPOD)}$) is equal to

$EPR_{POD} = 3I_0 R_{MATPOD}$ V

where:
I_0 - the zero sequence current A

7.1 D2 The Earth potential Rise (EPR) of the Zone substation (ZS) earth mat ($Z_{MATZSeq}$) is equal to

$EPR_{ZS} = 3I_{go}Z_{MATZSeq}$ V

I_{go} - the zero sequence current returning to the source via zone substation earthing system and the general mass of earth A

$Z_{MATZSeq}$ - the zone substation equivalent earthing system impedance (Ω). It was described in detail in section 7.1 C2.2 above.

7.1 D3 The Earth Potential Rise (EPR) of the sub-transmission cable sheath bonding electrode

With reference to figures 7.1 and 7.4:

$EPR_{RCE\,t} = 3I_{sh0}\, R_{CE\,t}$ V

I_{sh0} - zero sequence current returning to the source through the 33kV cable sheath and this electrode A

$R_{CE\,t}$ - the resistance of the 33kV cable sheath bonding electrode Ω

7.1 D4 The Transferred Earth Potential Rise ($TEPR_{DS}$) through a distribution cable sheath to a Distribution substation earthing system (R_{CEd})

With reference to figures 7.1 and 7.6:

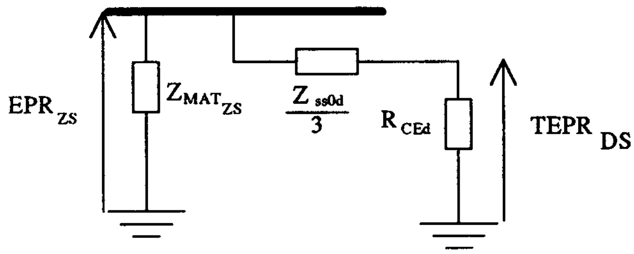


Figure 7.6 In this figure, the circuit diagram of the transferred EPR through a 11kV cable sheath to a distribution substation is shown. All impedance are in ohms.

$$TEPR_{DS} = EPR_{ZS}\left(\frac{R_{CEd}}{\frac{Z_{ss0d}}{3} + R_{CEd}}\right) V$$

R_{CEd} - a distribution substation earthing system resistance measured with respect to a remote earth Ω

Z_{ss0d} - the zero sequence self impedance of a distribution cable sheath Ω

7.1 D5 The Transferred Earth Potential Rise ($TEPR_{MEN}$) through the MEN system

An approximate answer is that $TEPR_{MEN} = EPR_{DS}$ because the voltage drop in the neutral conductor will be negligible.

However, if a more accurate result is required a detailed analysis using a ladder network should be carried out for the fault current magnitude and distribution, and TEPR in the MEN system.

7.1 E One Phase to Earth Fault on a (11kV) Cable Feeder at a Distribution Substation (Fe)

Assume a solid (zero impedance) fault.
With reference to figures 7.1 and 7.7:

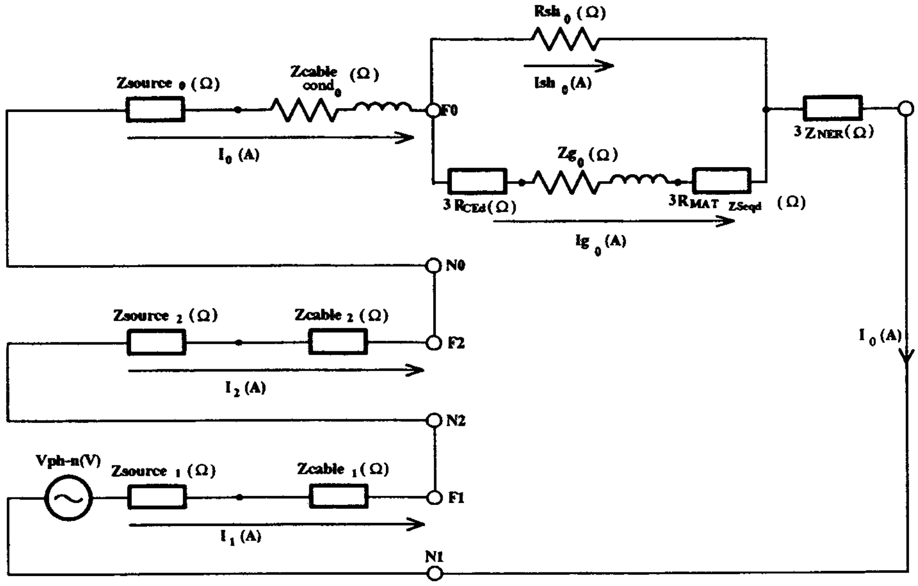


Figure 7.7 The sequence network for fault Fe_{ii}. In this figure, Zsource and $3Z_{NER}$ are 11kv system impedance

7.1 E1 The EPR at the Distribution Substation

$EPR_{DS} = 3I_{go} R_{CEd}$ V

I_{go} - zero sequence current returning through the Distribution substation earth mat and the general mass of earth A

R_{CEd} - the Distribution substation earthing system resistance measured with respect to a remote earth. It includes the MEN system resistance Ω

7.1 E2 The EPR at the Zone Substation

With reference to the figure 7.7

$EPR_{ZS} = 3I_{go} Z_{MATzseqd}$ V

I_{go} - zero sequence current returning through the Distribution substation earth mat A

$Z_{MATzseqd}$ - the zone substation total earthing system impedance (earth mat resistance in parallel with other distribution cable sheath bonding earth electrode resistance etc) measured with respect to a remote earth Ω. This impedance is different from $Z_{MATzseq}$ because it does not take into consideration the self impedance of the faulted cable sheath and its bonding earth electrode resistance.

7.1 E3 The Transferred Earth Potential Rise ($TEPR_{MEN}$) from the Distribution Substation to the MEN system

An approximate answer is that $TEPR_{MEN}$ = EPR_{DS} because the voltage drop in the neutral conductor will be negligible.

However, if a more accurate result is required a detailed analysis using a ladder network should be carried out for the fault current magnitude and distribution, and TEPR in the MEN system.

8 A NUMERICAL EXAMPLE

A complete set of calculations illustrating the use of the models developed in Section 7 of this paper were performed for typical phase to earth fault scenarios. These calculations are annexed in appendix B.

