EARTH POTENTIAL RISE

SUPPLEMENTARY

HANDBOOK

To assist in the control of electrical hazard to telecommunication users, staff and plant

Published and issued by:

The New Zealand Committee for the Co-ordination of Power and Telecommunication Systems Inc. (NZCCPTS)

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Foreword

In 1989, NZCCPTS published the NZCCPTS Earth Potential Rise Application Guide. The guide set out the agreed conditions and approved procedures which should be used for the planning, design and co-ordination of Power and Telecommunication Systems, so as to control the level of EPR hazard to Telecommunication Users, Staff and Plant within acceptable limits.

This guide has subsequently been superseded by the below AS/NZS 3835:2006 'Earth Potential Rise – Protection of telecommunications network users, personnel and plant' family of standards:

Code of Practice	AS/NZS 3835.1:2006
Application Guide	AS/NZS 3835.2:2006
Worked Examples (handbook)	HB 219:2006

However, there were a few parts in the NZCCPTS Earth Potential Rise Application Guide (primarily the Appendices) that are useful knowledge that is not covered in the above AS/NZS 3835 family of standards. To ensure these are not lost, they have been retained in this NZCCPTS Earth Potential Rise Supplementary Handbook.

As such, this NZCCPTS Earth Potential Rise Supplementary Handbook is not a stand-alone document, and instead needs to be read in conjunction with the above AS/NZS 3835 family of standards.

Acknowledgements

NZCCPTS is indebted to the Electricity Engineers' Association of New Zealand, Chorus, Transpower, KiwiRail and Energy Safety (WorkSafe NZ) for their contributions in the formation of this handbook.

Comments for revision of this guide are welcomed. Any comments or information that may be useful for inclusion in future issues should be forwarded to the Secretary of NZCCPTS by email to secretary@nzccpts.co.nz, or via his contact details on the 'Contact Us' page of the NZCCPTS website (www.nzccpts.co.nz).

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1. Transient EPR Voltage at the Onset of an Earth Fault

The nature of the transient voltage at the onset of an earth fault is examined in the IEEE Guide on EPR and Power Induction (Ref 13). The Guide concludes that at the onset of a fault a dc offset can occur with a magnitude depending on the point of the waveform that the fault occurs at. The effect of this can be allowed for by multiplying the RMS value by a factor of 1.2 to 1.5.

Telecommunication equipment insulation ratings are normally given in terms of a continuous RMS value and an impulse withstand level of a considerably higher value is invariably achieved.

Transient EPR voltages therefore do not have to be considered with respect to their effect on Telecommunication Plant insulation ratings.

APPENDIX A Manual Calculation Sheets for Earth Fault Current and EPR

Schedule for manual calculation of a radial feeder fault

Heading

By: ………………………. Date: ……………………..

Checked: ………………………. Date: ……………………..

Approved: ………………………. Date: ……………………..

Filed: ……………………….. Date: …………………….

Reason for calculation:

……………………………………………………………………………………………………….

……………………………………………………………………………………………………….

Location in system:

……………………………………………………………………………………………………….

……………………………………………………………………………………………………….

Single line diagram:

Include source bus, line and cable lengths and descriptions, local busses or component identifiers such as switch numbers, earth resistances.

Source parameters

Substation: …………………….. Feeders: ………………… Ph-N voltage, V_s: ………………

Date: …………….. Fault duty 3ϕ ……………. MVA 1ϕ ……………..MVA

Source of fault duty date: ………………………………………………………………………….

Earth mat impedance: Z_e = …………ohms. Data source: ……………………………………

……………………………………………………………………………………………………….

Line parameters (Reference voltage = kV, normal)

Description of Line or Cable	Positive Sequence Z_1 (Ω /km)	Zero Sequence Z_0 (Ω /km)
	+ j + j + j + j + j	+ j + j + j + j + j

Fault path impedance values

Component	**Positive Sequence Z_1 (Ω)**	**Zero Sequence Z_2 (Ω)**
Source earth mat impedance, Z_e (if not included in the Source Impedance below) NER resistance. (Net Star point - Earth mat) Fault Impedance, Z_f	Not applicable* Not applicable* Not applicable*	+ j + j + j
Subtotal Z_0	Not applicable*	+ j
3 x Subtotal Z_0	Not applicable*	+ j

Line/Cable Source Impedance		**Positive Sequence Z_1 (Ω)**	**Zero Sequence Z_0 (Ω)**
Line Type	**Line Length (km)**		
		+ j + j + j + j + j + j	+ j + j + j + j + j + j
Subtotals		+ j	+ j
2 x Z_1		+ j	Not applicable*
$2Z_1 + Z_0$ (Ω)		+ j	
$\lvert 2Z_1 + Z_0 \rvert$ (Ω)			

* Note that the impedances in the earth return path contribute only to Z_0.

Fault values calculation

1ϕ to earth fault current:

$I_f = 3V_s / |2Z_1 + Z_0|$

Fault duty $= 3V_s.I_f$

Earth potential rise at fault point:

EPR $= I_f . R_f$

Effects of Transients

The above procedure calculates steady state RMS values. The transient DC offset current asymmetry can increase the effective fault current (and EPR) by a factor usually not greater than 1.5, and close to large generating plant, dominant sub-transient reactance may result in similar transient increases. However proportionately higher hazard voltage limits apply for shorter exposure times, and these sub-transients typically decay in << 100 ms, so transient effects on EPR need only be considered in marginal circumstances close to generation sources.

APPENDIX B Calculation of Earth Resistance Using a 2-Layer Earth Resistivity Model

As illustrated in Appendix A, a knowledge of the value of earth resistance at source substations and at the point of fault is necessary when determining EPR.

Soil conditions at the site of an earth electrode may vary greatly with depth. It will rarely be economically justifiable or technically feasible to model all these variations. However, in some cases the representation of an earth electrode based on an "equivalent" two-layer earth method model is sufficient for determining earth resistance. The measurement and interpretation of resistivity survey data is discussed in Appendix A5 and it is usually practical to derive at least a two layer model for most sites.

The following definitions are relevant to this discussion:

ρ_1 = Resistivity of upper layer of soil
ρ_2 = Resistivity of lower layer of soil

K = Reflection Factor Co-efficient

$$= \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

H = Thickness of upper layer of soil (depth of boundary)

Earth Mat Resistance in 2-Layer Earth
If we now consider an earth mat electrode at a source substation its resistance, in a two layer earth resistivity model will vary greatly as a function of "K" and "H". These two relationships are illustrated in Figs A2.1 and A2.2. In general, the resistance of a mate is lowest if it is in the most conductive layer of soil (low ρ). As "H" increases the resistance of the grid approaches that of a grid in uniform soil of the same resistivity as the upper layer. Assuming that the mat is located in the upper soil layer with resistivity equal to ρ_1, the following can be generalized.

- For K - ve values (ρ 1> ρ_2) the resistance of the mat will be higher than that of an identical grid in uniform soil with resistivity ρ_2.
- For K + ve values (ρ_1< ρ_2) the resistance of the mat will be lower than that of an identical grid in uniform soil with resistivity ρ_2.

The curves in Fig B.1 below illustrate the variation of earth mat resistance for a particular square earth mat electrode situated 0.5 meter below the surface in a particular choice of soil resistivity ρ_1, with ρ_2 increasing, decreasing from the condition $\rho_2 = \rho_2$ for K increasingly + ve, becoming more -ve, respectively. This information is taken from Appendix E of reference 16.

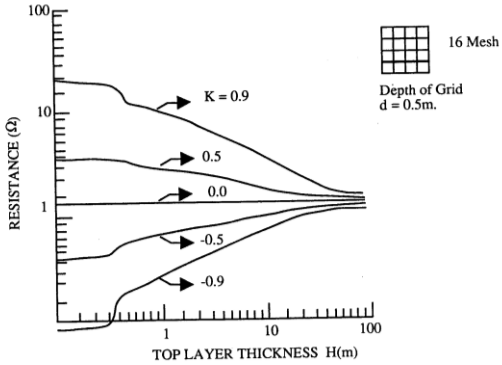


Fig B.1 Sixteen Mesh Grid Resistance

APPENDIX C - Measurement of Earth Resistivity

C.1 Test Method

Several techniques exist for measuring earth resistivity (Refer IEEE Std 81-1983). The Wenner four terminal method is the most commonly used. This method can be briefly described as follows:

1. Four probes are driven into the earth (depth b) at equally spaced intervals (spacing a).
2. The voltage between the two inner (or potential) electrodes is measured and divided by the current flowing between the two outer (or current) electrodes to produce a value of mutual resistance R.
3. Results are measured for various values of separation, a, along at least 2 directions, usually at right angles (referred to later in this section as A and B axes).

For the Wenner test configuration with electrode spacing "a", a megger reading of R ohms corresponds to an apparent soil resistivity of

$$\rho = 2\pi a R k \qquad (1)$$

where k is a mutual compensation factor which varies with the ratio (y) of electrode depth to separation.

$$y = \frac{\text{depth of electrodes}}{\text{electrode separation}}$$

$$k = \frac{2}{1+\frac{2}{\sqrt{1+4y^2}}-\frac{1}{\sqrt{1+y^2}}}$$

= 1.0 for y = 0
1.7 for y = 1.0
2.0 for y = infinity

C.2 Interpreting the Results

Producing a single figure for soil resistivity from the Wenner method assumes the soil resistivity is uniform. Obviously this is never true. However, on a few occasions this assumption can be made without producing significant error.

In many cases, it is possible to regard the soil as consisting of two resistivity layers, separated at a horizontal boundary. Again, this assumption is never true, but the assumption can be made frequently without introducing significant error into the calculation for grid resistance.

Equation (1) above can be reordered so that:

$$\frac{a}{\rho} = \frac{1}{2\pi Rk}$$

and so a graph of 1 / 2 π R k (vertical axis) against a (horizontal axis) will yield resistivity (from reciprocal slopes) as a function of depth. In this way a reasonably accurate knowledge of resistivity layering can be obtained but only to a depth of approximately 14 meters; (readings for electrode spacings greater than 14 meters should be obtained if possible. Sensitivity at larger electrode separation distances may be improved by shifting the potential electrodes closer to the current electrodes (See Method) as shown in Figure A5.1.