The scenarios studied are for the network discussed in Section 7, where a POD substation was connected to a zone substation by an overhead line and a cable for the following five single phase to earth fault locations:

a) Fault at Point of Delivery (POD) substation on 220kV side inside POD earth mat confines (Fa).
b) Fault at POD substation on 33kV side inside POD earth mat confines (Fb).
c) Faults on a 33kV sub-transmission overhead line from a POD substation to a zone substation, outside the POD and zone substation earth mat confines (Fci and Fcii).
d) Fault on a 33kV sub-transmission cable from a POD substation to a zone substation, inside zone substation earth mat confines (Fd).
e) Fault on a 11kV feeder from zone substation to a distribution substation earth mat (Fe).

Table 8.1 below summarises EPR and the TEPR results for all of these faults at the various fault locations in the network shown in figure 7.1.

Description of Earth Mats		The EPR and the TEPR for the following faults (Volts)					
		Fa	**Fb**	**Fci**	**Fcii**	**Fd**	**Fe**
1	Point of Delivery substation	7446	0	371	5351	4250	N/A
2	At 33kV Pole	N/A	N/A	18,545	N/A	N/A	N/A
3	Sub-transmission cable Sheath bonding electrode	N/A	N/A	N/A	3816	6470	Reader to Calculate
4	Zone substation earth mat	N/A	N/A	N/A	868	694	52
5	Distribution substation (1) earth mat. No MEN connected at this substation at this stage	N/A	N/A	N/A	814	662	3102
6	Distribution substation earth Mat (2) with MEN connected At this substation	N/A	N/A	N/A	318	217	Reader to calculate

Table 8.1 Summary of EPR calculation results from Appendix B

The graphs in figures 8.1 to 8.6 below show the influence of the resistance of the various earth mats on EPR in the 33kV and the 11kV networks modelled.

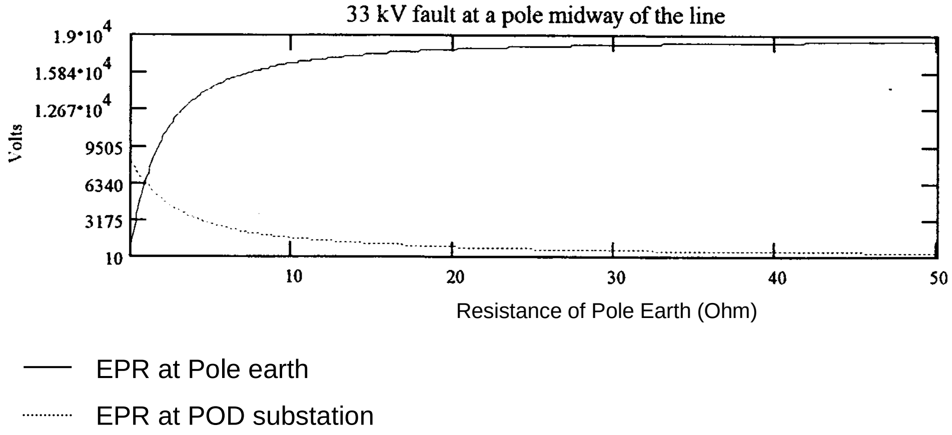


Figure 8.1 EPR at the Pole earth and the POD substation earth mat due to a 33kV Ph-E fault at a pole midway along the line F(ci)

Figure 8.1 above shows the EPR at the pole and the POD substation for different pole earth resistance values. It can be seen that increasing the pole earth resistance causes reduced EPR at the POD substation. It also shows that EPR at the pole will be very high if the POD substation earth mat resistance is very low compared to the pole earth resistance. The EPR at the pole earth can be reduced by installing a NER at the source substation as shown in figure 8.2 below.

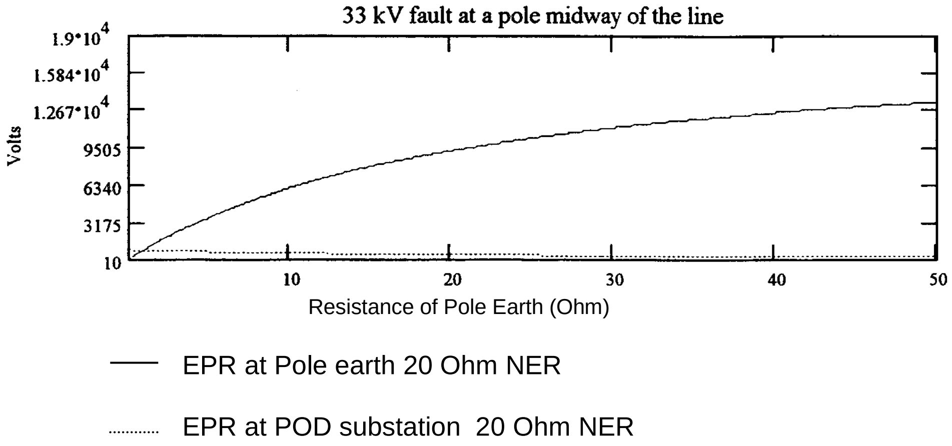


Figure 8.2 EPR at the Pole earth and the POD substation due to a 33kV Ph-E fault at a pole midway along the line (F(ci)). A 20 Ohm NER is connected at the source substation

In figure 8.3 below, the influence of the 33kV cable sheath bonding electrode resistance on the EPR at the POD substation, zone substation and 11kV distribution substation is shown. From this figure, it is observed that after certain maximum threshold value of the electrode resistance, an additional increase in the cable sheath electrode resistance has an insignificant effect on the EPR at the various locations in the 33kV and 11kV networks.

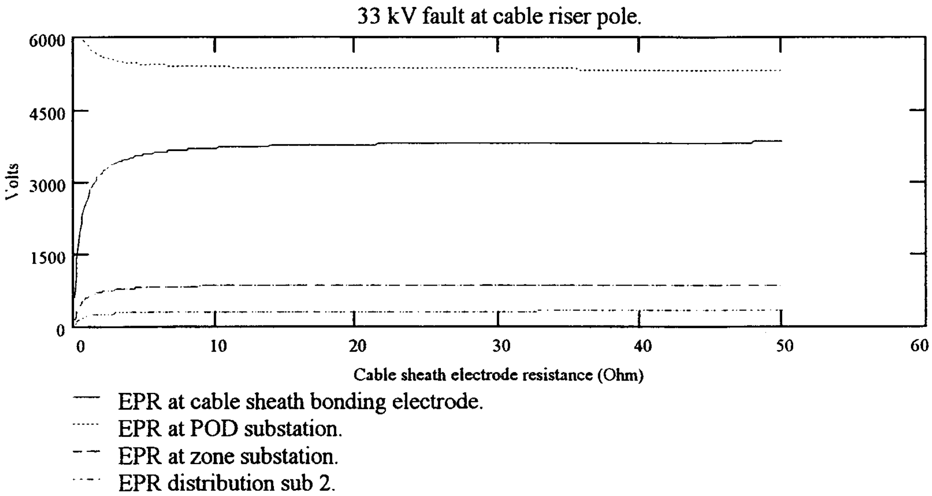


Figure 8.3 EPR due to a 33kV Ph-E fault at the 33kV cable to line termination joint (Fcii) for increasing value of the cable sheath bonding electrode resistance. The EPR at the sheath bonding electrode, POD substation, zone substation and distribution substation earth mats are shown

From figure 8.3, it can be observed that (for 1 Ohm POD substation earth mat resistance) the POD substation EPR is always higher than the EPR in the rest of the network for all values of the cable sheath bonding electrode resistance.

The benefit of using a 20 Ohm NER for reducing EPR for the above fault scenario is shown in figure 8.4 below.

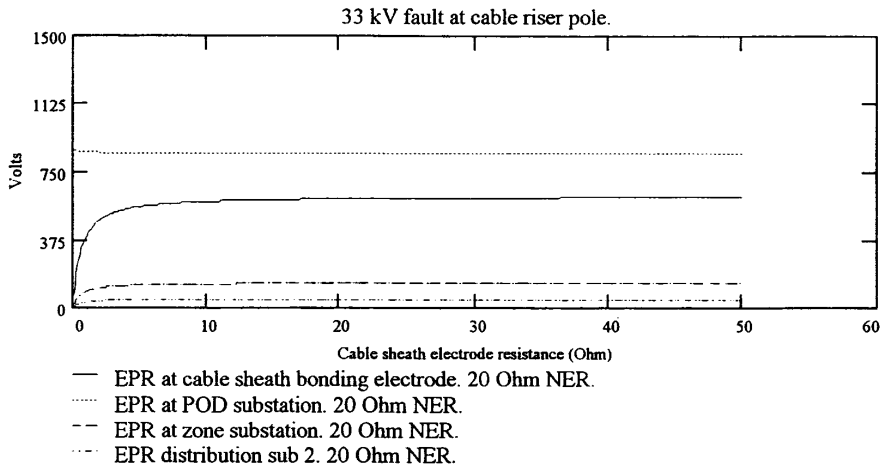
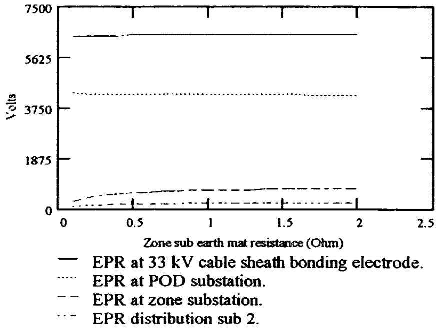


Figure 8.4 EPR due to a 33 kV Ph-E fault at the 33 kV cable to line termination joint (Fcii) for increasing value of the cable sheath bonding electrode resistance. A 20 Ohm NER is connected at the source. The EPR at the sheath bonding electrode, POD substation, zone substation and distribution substation earth mats are shown.

From figure 8.4 above, it can be seen that the EPR at the POD reduces from 5,300V to 850V with a 20 Ohm NER. Likewise, EPR in the rest of 33kV and 11kV networks are reduced.

Figures 8.5a and b below show EPR in the 33kV and the 11kV networks due to a 33kV fault at the zone substation (Fd) for various zone substation earth mat resistance values.



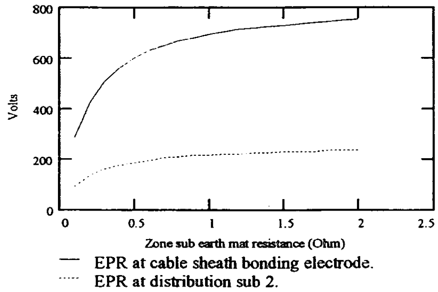


Figure 8.5a **Figure 8.5b**

Figure 8.5 EPR due to a 33kV Ph-E fault at the zone substation (Fd) for increasing value of the zone substation earth mat resistance. The EPR at the 33kV cable sheath bonding electrode, POD substation, zone substation and a distribution substation earth mats are shown.

From figures 8.5a and b above, it can be observed that the EPR at the 33kV cable sheath bonding electrode (25 Ohm) and the POD substation earth mat (1 Ohm) is relatively very high for this particular fault for various values of the zone substation earth mat resistance. From 8.5b it can be seen that there is very little increase in the zone substation EPR for the earth mat resistance values greater than 1 Ohm.

Figures 8.6a, b and c below show the EPR in the 33kV and 11kV network due to a 11kV fault (Fe) at a distribution substation without a MEN connected to its earth mat.

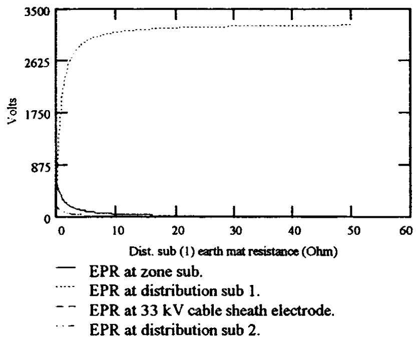


Figure 8.6 a

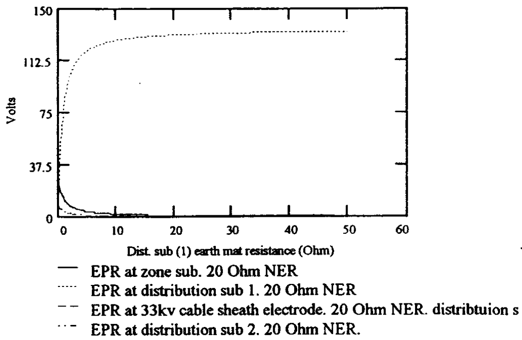


Figure 8.6 b

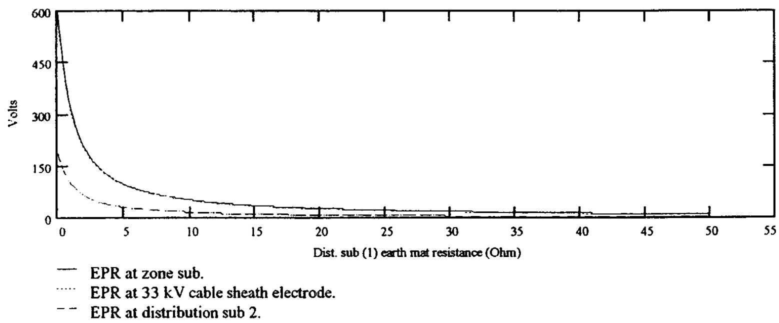


Figure 8.6 c

Figure 8.6 EPR due to a 11kV Ph-E fault at a distribution substation (Fd) without MEN connection, for increasing values of the distribution substation earth mat resistance. The EPR at the 33kV cable sheath bonding electrode, zone substation and distribution substation earth mats are shown.