In this case, true R values can be obtained by multiplying the results by the factor

$$\frac{1-\beta^2}{8\beta^2}$$

where β is the distance between potential probes divided by the distance between current probes. (Values of greater than 0.8 should be avoided). [Refer to IEEE Std 81-1983.]

The example in Figure A5.2, illustrates the application of this graphical technique.

Straight line approximations have been drawn through the points obtained; the abrupt changes in slope were designated as Breakpoints. The inverse slopes of each straight line segment and the breakpoints give resistivity and layer depth values respectively.

Both A and B test results indicate that there are two identifiable resistivity layers to a depth of approximately 14 meters. As mentioned previously, readings for much larger electrode separations are highly desirable and should be sought whenever practical. Resistivity information to greater depths enhances the quality of earth grid modelling and earthing modelling and earthing analyses in general.

Usually the straight line approximation technique will yield two or three layers.

C.3 Observations and Cautions

The ease with which straight lines can be drawn through the graphed points gives some idea of the extent of inhomegeneity of each layer.

Deviations may also occur as a result of poor electrode contact with the soil, but such anomalies should be detectable as each measurement is made.

Although the A and B results in Fig A5.2 lead to slightly different layer depths, the test results are of value because the A and B resistivities are consistent.

If the A and B breakpoints and slopes differ greatly then additional measurements will be required to check whether such discrepancies are meaningful or simply inaccurate. Tests in intermediate directions to the A and B axes, or possibly tests in a different location, would serve as useful checks.

Discrepancies may in fact be due to layer distortions, soil granulation, or the effects of nearby underground conductors and consequently a reasonable knowledge of these factors, although adding complexity to earthing studies, is essential. The problem of water pipes, oil pipes, or earth conductors of any description near to test locations is difficult to overcome entirely since the further the test site is from the earth grid, the more likelihood there is of the "actual" resistivities at the "test" and "earth grid" areas being different, e.g. resistivity information from a "conductor free" paddock a mile away from the substation area in question would probably be of little value.

Undesirable interaction of underground conductors with test results can be minimized - but never eliminated - if tests are performed in directions other than parallel to and in location as remote "as practical" from such conductors.

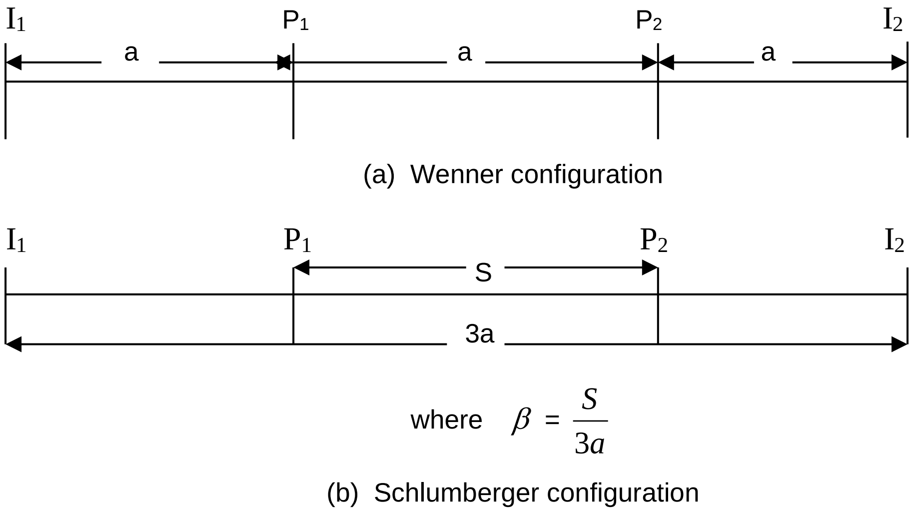


Fig C.1 Electrode Spacings of Earth Resistivity Test Methods

Electrode Spacing 'a' meters	R ohms		$2\pi k$	$1/2\pi Rk$	
	A Axis	B Axis		A Axis	B Axis
0.5	76.0	78.0	7.175	0.0018	0.0018
1.0	21.5	21.5	6.528	0.0071	0.0071
1.5	9.0	9.5	6.396	0.0017	0.0017
2.0	6.4	6.7	6.346	0.025	0.024
2.5	5.8	5.2	6.321	0.027	0.030
3.0	5.0	4.4	6.308	0.032	0.036
4.0	3.0	3.6	6.302	0.053	0.044
5.0	2.2	2.5	6.296	0.072	0.064
6.0	1.85	2.2	6.289	0.082	0.072
7.0	1.6	1.9	6.289	0.099	0.084
8.0	1.4	1.7	6.289	0.114	0.094
9.0	1.2	1.05	6.289	0.133	0.151
10.0	1.05	0.7	6.283	0.152	0.227
12.0	0.65	0.55	6.283	0.245	0.289
14.0	0.45	0.35	6.283	0.354	0.455

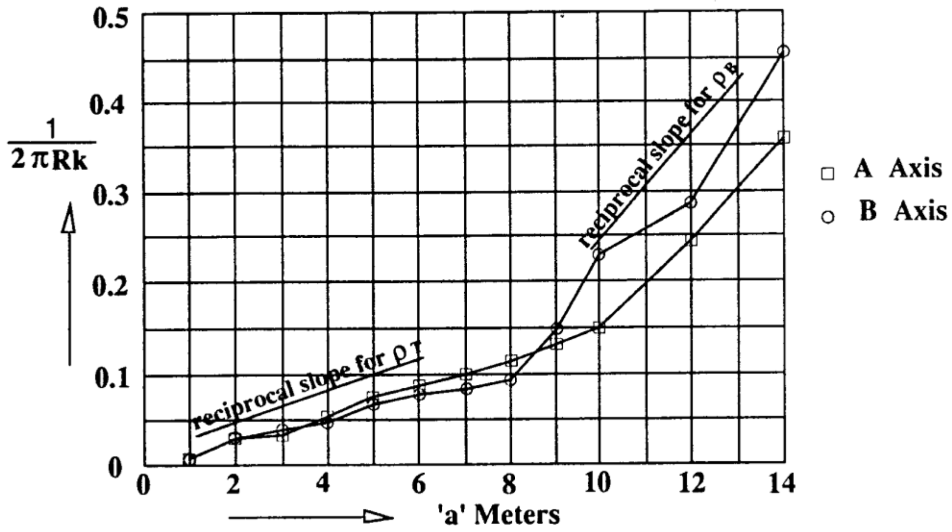


Fig C.2 Interpretation of Wenner Test Results

APPENDIX D Measurement of Earth Resistance

D.1 General

The basic technique for the measurement of an earth electrode resistance has been established for a number of years, but there are many difficulties and sources of error which are not necessarily fully understood. Earth resistance measurement is quite unlike any normal resistance measurement and has a number of special characteristics. The resistance consists of a body of earth surrounding the electrode, i.e. at the electrode itself. Also, there may already be current flowing in the earth owing to electrolysis and leakage from electric supply or traction systems. An earth electrode may be a rod or pipe driven into the earth, a buried strip or plate, or a number of these spread over an area and connected in parallel.

D.2 The Fall-of-Potential Method

The method of measurement which is most commonly employed is known as the fall-of-potential method, and in its simplest form is shown in Fig.1. In Fig D.1, the electrode under test is E, and two auxiliary earth electrodes PE and CE are employed. A current I is passed between E and CE. The passage of this current produces a potential drop V in the earth. The potential drop between E and PE is measured. The quotient V/I gives a resistance which, under certain conditions to be discussed later, is the true resistance of the earth electrode.

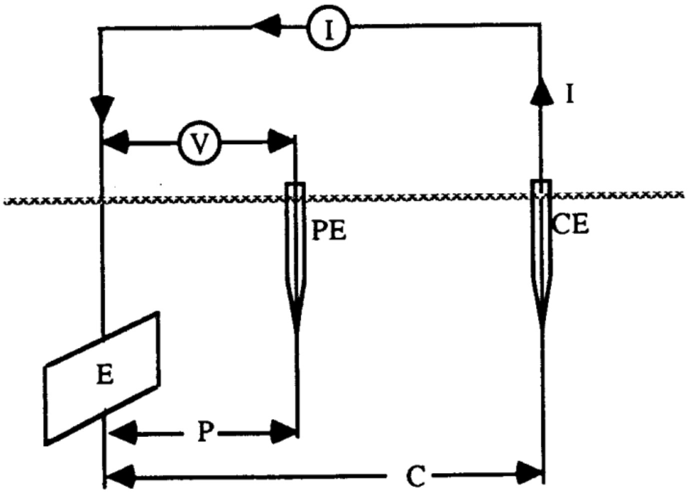


Fig D.1 Fall of potential Method

D.3 Earth Resistance Curves

If CE is placed at a fixed distance C from the Earth electrode, and PE is placed at various points on the line joining E and CE, a series of values of measured resistance can be obtained and plotted against P (Fig D.2). As C increases, the centre part of the curve tends to the horizontal; it is usually stated that the current electrode must be placed sufficiently far from E for the centre position of the curve to be horizontal, and that this horizontal section gives the true resistance of E. Actually, the curve never becomes horizontal, but it may appear to do so owing to the lack of sensitivity of the instruments used; even when this condition is obtained, the resistance may be considerably in error.