From figures 8.6a, b and c, it can be seen that for distribution substation earth mat resistances greater than 10 Ohm, there is very little influence on the magnitude of EPR in the 33kV and 11kV networks. Once again, the benefit of a 20 Ohm NER in reducing EPR can be seen in figure 8.6b. For very low values of the distribution substation earth mat resistance, the EPR at 33kV cable sheath bonding electrode and the zone substation earth mat will be relatively high.

In figures 8.3 to 8.6, it was shown that there exists a maximum threshold earth mat resistance for a given earth mat in an interconnected earthing system, beyond which there is insignificant increase in the EPR. This is a very important observation since reducing one substation earth mat’s resistance to reduce its EPR, can cause an increase in EPR in the other parts of the network.

It was also shown that if the receiving substation earthing system impedance was lower than the source substation, then the source substation may have highest EPR in that network. Relatively high earthing system resistance at the receiving substation means lower EPR at the source substation.

CONCLUSIONS

In this paper, equations for calculating positive and zero sequence impedances for an overhead line and an underground three core, insulated metallic sheath covered cable are given. Appropriate symmetrical component circuit models were developed to calculate the phase to earth fault current and fault current split between the cable sheath and the earth mat.

When using the symmetrical components method of analysis of unbalanced faults in cable networks, the zero sequence impedance model of the 3-core, insulated metallic sheath cable is important for calculating EPR. Cables installed in different locations in a network (e.g. all cable, cable-line, line-cable, cable-line-cable and line-cable-line) will have different zero sequence impedance circuit models. Since EPR is caused by the zero sequence current, it is important to use the correct zero sequence impedance model.

The fault current splits calculated by models developed in this paper were checked for their validity against the more sophisticated Alternate Transients Program (ATP) models. The results of this comparison show that the models presented in this paper are sufficiently accurate for current split calculations.

Numerical examples are given to illustrate the application of the models for calculating fault current splits and the earth potential rise for various fault locations in a typical sub-transmission and distribution network.

The calculations show that even though 96% of the total fault current in the 11kV cable network with bonded cable sheaths returns to the source via the sheath, the EPR for 10 Ohms earthing system resistance can be as high as 3100 Volts (i.e. 49% of the system voltage).

The calculations show that the benefits of cable sheath bonding on EPR levels are mixed. For the case of the 11kV cable sheath bonded to both the 33/11kV zone substation and 11kV/415V distribution substation earthing systems, the effects of cable sheath bonding are:

(i) For an 11kV ph - E fault at the distribution substation, the EPR at both the zone and distribution substations will be low.

(ii) For a 33kV ph-E fault at the zone substation, the resultant EPR at the zone substation will be reduced, but at the COST of transferring almost all this EPR to the distribution substation earthing system (which would otherwise have had no EPR). However, in an extensively MEN system, this EPR level will be insignificant, and bonding of cable sheaths will reduce it even further.

A neutral earthing resistor (NER) will act as a voltage divider in the fault circuit and can substantially reduce the EPRs in the network.

The sequence impedance parameters (for lines and cables) and fault circuit models developed in this paper can also be used to calculate parameters required by power system analysis software such at PTI's PSS/U.

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APPENDIX A

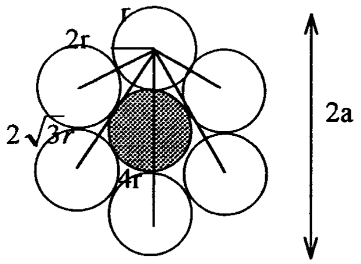
CALCULATIONS OF GMR, POSITIVE AND ZERO SEQUENCE LINE AND CABLE PARAMETERS

A.1 Calculation of Geometric Mean Radius of ASCR Conductor

The GMR of ASCR conductors are calculated by considering positions of Aluminium strands in the conductor. It is assumed that no current flows in the steel strands and therefore are omitted from the calculation.

For illustration, the GMR calculation for the DOG (Al - 6/4.72 mm and Fe - 7/1.57 mm) conductor is given below.

The diameter of 7/1.57 mm strands is equal to 4.72 mm



GMR = $\sqrt[36]{(e^{-\frac{1}{4}}r)^6(2r)^{12}(2\sqrt{3r})^{12}(4r)^6}$

GMR = 2.3038r

GMR = (0.768)(7.1mm)

GMR = 5.453 mm

A.2 Calculation of the Line Parameters

33kV Line - Physical dimensions

Conductor type = DOG (6/4.72 Al & 7/1.57 Steel strands)

Resistance of the Conductor @ 20 deg C (ohms/km) R := 0.2722

Approximate overall diameter (mm) d := 14.2

Radius of the conductor mm a “= $\frac{d}{2}$

Spacing between lines (mm) dab := 1090 dbc := 880 dac := 1970

Deep layer soil resistivity (ohm-m) ρ := 200 frequency (Hz) f := 50

GMR := a0.768 GMD := $\left[(dab.dbc.dac)^{\frac{1}{3}}\right]$ GMR3cond := $\left[GMR^3.dab^2.dbc^2.dac^2)^{\frac{1}{9}}\right]$

GMR = 5.4528 GMD = 1236.3036 GMR3cond = 202.748

Positive sequence Impedance (ohms/km)

$Z1 = R + j \cdot \left(2.893 10^{-3} . f . \log\left(\frac{GMD}{GMR}\right)\right)$ Z1 = 0.2722 + 0.3407j

Zero sequence Impedance (ohms/km)

$$Z0 := 3. \left[\frac{R}{3} + 988.2.10^{-6} . f + j.2.893.10^{-3} . f . \log\left[\frac{658368 . \sqrt{\frac{\rho}{f}}}{GMR3cond}\right]\right]$$ Z0 = 0.4204 + 1.6545j

A.3 Calculation of the Cable Parameters

33kV PILCA cable. Physical dimensions

Conductor type = 150 AL (37 strands) assume round conductor

Resistance of the Conductor @ 20 deg C (ohms/km) R :=0.2060

Radius of the conductor (mm) a := 6.764

Spacing between conductors (mm) S := 27.76

Resistivity of the sheath (ohm-m) $\rho sh := 21.4.10^{-8}$

Inside radius of the sheath (mm) ri := 30.36

Outside radius of the sheath (mm) ro := 33.09

Soil resistivity (ohm-m) $\rho := 200$ frequency (Hz) f := 50

GMR :=a.0.768 $GMRsh := \frac{ro+ri}{2}$ dsh := GMRsh $GMR3cond := \left[(GMR.S^2)^{\frac{1}{3}}\right]$

GMR = 5.1948 GMRsh = 31.725 dsh = 31.725 GMR3cond = 15.8782

$$Rsh := \frac{\rho sh.10^9}{\pi.\left(ro^2 - ri^2\right)}$$ Rsh = 0.3933

Positive sequence impedance (ohms/km)

$Z_1 := R + j \cdot \left(2.893 10^{-3} . f . \log\left(\frac{S}{GMR}\right)\right)$ $Z_1 = 0.206 + 0.1053j$

Zero sequence Self Impedance of the conductor (ohms/km)

$$Z_{sc0} := 3. \left[\frac{R}{3} + 988.2.10^{-6} . f + j.2.893.10^{-3} . f . \log\left[\frac{658368 . \sqrt{\frac{\rho}{f}}}{GMR3cond}\right]\right]$$ $Z_{sc0} = 0.3542 + 2.1345j$

Zero sequence Self Impedance of the sheath (ohms/km)

$$Z_{ss0} := 3. \left[Rsh + 988.2.10^{-6} . f + j.2.893.10^{-3} . f . \log\left[\frac{658368 . \sqrt{\frac{\rho}{f}}}{GMR3cond}\right]\right]$$ $Z_{ss0} = 1.328 + 2.004j$

Zero impedance Mutual Impedance (ohms/km)

$$\mathbf{Z_{mcs0}} := 3.\left[988.2.10^{-6}.f + j.2.893.10^{-3}.f.\log\left[\frac{658368.\sqrt{\frac{\rho}{f}}}{dsh}\right]\right] \qquad \mathbf{Z_{mcs0} =} 0.1482 + 2.004j$$

Zero sequence impedance of the cable for the Model (ohms/km)

$Z_{cond0} := Z_{sc0} - Z_{mcs0}$ $\qquad$ $Z_{cond0} = 0.206 + 0.1304j$

$R_{sh0} := Z_{ss0} - Z_{mcs0}$ $\qquad$ $R_{sh0} = 1.1798$

$Z_{g0} := Z_{mcs0}$ $\qquad$ $Z_{g0} = 0.1482 + 2.004j$

APPENDIX B

A NUMERICAL EXAMPLE

No Neutral Earthing Resistors (NERs) used in this example

SYSTEM DATA

220kV SYSTEM DATA

Source Voltage (Volts) & Impedance (Ohm)

$V_{sl.220} := \frac{220000}{\sqrt{3}}$ $V_{sl.220} = 127017$ V

220kV Positive sequence impedance	$Z_{1.220} := 2.2361 + 19.4762j$
220 kV Negative sequence impedance	$Z_{2.220} := 2.3474 + 20.2022j$
220kV Zero sequence impedance	$Z_{0.220} := 0.7018 + 10.8222j$

33kV SYSTEM DATA

Source Voltage (Volts) and Impedance (ohms)

$V_{sl.33} := \frac{33000}{\sqrt{3}}$ $V_{sl.33} = 19053$ V

33kV Positive sequence impedance	$Z_{1.33} := 0.0851 + 1.3500j$
33kV Negative sequence impedance	$Z_{2.33} := 0.1020 + 1.3600j$
33kV Zero sequence impedance	$Z_{0.33} := 0.1000 + 0.9310j$

33kV Sub-Transmission Cable Impedance

Cable size and Type : 150 Al PILCA Length (km) $C_{33} := 0.75$

Cable sequence impedance (ohms/km)

33kV Cable positive sequence impedance	$Z_{cl.33} := 0.2060 + 0.1053j$
33kV Cable Negative sequence impedance	$Z_{c2.33} := Z_{cl.33}$
33kV Cable conductor zero sequence impedance	$Z_{cond0.33} := 0.2060 + 0.1304j$
33kV Cable sheath zero sequence impedance	$R_{sh0.33} := 1.1798$
33kV Cable ground return zero sequence impedance	$Z_{g0.33} := 0.1482 + 2.0040j$
33kV Cable sheath zero sequence self impedance	$Z_{ss0.33} := 1.3280 + 2.0040j$

33kV Sub-Transmission Line Impedance (ohms/km)

Line size and Type: DOG Length (km) $L_{33} := 1.5$

33kV Line Positive sequence impedance	$Z_{L1.33} := 0.2722 + 0.3407j$
33kV Line Negative sequence impedance	$Z_{L2.33} := Z_{L1.33}$
33kV Line zero sequence impedance	$Z_{L0.33} := 0.4204 + 1.6545j$

33kV NER And Earthing Impedance (ohms)

33kV neutral earthing resistor resistance	$NER_{33} := 0$
33kV source sub earth mat resistance	$R_{matpod} := 1.0$

33kV Cable sheath bonding earth electrode resistance $R_{CE\ t} := 25$

33kV line to earth fault resistance (e.g. at a pole) $R_{earth} := 50$

11kV SYSTEM DATA

Source Voltage (volts) & Impedance (ohms)

$V_{sl.11} := \frac{11000}{\sqrt{3}}$ $V_{s1.11}$ - 6351 V

11kV Positive sequence impedance $Z_{1.11} := 0.8898 + 0.6187j$

11kV Negative sequence impedance $Z_{2.11} := Z_{1.11}$

11kV Zero sequence impedance $Z_{0.11} := 0.04261 + 0.4261j$

11kV Distribution Cable Impedance

1. Cable size and Type : 300 Al PILCA Length (km) $L_1 := 0.75$

Cable sequence impedance (ohms/km)

11kV Cable Positive sequence impedance $Z_{c1.1} := 0.1086 + 0.0711j$

11kV Cable Negative sequence impedance $Z_{c2.1} := Z_{c1.1}$

11kV Cable conductor zero sequence impedance $Z_{cond0.1} := 0.1001 + 0.1049j$

11kV Cable sheath zero sequence impedance $R_{sh0.1} := 1.754$

11kV Cable ground return zero sequence impedance $Z_{g0.1} := 0.1480 + 2.0337j$

11kV Cable sheath zero sequence self impedance $Z_{ss0.1} := 1.9020 + 2.0337j$

2. Cable size and Type : 300 Al PILCA Length (km) $L_2 := 1.25$

Cable sequence impedance (ohms/km)