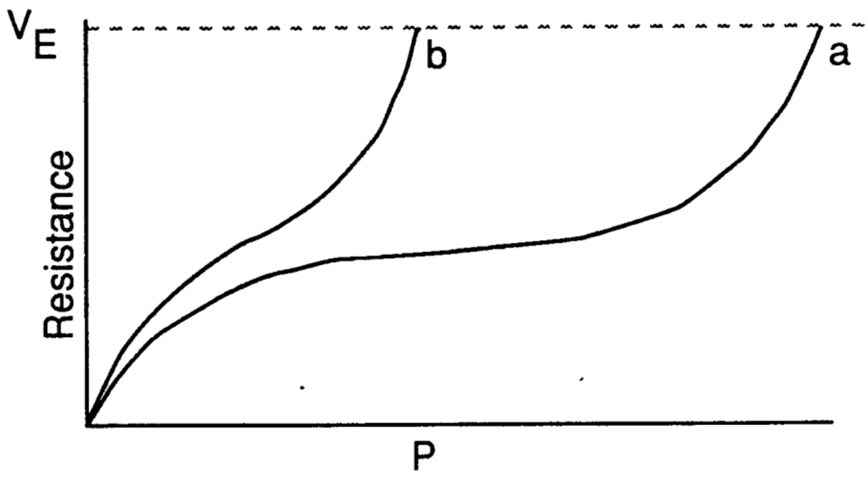


Fig D.2 Earth Resistance Curves

Another way in which the above is sometimes stated is that the resistance areas of E and CE must not overlap; the resistance area is defined as the area on the surface of that body of earth which contributes the greater portion of the electrode resistance. This area is governed by the sensitivity of the measuring instruments used and so is necessarily vague. In addition, its shape depends on the position of the electrodes relative to their size.

It must be borne in mind that measurements of earth resistance are far removed from precision measurement, and quite considerable errors can be present. In some cases, therefore, the resistance given by the nearly horizontal portion of the curve 'a' in Fig D.2 may be sufficiently accurate. There are, however, numerous cases where the curve will be of the form 'b', owing to practical difficulties involved in placing CE sufficiently far away from E; in such cases it is necessary to know how to obtain the true resistance from such a curve.

D.4 Limitations of the ‘Fall of Potential’ Method

The method can be used only when the separation between E and CE is large compared to the earth electrode dimensions, and consequently it suffers from the following disadvantages:

- It is always possible to lay out a cable of such length, especially in urban areas where traffic, etc. interferes.
- The weight of the long leads causes considerable difficulty, especially in rural areas and in hilly terrain.
- Effects due to stray currents over a wide area may be quite pronounced. Such stray currents may be due to nearby traction and other electrical installations, etc.
- For long wires, the inductance and capacitance to earth and between them cause considerably error.

D.5 Tagg's 61.8% Rule

In order to avoid difficulties Tagg showed that, for hemispherical electrodes, the distance C between E and CE can be made as small as is practicable, and yet true resistances can be obtained if the distance P between E and PE is 61.8% of C. This conclusion, although based on analysis of hemispherical electrodes, is found to yield excellent results for rod electrodes as well, provided that C > 10 x length of electrode, for shorter distance C, the results are considerably different from the true values.

D.6 Instrumentation

One of the most commonly used instruments is the indicating ohmmeter which functions as a voltmeter and inverse ammeter combined so that it reads V/I or resistance.

When using a typical ohmmeter you must allow for the fact that the potential coil of the instrument takes power to operate it. It therefore draws current from electrodes E and PE and because of this a voltage drop will occur between electrode PE and ground due to the resistance of electrode PE. This voltage drop will cause the meter to indicate a resistance which is lower than the true value and compensation must therefore be allowed for the resistance of electrode PE. As it is inconvenient and often very difficult to measure the resistance of electrode PE, it is usual to take readings on two different ranges of the instrument; as each range will impose a different burden on electrode PE. Different errors will be obtained and by computing both of these readings in a simultaneous equation or using a correction nomogram, the true resistance of electrode E can be calculated. It should be noted that a nomogram can only be used for the earth testing instrument for which it is intended. tempts to use a nomogram for other than its own instrument will cause errors.

Some modern instruments provide an adjustable compensation for potential spike resistance. Other instruments have a high input impedance and do not require compensation.

APPENDIX E Worked Example - 33 / 11 kV Substation

E.1 Introduction

One consideration of a 33 / 11kV substation design is the EPR associated with a fault to the substation earth mat. The EPR is highest for a 33kV fault to earth. This example examines the case of a 33kV single phase fault at the Orion Sockburn substation supplied from the Transpower Islington substation 33kV bus.

E.2 Problem Description

The single line diagram below describes the Islington point of supply (POS) to Sockburn substation system including earth mat resistances, NER's and single phase fault path. There are two 22 Ω NERs at the Islington 33 kV bus and a common 20 Ω NER on the Sockburn substation 11 kV bus. Normally the Sockburn 33kV bus is split; with transformers T1 & T2 feeding a common 11kV bus with a single 20 ohm NER.

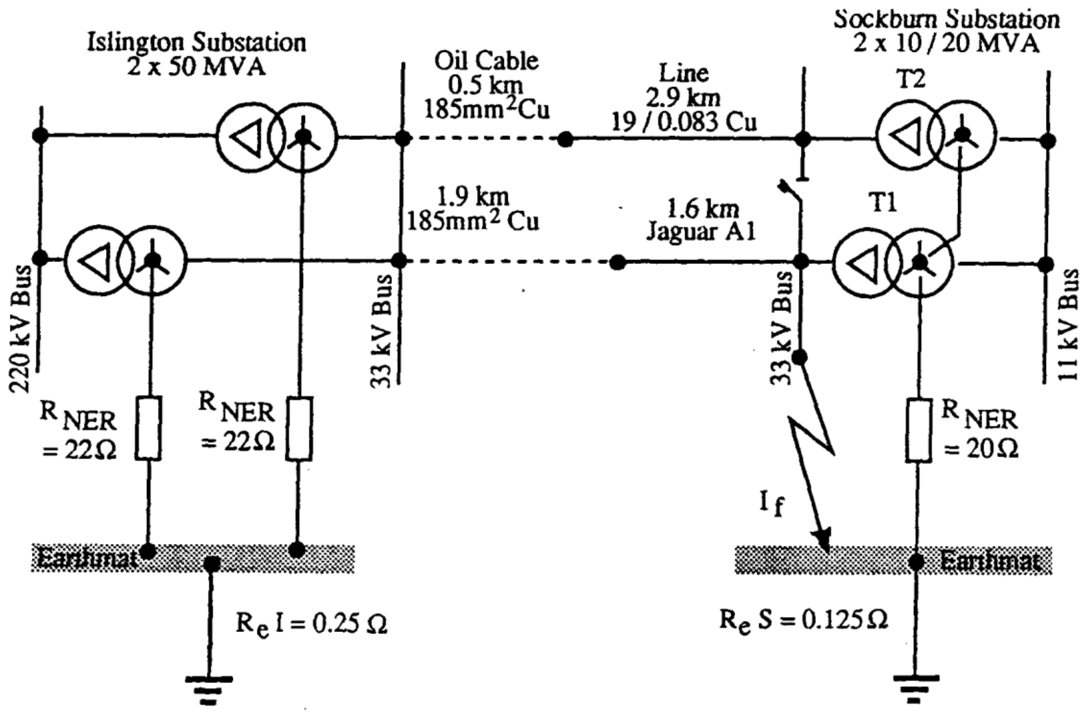


Fig E.1 Islington POS - Sockburn Substation

Source impedances were obtained from the results of the (former CCEPB) Fault Program. The EPR and fault current for the existing case without NER's were calculated manually using the form in Appendix A. EPR's and fault currents were calculated for various fault resistances. R_f represents the Sockburn substation earth plus any other resistance in the fault path. In all cases, the earth return current through cable sheathes is assumed to be negligible.

E.3 Calculation of Earth Fault Current and EPR

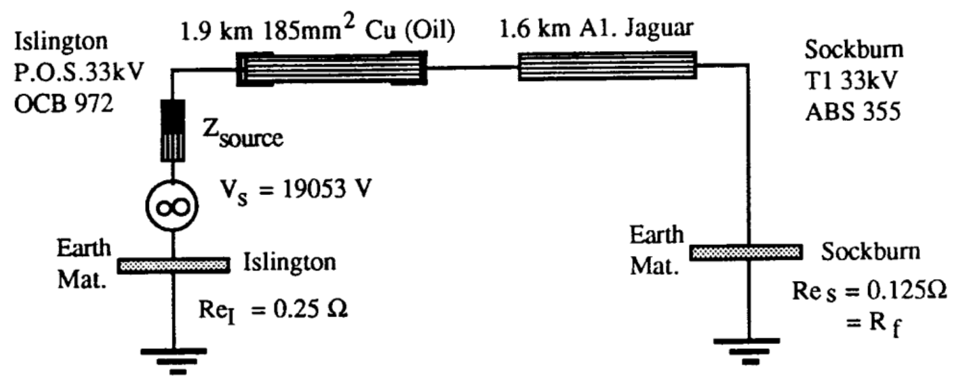
Schedule for manual calculation of a radial feeder fault.

Heading			
SINGLE PHASE EARTH FAULT AT SOCKBURN SUBSTATION 33kV (EXCLUDING NER'S)	By: Lim Mei Leng	Date: 18.7.88	
	Checked: N.W. Ross	Date: 20.7.88	
	Approved: N.W. Ross	Date: 20.7.88	
	Filed	Date	

Reason for calculation Worked example B1 for EPR Guide

Location in system ……Islington P.O.S. 33kV to Sockburn T1 33kV

Single line diagram:
Include source bus, line and cable lengths and descriptions, local busses or component identifiers such as switch numbers, earth resistances. The normal situation with the 33kV Sockburn bus split is considered with the backfeed through the 2.9km line, T2 and T1 ignored as contributing under 6%. Coupling of the 33kV bus would add about 25% to fault current but is ignored as it is not used in service.



(1) Source Parameters

Substation Islington P.O.S. Feeder ISL-SOCK NO. 1 Ph-N Voltage, V_s 19053

Date 15.7.88 Fault Duty 3Ø 759.5 MVA, 1Ø 819.8 MVA

Source of Fault Duty Date CCEPB Fault Program EPRSKO.TXT

Earth Mat Impedance Z_e = 0.25 Ohms. Data Source: NZE

(May 86 - File 7/6)

(2) Line Parameters

For use in the sample calculations which follow.
Impedances are given referred to a base voltage of 33kV nominal.

DESCRIPTION OF LINE OR CABLE		POSITIVE SEQUENCE, Z_1 (Ω/km)	ZERO SEQUENCE Z_0 (Note 1) (Ω/km)
185 mm² Cu. Oil	33kV	0.128 + j 0.093	0.276 + j 2.180
Jaguar	33kV	0.137 + j 0.321	0.285 + j 1.635
95 mm² Cu. Cable	11kV	0.193 + j 0.082	0.341 + j 2.257
19/0.083 Cu.	11kV	0.265 + j 0.354	0.413 + j 1.687

Note
1 Assuming no cable sheath return path

(3) Fault Path Impedance Values

Component			Positive Sequence, Z_1 Ω	Zero Sequence Z_0 Ω
Source earth mat impedance, Z_e if not included in the Source Impedance below.			0 + j 0	0.000 + j 0.000
NER resistance. (Net Star-Earthmat value)			0 + j 0	0.000 + j 0.000
Fault Impedance, Z_f (Substation Earthmat Resistance)			0 + j 0	0.125 + j 0.000
			Subtotal	0.125 + j 0.000
Earthing Circuit Components			3 x Subtotal	0.375 + j 0.000
Source impedance			0.045 + j 1.492	0.792 + j 1.018
Line		**Length (km)**		
185 mm Cu Oil	033	1.900	0.792 + j 1.018	0.045 + j 1.492
Jaguar	033	1.600	0.243 + j 0.177	0.524 + j4.142
			0.219 + j 0.513	0.456 + j 2.616
			+ j	+ j
			+ j	+ j
			+ j	+ j
			+ j	+ j
TOTALS			Z_1 = 0.507 + j 2.120	Z_0 = 2.148 + j 7.777
Note that the impedances in the earth return path contribute only to Z_0, and must be multiplied by 3			$2 Z_1$ = 1.015 + j 4.239 $2 Z_1 + Z_0$ = 3.16 + j 12.02	

as provided in this table.	$\|2Z_1 + Z_0\| = 12.42\ \Omega$ Angle = 75.3º

(4) Fault Values Calculation

1Ø to Earth Current

$1_f = 3V_s / |2Z_1 + Z_0|$

$= (3 \times 19053) / 12.42$

= 4600 Amps

Fault Duty

$= 3V_s.I_f$

= 262.9 MVA

Earth Potential Rise at Fault Point:

EPR $= I_f . R_f$

= 0.575 kV

(5) Notes

The above calculates steady state rms values.

Worst case results are obtained when subtransient reactance's are used in the impedance evaluation. This relevant only to generation sources.

(6) Abbreviations

0** = **kV. i.e. 033 means 33kV

POS = Point of supply

E.4 Results

The fault currents and EPR's of a single phase 33kV fault at Sockburn substation for various fault resistances are tabulated below. Note that the fault resistance (impedance) would be the same as the earth mat resistance in the manually calculated case.

The results are also plotted in the graph of Fig. B1.2

Single Phase Fault Current I_f and EPR at Sockburn Substation.

Fault Resistance R_f (Ω)	No Islington NER		With Islington NER	
	EPR (kV)	I_f (kA)	EPR (kV)	I_f (kA)
0.0	0.000	4.634	0.000	1.540
0.1	0.461	4.607	0.150	1.503
0.125	0.575	4.600	0.188	1.500
0.5	2.240	4.480	0.730	1.459
1.0	4.268	4.268	1.408	1.408
1.25	5.223	4.178	1.729	1.383
1.5	6.101	4.067	2.039	1.360
1.75	6.919	3.954	2.339	1.337
2.0	7.679	3.840	2.629	1.315
2.5	9.034	3.613	3.181	1.272
3.0	10.187	3.396	3.698	1.233
4.0	11.999	3.000	4.640	1.160
5.5	13.834	2.515	5.860	1.065

E.5 Conclusions

The inclusion of Islington NER's into the system greatly reduces the EPR for a 33kV single phase fault.

Thus NER's become an attractive and economical method of reducing EPR for substations sited in a high resistivity area, requiring extensive labour and materials to build a low resistance earth mat.

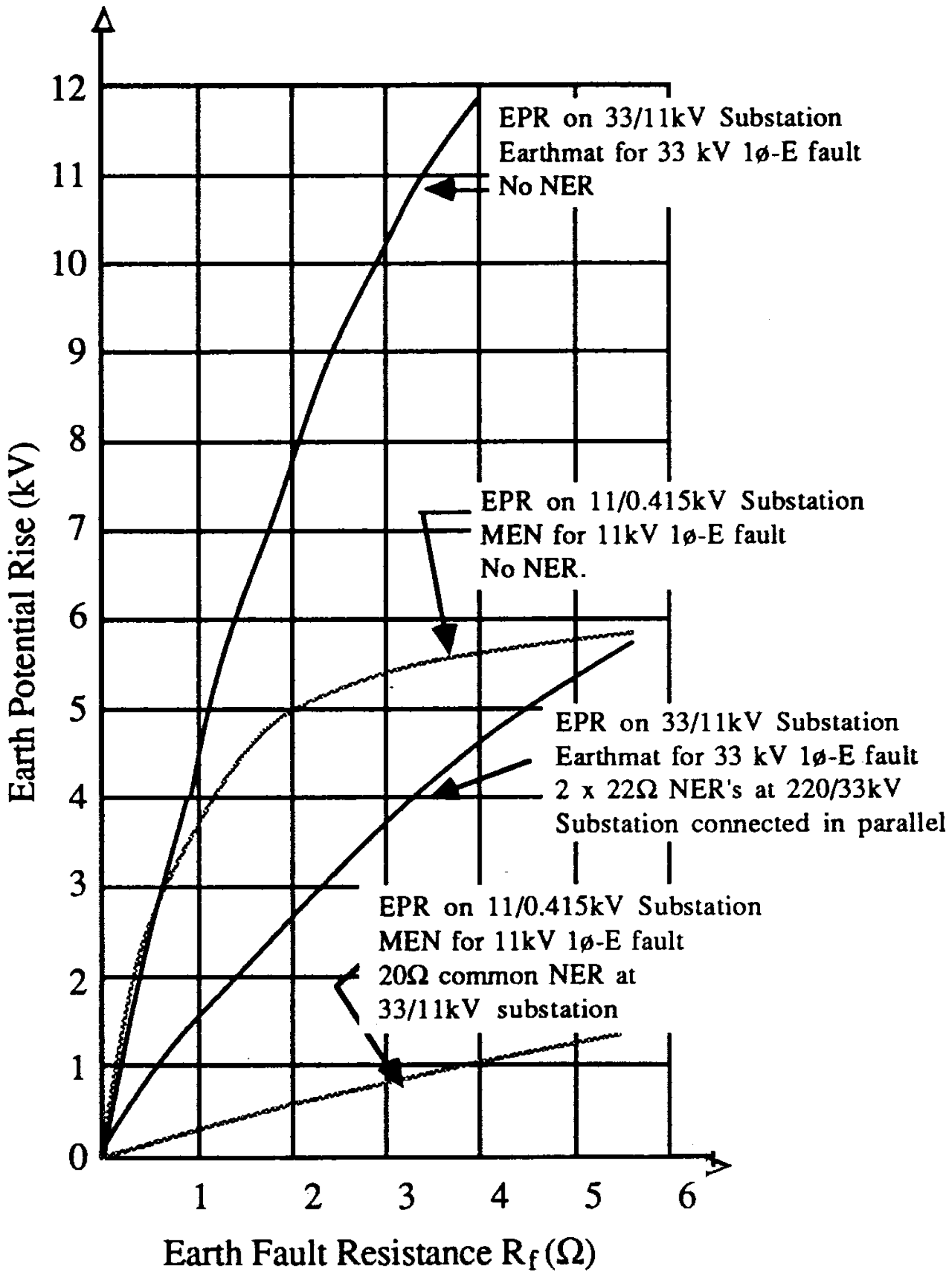

12
11
10
9
8
7
6
5
4
3
2
1
0
Earth Potential Rise (kV)
1
2
3
4
5
6
Earth Fault Resistance Rf (Ω)
EPR on 33/11kV Substation
Earthmat for 33 kV 1ø-E fault
No NER
EPR on 11/0.415kV Substation
MEN for 11kV 1ø-E fault
No NER.
EPR on 33/11kV Substation
Earthmat for 33 kV 1ø-E fault
2 x 22Ω NER's at 220/33kV
Substation connected in parallel
EPR on 11/0.415kV Substation
MEN for 11kV 1ø-E fault
20Ω common NER at
33/11kV substation

Fig E.2

APPENDIX F Worked Example - Transpower 220 / 66 / 11kV Substation

F.1 Introduction

This appendix presents calculations for determining short circuit currents and EPR's resulting from various faults at Transpower's Bromley Substation.

Bromley is a transmission and supply substation with three busbar voltages. It has two 220/66/11kV 100 MVA Ynyn0d 11 three-winding transformers and three 66/11kV 30 MVA Dyn3 two-winding supply transformers.

Figure F.1 is a simplified single line diagram of the substation.

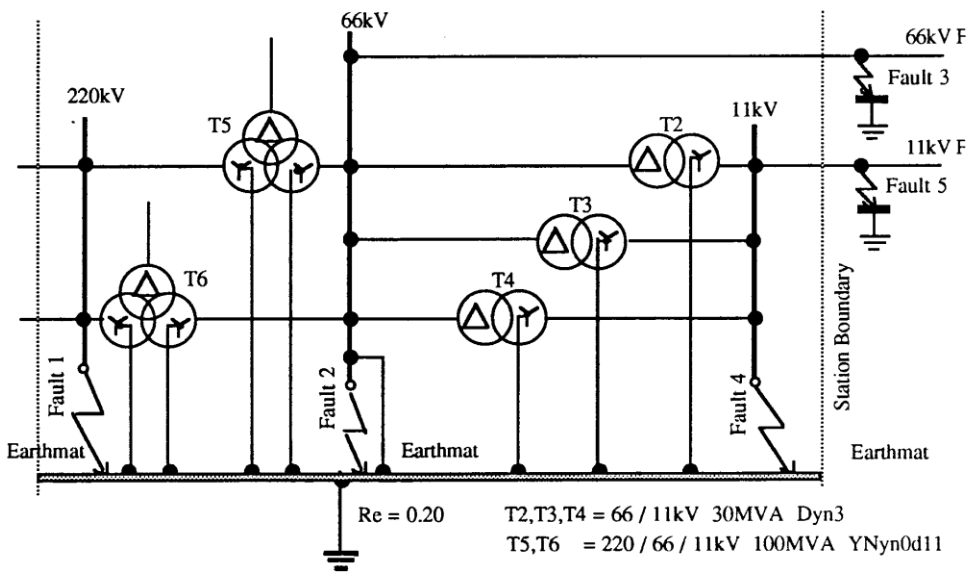


Fig F.1 Transpower Transmission / Supply Substation Electrical Arrangement

F.2 Assumptions

1. Bromley is electrically remote from rotating machines. Therefore the positive and negative phase sequence impedances of the 220kV transmission system are equal.