11kV Cable Positive sequence impedance $Z_{cl.2} := 0.1086 + 0.0711j$

11kV Cable Negative sequence impedance $Z_{c2.2} := Z_{c1.1}$

11kV Cable conductor zero sequence impedance $Z_{cond0.2} := 0.1001 + 0.1049j$

11kV Cable sheath zero sequence impedance $R_{sh0.2} := 1.754$

11kV Cable ground return zero sequence impedance $Z_{g0.2} := 0.1480 + 2.0337j$

11kV Cable sheath zero sequence self impedance $Z_{ss0.2} := 1.9020 + 2.0337j$

3. Cable size and Type : 300 A1 PILCA Length (km) $L_3 ;= 0.25$

Cable sequence impedance (ohms/km)

11kV Cable Positive sequence impedance $Z_{c1.3} := 0.1086 + 0.0711j$

11kV Cable Negative sequence impedance $Z_{c2.3} := Z_{c1.1}$

11kV Cable conductor zero sequence impedance $Z_{cond0.3} := 0.1001 + 0.1049j$

11kV Cable sheath zero sequence impedance $R_{sh0.3} := 1.754$

11kV Cable ground return zero sequence impedance $Z_{g0.3} := 0.1480 + 2.0337j$

11kV Cable sheath zero sequence self impedance $Z_{ss0.3} := 1.9020 + 2.0337j$

4. Cable size and Type : 300 Al PILCA Length (km) $L_4 := 0.752$

Cable sequence impedance (ohms/km)

11kV Cable Positive sequence impedance	$Z_{c1.4} := 0.1086 + 0.0711j$
11kV Cable Negative sequence impedance	$Z_{c2.4} := Z_{c1.1}$
11kV Cable conductor zero sequence impedance	$Z_{cond0.4} := 0.1001 + 0.1049j$
11kV Cable sheath zero sequence impedance	$R_{sh0.4} := 1.754$
11kV Cable ground return zero sequence impedance	$Z_{g0.4} := 0.1480 + 2.0337j$
11kV Cable sheath zero sequence self impedance	$Z_{ss0.4} := 1.9020 + 2.0337j$

11kV NER and Earthing Impedance (ohms)

11kV Neutral earthing resistor resistance	$NER_{11} := 0$
11kV Zone substation earth mat resistance	$R_{MATzs} := 1.0$
11kV Cable no. 1 - distribution sub electrode res.	$R_{CE.1} := 10$
11Kv Cable No. 2 - distribution sub electrode res.	$R_{CE.2} := 10$
11kV Cable No. 3 - distribution sub electrode res.	$R_{CE.3} := 10$
11Kv Cable No. 4 - distribution sub electrode res.	$R_{CE}.4 := 10$

LV Consumer Earth Electrode Resistance (ohms)
Assume each distribution substation MEN is isolated from the adjacent distribution substation MEN. The MEN is not connected to the HV source substation. Also assume that distribution sub No. 1 has no MEN installed at this stage. This is typical of new URD subdivision installations.

number of consumers per MEN n : = 50

electrode resistance $R_e := 25$

CALCULATIONS

7A1 The EPR at the POD Station (Fault Fa) Refer fig. 7.1 in the text

Zero sequence fault current

$$I_{0.220} := \frac{V_{s1.220}}{Z_{1.220} + Z_{2.220} + Z_{0.220} + 3.R_{MATPOD}}$$

$I_{0.22} := 401.8 - 2449.2J$ A

$|I_{0.220}| = 2482$ A

Fault current (Amps)

$If_{220} := 3I_{0.220}$

$If_{220} = 1205.5 - 7347.7J$ A

$|If_{220}| = 7445.9$ A

$EPR_{POD} := If_{22o} .R_{MATPOD}$

$|EPR_{POD}| = 7445.9$ Ohm

7C1 Fault at the sub-transmission line pole (midway of the line) (Fci). With reference to figure 7.3

Sequence network impedance (ohms)

$Z_{pos.33} : Z_{1.33}\, Z_{L1.33} . \frac{L_{33}}{2}$ $\qquad Z_{pos.33} = 0.2893 + 1.6055j$

$Z_{neg.33} := Z_{2.33} + Z_{L2.33} . \frac{L_{33}}{2}$ $\qquad Z_{neg.33} + 0.3061 + 1.6155j$

$Z_{zero.33} := Z_{0.33} + Z_{L0.33} . \frac{L_{33}}{2} + 3.4_{earth} + 3.R_{MATPOD}$ $\qquad Z_{zero.33} = 153.4153 + 2.1719j$

Zero sequence fault current (Amps)

$$I_0 := \frac{V_{s1.33}}{Z_{pos.33} + Z_{neg.33} + {}_{zero.33} + 3.NER_{33}}$$

$I_0 = 123.6 - 4.3J$ A

$|I_0| = 123.6335$ A

Fault current (Amps)

$If = 3.I_0$

$If = 370.7 - 13j$ A

$|If| = 370.9$ A

7C1.1 The EPR of the sub-transmission line pole (R_{earth})

(Volts)

$EPR_{Rearth} := 3.I_0 .R_{earth}$

$|EPR_{Rearth}| = 18545$ V

2C1.2 The EPR at the POD station (Volts)

$EPR_{POD} := 3.I_0 .R_{MATPOD}$

$|EPR_{POD}| = 370.9$ V

7C2 Fault on the sub-transmission line to cable termination joint (Fcii). With reference to figure 7.4

Sequence network impedance (Ohms)

$Z_{pos.33} := Z_{1.33} = Z_{L2.33} .L_{33}$ $\qquad Z_{pos.33} = 0.4934 + 1.8611j$

$Z_{neg.33} := Z_{2.} + Z_{L2.33} .L_{33}$ $\qquad Z_{neg.33} = 0.51\text{-}03 + 1.8711j$

Calculate $Z_{MATzseq}$ (Ohms)

Zss - total self impedance of the 11kV feeder cables including their sheath bonding electrode resistance.

$$Z_{MEN} := \frac{1}{.\left(n.\frac{1}{R_e}\right)} \qquad Z_{MEN} = 0.5$$

The equivalent impedance of the distribution sub earthing : electrodes + MEN. MEN at distribution sub No. 1 not installed at this stage.