2. The 220kV system is the only source of short circuit current.

3. The substation transformers have equal phase sequence impedances. T2, T3, and T4 are normally operated in parallel, as are T5 and T6.

4. Transformer winding resistances are ignored.

5. A base of 100 MVA is used for per unit calculations.

6. Transformer neutrals are bonded directly to the substation earthgrid.

7. No current is able to return to the substation via aerial line earthwires or power cable metallic sheaths during external faults.

F.3 Electrical Data

F.3.1 Power System Data

Date: 1 September 1987

Substation: Bromley

Short Circuit Fault Duty Data:

Substation Bus No	Voltage (kV)	Fault Duty (3 phase)	MVA (1 phase)	Date
Bromley	220	2143	1892	1987
Bromley	220	2207	1938	1992

Source of System Fault Duty Data: Power system planning short circuit study.

F.3.2 Fault Types and Locations Investigated

Single-phase-to-earth (L-G) short circuit faults at the following locations:

Fault 1: 220 kV busbars
Fault 2: 66 kV busbars
Fault 3: 66 kV overhead line 1000m outside the substation
Fault 4: 11 kV supply busbars
Fault 5: 11 kV cable 1000m outside the substation

F.3.3 Station Earthmat Resistance

Calculated: 0.14 ohms from computer program ELEGRIDK study on 1 September 1987
Measured: 0.20 ohms on 8 February 1983

F.3.4 Transformer Impedance Data

	Impedance	Rating
T2 66 / 11kV	Xhl = 9.57%	30 MVA
T3 66 / 11kV	Xhl = 10.00%	30 MVA
T4 66 / 11kV	Xhl = 9.69%	30 MVA
T5 220/ 66 11kV	Xht = 8.20%	
	Xhl = 8.44%	
	Xtl = 8.57%	100 MVA
T6 220 / 66 /11kV	Xht = 7.91%	
	Xhl = 10.10%	
	Xtl = 10.40%	100 MVA

F.3.5 Cable and Overhead Line Impedance

66kV 37 / 0.102 ACSR overhead line

$$Z_1 = Z_2 = 0.18 + j0.35 \text{ ohms / km}$$
$$Z_0 = 0.46 + j0.90 \text{ ohms / km}$$

11kV 645 sq.mm single-core cable

$Z_1 = Z_2 = 0.06 + j0.15$ ohms / km
$Z_0 = 0.31 + j0.70$ ohms / km

F.4 Calculation of Per Unit Impedances

F.4.1 220kV System

Procedure: From the data in F.3.1 the phase sequence impedances can be calculated. Using Transpower's power system fault duty data (1992 predicted value) and assuming reactance only.

$$X_1 = X_2 = \frac{100}{2207} \text{ per unit}$$

$$= 0.045 \text{ pu}$$

$$\text{Also, } I_{1\,ph-g} = \frac{1938}{100} \text{ pu} = 19.38 \text{ pu}$$

By substitution:

$$19.38 = \frac{3}{0.045+0.045+X_0}$$

$$\text{Hence, } X_0 = 0.065 \text{ pu}$$

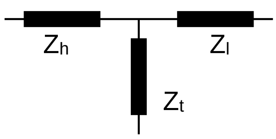
F.4.2 220 / 66 / 11kV Transformers (T5, T6)

Procedure:
1. Convert percent impedances based on the transformer power rating (100 MVA) to per unit based on 100 MVA.
2. Calculate the impedances of the equivalent transformer of T5 and T6 in parallel.
3. Calculate the 3 winding transformer equivalent circuit impedances, Z_h, Z_l and Z_t (HV, LV & Tertiary Wdg legs respectively.) for the positive = negative and zero sequence equivalent circuits using the formulae:

$$Z_l = \frac{Z_{hl} + Z_{tl} - Z_{ht}}{2}$$

$$Z_h = \frac{Z_{hl} + Z_{ht} - Z_{ht}}{2}$$

$$Z_t = \frac{Z_{tl} + Z_{ht} - Z_{hl}}{2}$$



The calculated impedances are in F.5:

Z_{l1} = j 0.027 pu
Z_{h1} = j 0.020 pu
Z_{tl} = j 0.021 pu

F.4.3 66 / 11kV Transformers (T2, T3, T4)

Procedure:
1. Convert percent impedances based on the transformer power rating (30 MVA) to per unit based on 100 MVA.
2. Calculate the equivalent impedance of the three transformers in parallel.

The result is Z_{hl} = j 0.108 pu.

F.4.4 66kV Aerial Line and 11kV Cable

Procedure:
1. Divide the impedances (ohms/km) by the base impedance for the respective voltage and multiply by the distances (km) to the fault to obtain the per-unit impedances.

66kV line	=	0.004	+	j 0.008 pu
Z_1	=	0.004	+	j 0.008 pu
Z_2	=	0.011	+	j 0.021 pu

11kV cable:

Z_1	=	0.050	+	j 0.012 pu
Z_2	=	0.050	+	j 0.012 pu
Z_0	=	0.256	+	j 0.579 pu

F.4.5 Station Earthmat Per-unit Resistances

The earthmat resistance should be included in the phase sequence impedance networks if it is of the same order of magnitude as the other impedances referred to the calculation's base voltage and base MVA..

At 220kV base voltage, 100 MVA base

$$Z_{0\,220} = 3 \times R_{e\,220} = \frac{3\,x\,0.20}{484} = 0.001 \text{ pu}$$

At 66kV base voltage, 100 MVA base,

$$Z_{0\,66} = 3 \times R_{e\,66} = \frac{3\,x\,0.20}{43.6} = 0.014 \text{ pu}$$

At 11kV base voltage, 100 MVA base

$$Z_{0\,11} = 3 \times R_{e\,11} = \frac{3\,x\,0.20}{1.21} = 0.496 \text{ pu}$$

F.5 Table of Impedances to be used in Fault Calculations

			$Z_1 = Z_2$	Z_0
1.	**220kV system**		0.0 + j 0.045	j 0.065
2.	T6 & T6	Z_h	0.0 + j 0.020	j 0.020
		Z_l	0.0 + j 0.027	j 0.027
		Z_t	0.0 + j 0.021	j 0.021
	Earthmat 9to base 22okV)			0.001 + j 0

3.	**66kV system, line**	0.004 + j 0.008	0.011 + j 0.021
4.	Earthgrid (to base 66kV)		0.014 + j 0
5.	T2, T3 & T4	0.0 + j 0.108	0.0 + j 0.108
6.	**11 kV system cable**	0.05 + j 0.012	0.256 + j 0.0579
7.	Earthgrid (to base 11kV)		0.496 + j 0.0

See Fig F.2 for Sequence Impedance models.