$$Z_{dsMEN.1} := R_{CE.1} \qquad Z_{dsMEN.2}\left(\frac{1}{R_{CE.2}}+\frac{1}{Z_{MEN}}\right)^{-1}$$

$$Z_{dsMEN}\ 3 := \left(\frac{1}{R_{CE.3}}+\frac{1}{Z_{MEN}}\right)^{-1} \quad Z_{dsMEN.4} := \left(\frac{1}{R_{CE.4}}+\frac{1}{Z_{MEN}}\right)^{-1}$$

$$Z_{ss} := \left(\frac{1}{\frac{Z_{ss0.1}.L_1}{3}+Z_{dsMEN.1}}+\frac{1}{\frac{Z_{ss0.2}.L_2}{3}+Z_{dsMEN.2}}+\frac{1}{\frac{Z_{SS0.3}.L_3}{3}+Z_{dsMEN}}+\frac{1}{\frac{Z_{ss0.4}.L_4}{3}+Z_{dsMEN.4}}\right)^{-1}$$

$Z_{ss} = 0.2926 + 0.1198j$

$$Z_{MATzseq} := \left[\left(\frac{1}{R_{MATzs}}\right)+\frac{1}{Z_{ss}}+\frac{1}{Z_{MEN}}\right]^{-1} \qquad Z_{MATzseq} = 0.1621 + 0.0328j$$

$$Z_{sero.33} := Z_{0.33} + Z_{L0.33} .L_{33} + \left(\frac{1}{3.R_{CE\,t}}+\frac{1}{Z_{ss0.33}.C_{33}+3.Z_{MATzseq}}\right)^{-1} + 3.R_{MATPOD}$$

$z_{ZERO.33} = 5.2164 + 4.9519J$

Zero sequence fault current (Amps

$$I_0 := \frac{V_{s1.33}}{Z_{pos.33} + Z_{neg.33} + Z_{zero.33} + 3.NER_{33}}$$

I_0 = 1038.6 - 1450j A

$\left|I_0\right|$ = 1783.6 A

Fault current (Amps)

$I_f = 3.1_0$

I_f = 3115.9 - 4350.1j A

$\left|I_f\right|$ = 5350.9 A

Zero sequence fault current returning through the cable sheath (Amps)

$$I_{sh0} := I_0. \frac{3.R_{CE\,t}}{3.R_{CE\,t + Z_{ss0.33}}.C33 + 3.Z_{MATzseq}}$$

I_{sh0} = 988.3 - 1442.6j A

$\left|I_{sh0}\right|$ = 1748.7 A

Zero sequence fault current returning through earth (Amps)

$$I_{g0} := I_0 . \frac{Z_{ss0.33}.C_{33} + 3.Z_{MATzseq}}{3.R_{CE\,t} + Z_{ss0.33}.C + 3.Z_{MATzseq}}$$

I_{g0} = 50.3 - 7.4j

$\left|I_{g0}\right|$ = 50.9

7C2.1 The Earth Potential Rise (EPR) of the sub-transmission cable sheath bonding electrode (R_{CEt}) (Volts)

$EPR_{RCE\,t} = 3.1_{g0} .R_{CE\,t}$

$EPR_{RCE\,t}$ = 3775 - 555.9j V

$\left|EPR_{RCEt}\right|$ = 3815.7 V

7C2.2 The EPR at the POD station (Volts)

$EPR_{POD} := 3.I_0 .R_{MATPOD}$

EPR_{POD} = 3115.9 - 4350.1j V

$\left|EPR_{POD}\right|$ = 5350.9

7C2.3 The Transferred EPR at the Zone substation (Volts)

$EPR_{zs} := 3.I_{sh0} .Z_{MATzseq}$

EPR_{zs} =622.4 - 604.4j

$\left|EPR_{zs}\right|$ = 867.6

7C2.4a The Transferred EPR at the distribution substation 1 (Volts)

$$TEPR_{DS.1} := EPR_{ZS} \cdot \left[\frac{Z_{dsMEN.1}}{\left(\frac{z_{SS0.1}}{3} + z_{DSmen.1}\right)}\right]$$

$TEPR_{DS.1} = 546.8 - 603.3j$

$\left|TEPR_{ds.1}\right| = 814.2$ V

7C2.4b The Transferred EPR at the distribution substation 2 (Volts)

$$TEPR_{DS.2} := EPR_{ZS} \cdot \left[\frac{z_{dsMEN.2}}{\left(\frac{Z_{ss0.2}}{3} + Z_{dsMEN.2}\right)}\right]$$

$TEPR_{DS.2} = 79.1 - 307.6J$

$\left|TEPR_{DS.2}\right| = 317.6$ V

7D One phase to Earth fault on the 33kV sub-transmission feeder to Zone substation inside the zone Substation earth mat confines (Fd). With reference to figure 7.5

Sequence network impedance

$Z_{pos.33} := Z_{1.33} + Z_{L1.33} \cdot L_{33} + Z_{cl.33} \cdot C_{33}$ $Z_{pos.33} = 0.6479 + 1.94j$

$Z_{neg.33} = Z_{2.33} + Z_{L2.33} \cdot L_{33} + Z_{c2.33} \cdot C_{33}$ $Z_{neg.33} = 0.6648 + 1.95j$

$$Z_{zero.33} := Z_{0.33} + Z_{L0.33} \cdot L_{33} + Z_{cond0.33} \cdot C_{33} + \left(\frac{1}{R_{sh0.33} \cdot C_{33} + 3 \cdot R_{CE\,t}} + \frac{1}{3 \cdot Z_{MATzseq} + 3 \cdot Z_{g0.33} \cdot C_{33}}\right)^{-1}$$

$Z_{zero.33} = 1.966 + 8.0037j$

Zero sequence fault current (Amps)

$$I_0 := \frac{V_{sl.33}}{Z_{pos.33} + Z_{neg.33} + Z_{zero.33} + 3 \cdot R_{MATPOD} + 3 \cdot NER_{33}}$$

$I_0 = 661.3 - 1252.8j$ A

$\left|I_0\right| = 1416.6$ A

Fault current

$I_f := 3 \cdot I_0$

$I_f = 1984 - 3758.3j$ A

$\left|I_f\right| = 4249.9$ A

Zero sequence fault current returning through cable sheath (Amps)

$$I_{sh0} := I_0 \cdot \frac{3.Z_{MATzseq} + 3.Z_{g0.33}.C_{33}}{R_{sh0.33}.C_{33} + 3.R_{CE\,t} + 3.Z_{MATzseq} + 3.Z_{g0.33}.C_{33}}$$