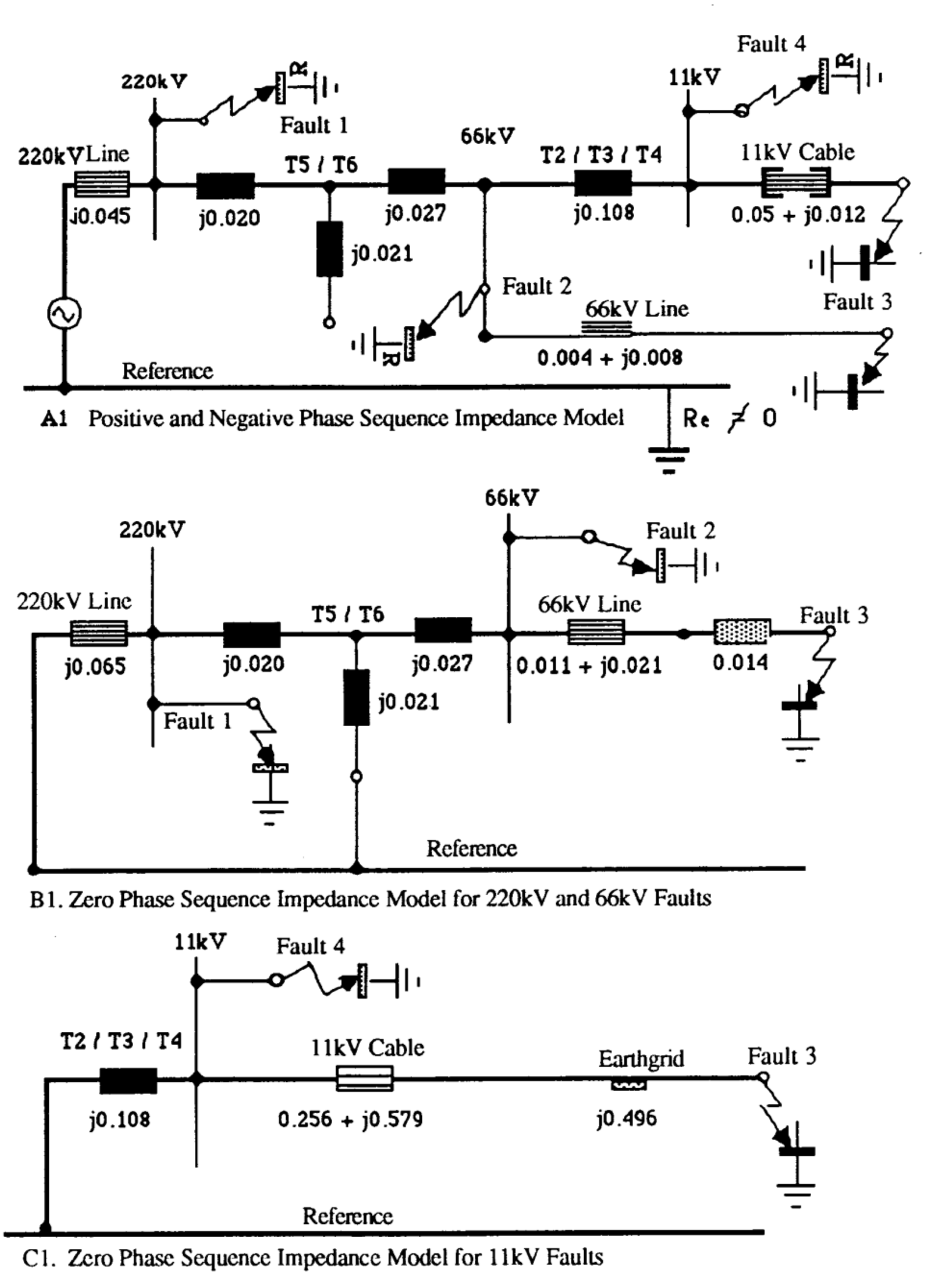


Fig F.2 Sequence Impedance models

F.6 EPR Calculations

For each of Faults 1 - 5, calculate:
1. Single - phase - to - earth fault current (I_f)
2. Earthgrid - to - ground current (I_g).
3. EPR = I_g x R_e

F.6.1 Fault 1

From F.4.1:

i_F = 19.38 pu
= 19.38 x 262 (220kV base current) A
= 5078 A

The entire fault current flows from the earthgrid into the ground and away to remote earthed neutrals of contributing 220kV fault current sources.

I_g = I_f = 5078 A

EPR = 5078 x 0.2
= 1016V

F.6.2 Fault 2

From reduction of phase sequence impedance circuits A and B in Fig F.2:

Z_1 = Z_2 = k 0.092 pu
Z_0 = j 0.044 pu

$$I_f = \frac{3X(1+j0}{j0.092+j0.092+j0.044}$$

= -j 12.2 pu
= j 13.2 x 875 (66kV base current) A
= j 11,550 A

This current circulates in the local earthgrid conductors and does not cause EPR. But, as a consequence of Fault 2 and the earthed neutrals of the 220kV windings of T5 and T6, zero sequence current does flow from the earthgrid to remote 220kV neutrals. This current is calculated as follows:

The phase sequence currents in the faulted phase are:

$$I_{a1} = I_{a2} = I_{a0} = \frac{I_f}{3} = -j\,4.4 \text{ pu}$$

The 220kV winding current in the faulted phase of T5 in parallel with T6 is:

I_h = I_{a0} = -j 4.4 x 262 A at 220kV
= -j 1,153 A

The 66kV winding current in the faulted phase of T5 in parallel with T6, referred to 220kV is:

$$I_l = I_{a0} \times \frac{j0.021}{j0.065+j0.020+j0.021}$$

The 220kV winding neutral current of T5 in parallel with T6 is:

$I_n \quad = \quad 3 \times (_I - I_h) = j\,2{,}775$ A

This entire current flows from the earthgrid into the ground. Hence:

$I_g \quad = \quad I_n = j\,2{,}775$ A
EPR $= \quad 2{,}775 \times 0.2$
$\quad = \quad 555$V

F.6.3 Fault 3

From reduction of phase sequence impedance circuits A and B in Figure F.2:

$Z_1 \quad = \quad Z_2 \quad = \quad 0.004 + j\,0.10$
$Z_0 \quad = \quad 3R_e + 0.011 + j\,0.065$
$\quad = \quad 0.014 + 0.011 + j\,0.065$
$\quad = \quad 0.025 + j0.065$

Thus $Z_1 + Z_2 + Z_0 = 0.033 + j\,0.265$

Ignoring resistance:

$$I_f \quad = \quad \frac{3x(1+j0)}{h0.265}$$

$\quad = \quad -j\,11.3$ pu
$\quad = \quad -j\,11.2 \times 875$ (66kV base current) A
$\quad = \quad -j\,9{,}888$ A

This current will return to the 66kV neutrals of T5 and T6 via the earthgrid. Hence it will cause EPR.

But, by the same reasoning as in F.6.2, there will also be a resultant zero sequence current in the 220kV neutrals of T5 and T6. The two currents must be added before EPR is calculated.

Using the method in F.6.2

$I_n \quad = \quad j\,2{,}376$ A

$I_g \quad = \quad -j\,9{,}888 + j\,2{,}376$
$\quad = \quad -j\,7{,}512$ A

EPR $\quad = \quad 7{,}512 \times 0.2$
$\quad = \quad 1{,}502$ V

F.6.4 Fault 4

From reduction of phase sequence impedance circuits A and C in Fig F.2:

$Z_1 \quad = \quad Z_2 \quad = \quad 0.050 + j\,0.212$ pu

$Z_0 \quad = \quad 3R_e + 0.256 + j\,0.687$
$\quad = \quad 0.496 + 0.256 + j\,0.687$
$\quad = \quad 0.752 + j\,0.687$ pu

$Z_1 + Z_2 + Z_0 \quad = \quad 0.852 + j\,0.899$

$$I_f = \frac{3x(1+j0)}{0.852 + j0.899}$$

= 2.42 angle 46.5 pu
= 2.42 x 5,250 A (11kV base current)
= 12,705 A

All of this current returns to the 11kV neutrals of T2, T3 and T4 via the ground and the earthgrid. Thus:

I_g = I_f = 12,705 A
EPR = 12,705 x 0.2 V
= 2,541 V

F.7 Conclusions

The summary of calculated EPR's is:

Fault 1	1,016 V
Fault 2	555 V
Fault 3	1,502 V
Fault 4	0 V
Fault 5	2,541 V

The remote 11kV fault causes the highest EPR. For this fault the earthgrid resistance is a significant component of the zero sequence impedance Z_0. If it had not been included, the calculated fault current would have been substantially higher.

F.8 Formulae for Calculating Per Unit Values of Parameters

F.8.1 Impedances

Referred impedance

$$Z\_ = \left[\frac{V_{base}}{V}\right]^2 x\, Z_{ohmic} \qquad (1)$$

Where Z is impedance at voltage V
Z is impedance at voltage 'V base'

$$Z_{pu} = \frac{Z_{ohmic}}{Z_{base}} = \left|\frac{I_{base}}{V_{base}}\right| x\, Z_{ohmic} = \left|\frac{\rho}{V_{ref}^2}\right| x\, Z_{ohmic} \qquad (2)$$

because if V_{ref} is the rated line-to-line voltage of an item of plant having a rated 3 phase power of 'P' MVA and an ohmic impedance of 'Z_{ohmic}' per phase at a line to line voltage 'V_{ref}', the following relations apply:

$$I_{base} = \frac{\rho}{\sqrt{3V_{base}}}\; and\; Z_{pu} = \left|\frac{V_{base}}{V_{ref}}\right|^2 x\, Z_{ohmic} \quad \text{from (1)}$$

When these are substituted in the first part of equation (2) and the result reduced, the second part of (2) is obtained. It and equation (3) can be used to calculate the per-unit impedances of the equivalent circuits to any chosen base MVA and base voltage.

$$Z_{pu\ base} = \left|\frac{\rho_{base}}{\rho}\right| \times Z_{pu\ (P)}$$

where ρ_{base} is the 3 phase base MVA chosen, ρ is the 3 phase plant power rating and the sequence impedance per phase $Z_{pu\ (P)}$ is referred to the base voltage chosen for carrying out the calculation.

If V base is the 3phase line to line voltage, MVA_{base} must be correspondingly the 3 phase power of the system. If V_{base} is the line to neutral voltage, then the power MVA_{base} must be the corresponding single phase power of one phase of the system.

F.8.2 Sequence Impedances

These re determined by breaking the circuit down into blocks whose positive, negative and zero sequence equivalent circuits are known and adding the resulting equivalent circuits for each block and sequence together. The equivalent sequence circuits for the circuit arrangements usually encountered in power systems are given in reference texts such as Appendix I-- Reference 25, Reference 27 or Reference 28 Volume 1.
It is assumed that Electrical Engineers who are carrying out the fault current calculations and Earth Potential Rise calculations described in this Guide will be familiar with the concepts and application of Symmetrical Components, reference impedances, per unit and per-cent impedances and their use in network analysis and fault current calculation. Reference such as those quoted above can be consulted if necessary.

F.8.3 Computer Software for Fault Current and Earth Potential Rise Calculations

The NZCCPTS is currently researching, testing and where the results of this work justify it, further developing fault calculation software which would be suitable for the types of calculation which could be needed when carrying out the procedures recommended by the NZCCPTS Guides. A criteria is that software should be able to run on the computer hardware NZCCPTS member organizations are likely to own or which they will have economic access to now, or as a result of arrangements which can be made in the near future. This work is targeted to be complete by the date when the final Guides go to press.

APPENDIX G Worked Example - Fault to MEN From 11kV Overhead Line

G.1 Introduction

Substation earth mat resistances also affect the EPR and fault current of an 11kV single phase fault to consumer MEN, the highest EPR being experienced by consumers close to the source substation. This example looks at NZIG, 470m from CCEPB Sockburn substation.

G.2 Problem Description

Sockburn Substation: 2 x 10 / 20 MVA

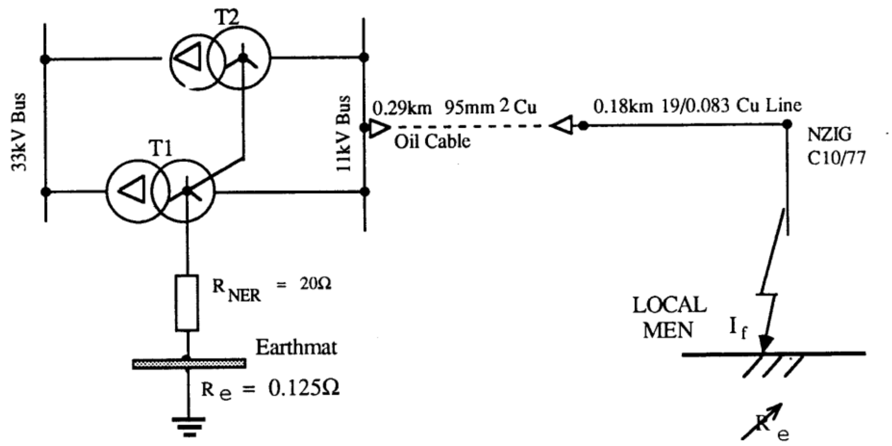


Fig G.1 Fault at NZIG Supplied from Sockburn Substation

Similarly to the method used in Appendix B1, the EPR's and fault currents from an 11kV single phase fault to NZIG MEN with and without and NER are calculated using the spreadsheet version of form A1. The calculation for the existing case without the NER is included in G.3. The earth return through the cable sheath is assumed to be negligible.

G.3 Calculation of Earth Fault Current and EPR

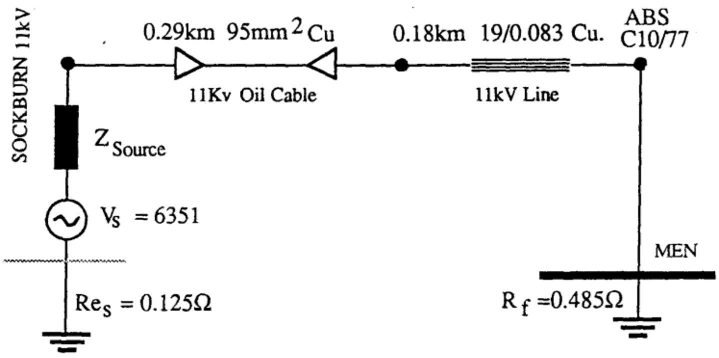
Schedule for manual calculation of a radial feeder fault

Heading	**BY:** Lim Mei Leng	**DATE:** 15/7/88
Single Phase Earth Fault at NZIG 011 O/H From Sockburn 011 (Excluding NER's)	**CHECKED:** N.W. Ross	**DATE:** 20/7/88
	APPROVED: N.W. Ross	**DATE:** 20/7/88
	FILED:	**DATE:**

Reason for Calculation: Worked Example G for EPR Guide

Location in System: Sockburn 001 - Overhead C 10/77

Single Line Diagram;
Include source bus, line and cable lengths and descriptions, local busses or component identifiers such as switch numbers, earth resistances.



(1) Source Parameters

Substation SOCKBURN Feeder: 121 Ph-N Voltage, V_s: 6351

Date: 15 July 1988 Fault Duty 3ø 171:9 MVA, 1ø 184.5 MVA

Source of Fault Duty Date: CCEPB Fault Program EPRSKO.TXT

Earth Mat Impedance: Z_e = 0 :125 ohms Data Source: As above

Data for use in Determining the Parameters in the Calculations which follow:
Soil Resistivity ' ρ ' is 200 Ω -m (urban = 200 Ω -m., Rural = 1500 Ω -m.)

Depth of the earth current* 'DE' = $\sqrt{(\rho / f)}$ = 1,316.8 meters
Typical Impedance values for use in the calculations.
(See §H.7 of Appendix B for the method of deriving the cable parameters and the zero sequence impedances; * 'DE' is used to calculate the resistance of the earth return path R_{ef} as in H.7.2, R_{ef} forms part of the zero sequence reactance in the calculation below).
Fault impedance R_f = 0.485 Ω .

Line / Cable Description		Z / km	Z / km (nl)
185mm^2 Cu Oil Cable	33kV	0.128 + j 0.093	0.276 + j 2.180
JAGUAR Cond. Line	33kV	0.137 + j 0.321	0.285 + j 1.635
95 mm^2 Cu Mind Cable	11kV	0.193 + j 0.082	0.341 + j 2.257
19 / 0.083 Cu cond. Line	11kV	0.265 + j 0.354	0.413 + j 1.687

Manual Calculations of Fault on: NZIG C10 / 77 off Sockburn Station
No ISL P.O.S. NER and no Sockburn NER

FAULT PATH IMPEDANCE VALUES

Components	Z_1 (Ω)	Z_0 (Ω)
Source earthmat (if not included in source impedance below) NER (Net Star-Earthmat resist.) Fault impedance, Z_f		0.000 + j 0.000 0.000 + j 0.000 0.485 + j 0.000
	Subtotal	0.485 + j 0.000
Z_{source} 0.70 84.5 0.63 50.9 (Z_1 & Z_0 : │mag│ angle) km 95mm^2 Cu Cable 011 0.290 19 / 0.083 Cu 011 0.180	3 * Subtotal 0.067 + j 0.697 0.056 + j 0.024 0.048 + j 0.064 + j	1.455 + j 0.000 0.397 + j 0.489 0.099 + j 0.655 0.074 + j 0.304 + j
TOTALS Z_1 = 0.171 + j 0.784 Z_0 = 2.026 + j 1.447 │Z_1│ = 0.803 Ang 77.7 •│Z0│ = 2.489 Ang = 35.5º $2Z_1$ = 0.342 = j 1.569		
$2Z_1 + Z_0$ = 2.37 + j 3.02 $2Z_1 = Z_0$ = 3.83 Ω Ang = 51.9º		

Calculation of Fault Currents and Resulting Earth Potential Rise

3 ø Fault Current
$I_f = V_s$ / │ Z_1 │
= 7,911 Amps

1 ø to Fault current
$I_f = 3V_s$ / │$2Z_1$│ + Z_0
= 4,969 Amps

3 ø Fault Duty
= $3V_sI_f$
= 150.7 MVA

1 ø Fault Duty
= $3V_sI_f$
= 94.7 MVA

EPR = 2.410 kV

G.4 Results

The EPR's and fault currents, I_f, at NZIG MEN for an 11kV single phase fault are tabulated below. These results are also plotted on the graph of Fig. B1.2

EPR and I for fault at 11kV overhead line C10/77 to NZIG MEN

Fault Resistance R_f (Ω)	No NER		20 Ω NER	
	EPR (kV)	I_f (kA)	EPR (kV)	I_f (kA)
0.0	0.000	6.047	0.000	0.312
0.1	0.586	5.862	0.031	0.311
0.485	2.410	4.969	0.148	0.305
0.5	2.467	4.933	0.152	0.305
1.0	3.857	3.857	0.298	0.298
1.25	4.289	3.431	0.368	0.294
1.5	4.613	3.075	0.436	0.291
1.75	4.860	2.777	0.503	0.288
2.0	5.053	2.526	0.569	0.284
2.5	5.330	2.132	0.696	0.278
3.0	5.517	1.839	0.817	0.272
4.0	5.748	1.437	1.044	0.261
5.5	5.930	1.078	1.353	0.246

G.5 Conclusions

The inclusion of the 20 ohm NER into the supply source, Sockburn Substation, greatly reduces the fault current and hence the EPR of an 11kV fault to a close-in MEN.

APPEHDIX H Worked Example - Fault to MEN from 11kV Buried Cable

H.1 Introduction

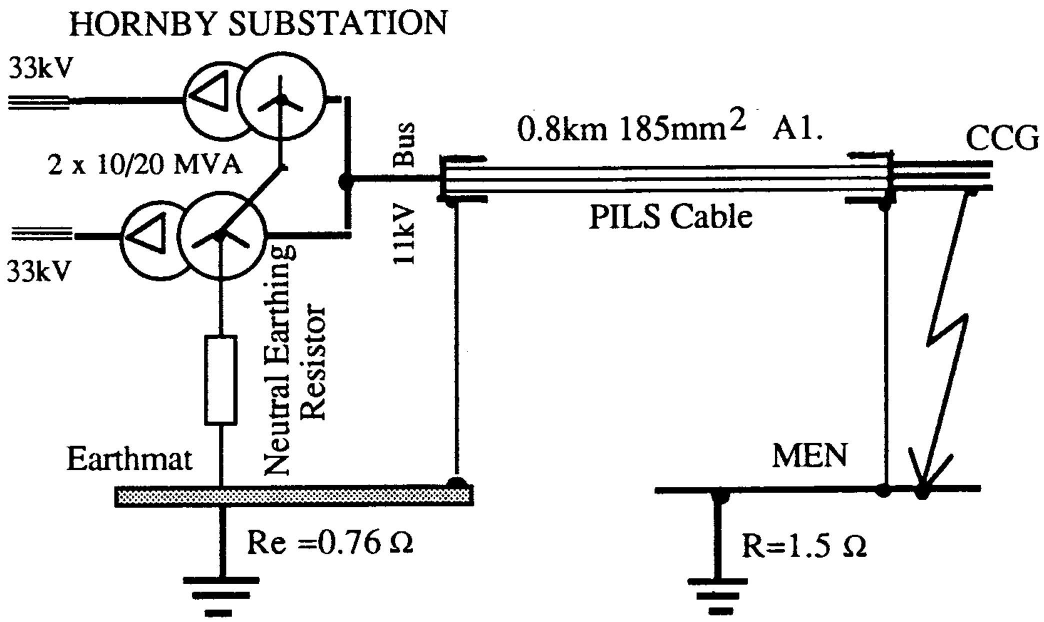
This worked example is the case of an 11kV single phase to earth fault at a consumer's premises. The consumer, CCG, is supplied from a DY11 33/11kV transformer at Hornby substation via 0.8km of 185mm^2 A1 3-core paper insulated cable with its lead sheath bonded to earth at both ends.

The earth return current is shared between the cable sheath and remote earth. There is mutual coupling between the sheath and the core carrying the fault current, and the model accounts for the inductive loop via remote earth.