I_{sh0} = 83.6 + 21.3j A

$|I_{sh0}|$ = 86.3 A

Zero sequence fault current returning through ground (Amps)

$$I_{go} := I_0 \cdot \frac{R_{sh0.33}.C_{33} + 3.R_{CE\,t}}{R_{sh0.33}.C_{33} + 3.R_{CE\,t} + 3.Z_{MATzseq} + 3.z_{g0.33}.C_{33}}$$

I_{go} = 577.7 - 1274.1j

$|I_{g0}|$ = 1399

7D1 The Earth Potential Rise of the POD station earth mat (Volts)

$EPR_{POD} := 3.I_0 .R_{MATPOD}$

$|EPR_{POD}|$ = 4249.9 V

7D2 The Earth potential Rise of the Zone substation earth mat (Volts)

$EPR_{zs} := 3.I_{g0} .Z_{MATzseq}$

EPR_{zs} = 406.2 - 562.8j V

$|EPR_{zs}|$ = 694.1 V

7D3 The EPR of the sub-transmission cable sheath bonding electrode (Volts)

$EPR_{RCE\,t} := 3.I_{sh0} .R_{CE\,t}$

$EPR_{RCE\,t}$ = 6269.7 + 1598.5j V

$|EPR_{RCE\,t}|$ = 6470.3 V

7D4 The transferred EPR though the distribution cable sheath to the distribution substation earthing system (no MEN at this site) (Cable 1) (Volts) Figure 7.6

$$TEPR_{DS.1} := EPR_{ZS} \cdot \frac{Z_{dsMEN.1}}{\left(\frac{Z_{ss0.2}.L1}{3} + Z_{dsMEN.1}\right)}$$

$TEPR_{DS.1}$ = 360.818 - 554.78j V $|TEPR_{DS.1}|$ = 661.8

The TEPR at distribution sub No. 2. This sub has MEN connected

$$TEPR_{DS.2} = EPR_{ZS} \cdot \frac{Z_{dsMEN.2}}{\left(\frac{Z_{ss0.2}.L_2}{3} + Z_{dsMEN.2}\right)}$$

$TEPR_{DS.2}$ = 7.8566 - 216.4946J V $|TEPR_{DS.2}|$ = 216.6 V

7E One Phase to Earth fault on the 11kV cable feeder at the distribution substation (Cable 1) (Fe). With reference to figure 5.7

Sequence network impedance (Ohms)

$Z_{pos.11} := Z_{1.11} + Z_{c1.1} .L_1$ $Z_{pos.11}$ = 0.1713 + 0.672j

$Z_{neg.11} := Z_{2.11} + Z_{c2.1} .L_1$ $Z_{neg.11}$ = 0.1713 + 0.672j

The bonded cable sheaths of the other three distribution substation also conducts ground return current to the source in parallel with the source sub earth mat. Z_{ss} is the equivalent impedance of 3 x 11kV cable sheaths + electrode + MEN and the 33kV cable sheath self impedance + $R_{CE\ t}$ .MEN of each distribution sub is assumed to have no metallic interconnection to the adjacent distribution sub MEN systems. It is also assumed that the distribution sub under investigation has no MEN system installed at this stage.

$$Z_{ss} := \left(\frac{1}{\frac{Z_{ss0.2}.L_2}{3} + Z_{dsMEN.2}} + \frac{1}{\frac{Z_{ss0.3}.L_3}{3} + Z_{dsMEN..3}} + \frac{1}{\frac{Z_{ss0.4}.L_4}{3} + Z_{dsMEN.4}} + \frac{1}{\frac{Z_{ss0.33}}{3} + R_{CE\,t}} \right)^{-1}$$

Z_{ss} = 0.2969 + 0.1235j

$$Z_{MATzseqd} := \left[\left(\frac{1}{R_{MATzs}} \right) + \frac{1}{Z_{ss}} + \frac{1}{Z_{MEN}} \right]^{-1}$$

$Z_{MATzseqd}$ = 0.1636 + 0.0333j

$$Z_{zero.11} := Z_{0.11} + Z_{cond0.1}\ .L_1 + \left[\frac{1}{R_{sh0.1}.L_1} + \frac{1}{3.R_{CE.1}\, Z_{g0.1}.L_1 + 3.Z_{MATzseqd}} \right]^{-1}$$

$Z_{zero.11}$ = 1.3791 + 0.5075j

Zero sequence fault current (Amps)

$$I_0 := \frac{V_{s1.11}}{Z_{pos.11+}\, Z_{neg.11} + Z_{zero.11} + 3.NER_{11}}$$

I_0 = 1710.5 - 1839.6j A

$|I_0|$ = 2511.9 A

Fault current (Amps)

$I_f = 3.I_0$

I_f = 5131.4 - 5518.7j A

$|I_f|$ = 7535.7 A

Zero sequence fault current returning via 11kV cable sheath (Amps)

$$I_{sh0} := I_0 . \frac{(3R_{CE.1} + Z_{g0.1} + 3.Z_{MATzseqd})}{R_{sh0.1}.L_1 + (3.R_{CE.1} + Z_{g0.1}.L_1 + 3.Z_{MATzseqd})}$$

I_{sh0} = 1644 - 1760.4j A

$|I_{sh0}|$ = 2408.7 A

Percentage of total fault current returning via sheath

I_{sh} (%) := $\frac{I_{sh0}}{I_0}$. 100 $|I_{sh(\%)}|$ = 95.9

Zero sequence fault current returning via earth (Amps)

$$I_{g0} := I_0 \frac{R_{sh0.1}.L_1}{R_{sh0.1}.L_1 + (3.R_{CE.1} + Z_{g0.1}.L_1 + 3.Z_{MATzseqd})}$$

I_{g0} = 66.5 - 79.2j A $|I_{g0}|$ = 103.4 A

Percentage of total fault current returning via earth

$I_g\,(\%) := \frac{I_{g0}}{I_0}\,.100$ $\qquad\qquad \left|I_g\,(\%)\right| = 4.1$

7E1 The EPR at the Distribution substation (Volts)

$EPR_{ds} := 3.I_{g0}\,.R_{CE.1}$

$EPR_{ds} = 1994 - 2376.1j$ V

$\left|EPR_{ds}\right| = 3101.9$ V

7E2 The EPR at the Zone substation

$EPR_{zs} := 3.I_{g0}\,.Z_{MATzseqd}$

$EPR_{zs} = 40.5 - 32.2j$ V

$\left|EPR_{zs}\right| = 51.8$ V