After deriving the equivalent model, the network is solved by manual calculations and by a computer program called PSSUI. Section H.7 provides the derivation of component values for use in the model, according to the commonly used equations from Westinghouse, reference 25.

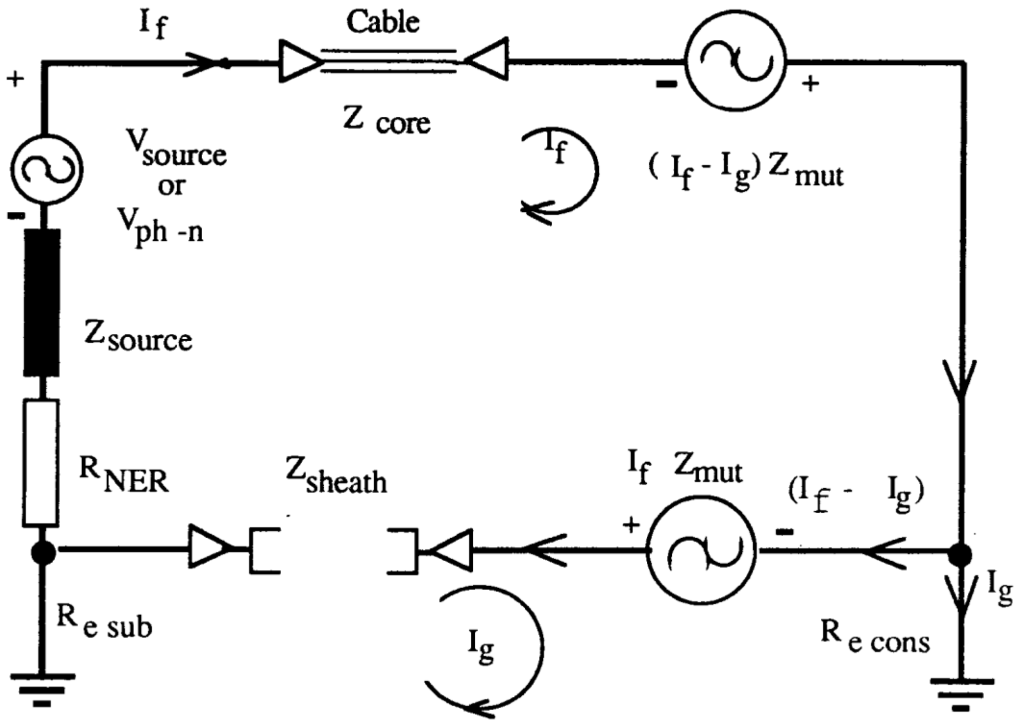
Comparative results are also stated to illustrate the effects of unbonding the cable sheath and including a neutral earthing resistor at the supplying substation.

H.2 Problem Description



H.3 Problem Model

The problem is modelled as two current loops leading to a pair of simultaneous equations that need to be solved. The component values are derived in section H.7. The resulting network to be solved is then as follows:



Where:	V_{ph-n}	=	6350 volts
	Z_{source}	=	$(2Z_1 + Z_0)/3$ at the source bus, obtained from the power system fault simulation program
		=	[2(0.061 + j0.697) + 1.205 + j0.487]/3
		=	0.442 + j0.627

The cable length is 0.8km. Hence, from section H.7

Z_{core}	=	0.8 (0.224 + j0.761) = 0.179 + j0.609
Z_{sheath}	=	0.8 (0.866 + j0.687) = 0.693 + j0.550
Z_{mut}	=	0.8 (0.059 + j0.687) = 0.0472 + j0.550
R_{sub}	=	Source substation (Hornby) earthmat resistance = 0.76
R_{cons}	=	Consumer (CCG) MEN earth resistance = 1.5
R_{NER}	=	0

H.4 Results by Manual Calculation

Using Kirchoff's voltage law, the two simultaneous equations are:

$V_{ph-n} + I_f\,(2Z_{mut} - Z_{source} - Z_{core} - Z_{sheath} - R_{NER}) + I_g\,(Z_{sheath} - Z_{mut}) = 0$

$I_f + (Z_{sheath} - Z_{mut}) - I_g\,(Z_{sheath} + R_{cons} + R_{sub}) = 0$

Let $D = 2Z_{mut} - Z_{source} - Z_{core} - Z_{sheath} - R_{NER}$

$F = Z_{sheath} - Z_{mut}$

$G = Z_{sheath} + R_{cons} + R_{sub}$

Then $I_f = \dfrac{-G}{GD+F^2} V_{ph-n}$

and $I_g = \dfrac{-F}{GD+F^2} V_{ph-n}$

For the worked example:

$D = 1.2196 + j.-0.686$	$= 1.3993$ ang $- 150.6$
$F = 0.6485 + j0$	$= 0.6458$ ang 0
$G = 2.953 + j0.550$	$= 3.00$ ang 10.6
$GD + F^2 = -2.805 + j - 2.699$	$= 3.893$ ang $- 136.1$
$I_f = 4{,}900$ ang $- 33.4$	$= 4{,}093 + j -2{,}694$
$I_g = 1{,}054$ ang $- 43.9$	$= 759 + j - 1{,}963.3$

and $I_{sheath} = I_f - I_g$

$= 3{,}869$ ang $- 30.5$ $= 3{,}334 + j - -730.5$

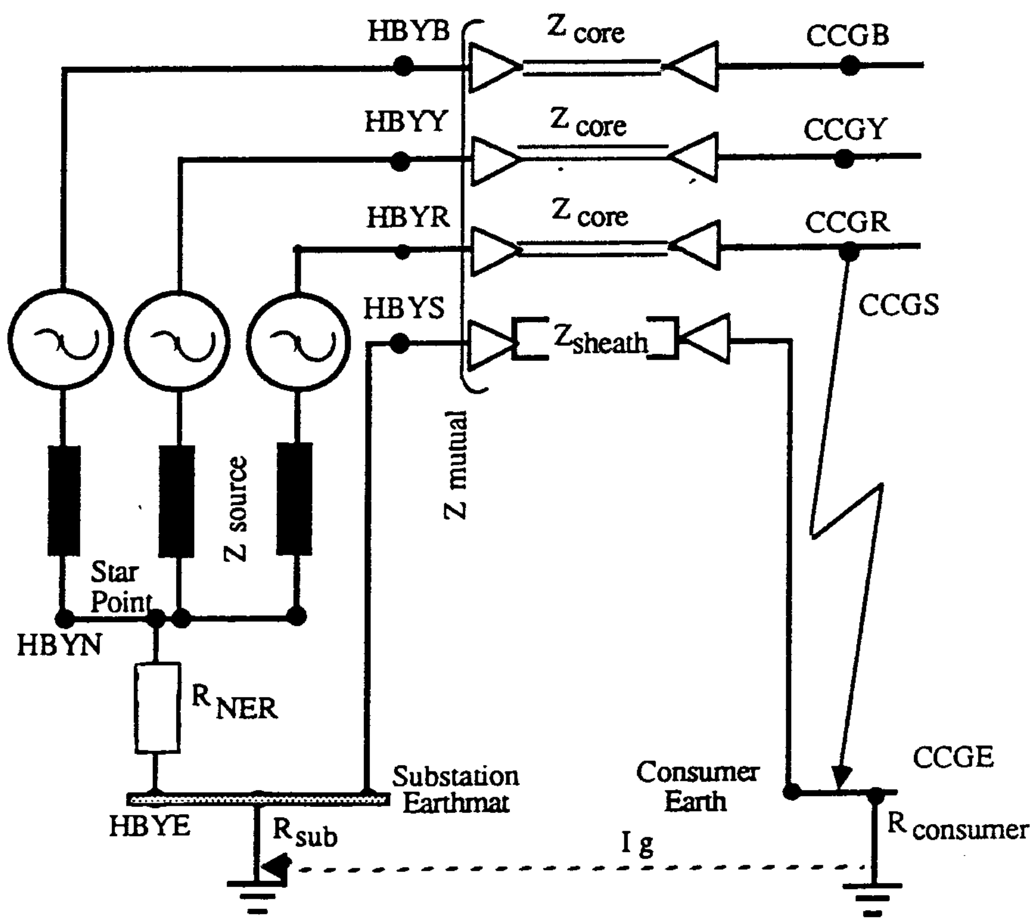
The earth potential rise on the consumer's MEN is then,

$V_{EPR} = I_g \times 1.5$
$= 1{,}581$ volts

H.5 Results by Computer Program PSSUI

The worked example was also solved using the computer program 'Power System Simulator For Utilization Level Circuits, Independent' available in N.Z. from Worley Consultants Ltd. It is one of a set of general purpose programs for power system simulation and the 'independent' version denotes the ability to represent individual phases and connections within the network. Mutual coupling between branches is included and all voltages are calculated with respect to remote earth. Providing the data is available, it is able to solve a network of any configuration.

In applying the program to this example, the following circuit model was used:



H.5.1 Input Data File

The input data file used by the program follows. The values and terminology are self-explanatory.

```
1.0  0.1        0.0001
HBYR
HBYY
HBYB
HBYS
HBYE
HBYN
CCGR
CCGY
CCGB
CCGS
CCGE
END  /  OF BUSES
HBYR        HBYN      6350        0        314       0.442      0.627
HBYY        HBYN      6350     -120        314       0.442      0.627
HBYB        HBYN      6350      120        314       0.442      0.627
END  /  OF RESOURCES
HBYR        CCGR      0.224     0.761      0.8       1
HBYS        CCGS      0.059     0.687
0/
HBYY        CCGY      0.224     0.761      0.8       1
0/
HBYB        CCGB      0.224     0.761      0.8       1
0/
HBYS        CCGS      0.866     0.687      0.8       1
0/
HBYN        HBYE      0.000     0.001      1.0       1
0/
HBYE        0         0.760     0.000      1.0       1
0/
CCGE        0         1.500     0.000      1.0       1
0/
HBYS        HBYE      0.000     0.001      1.0       1
0/
CCGS        CCGE      0.000     0.001      1.0       1
0/
CCGR        CCGE      0.000     0.001      1.0       1
0/1
END  /  OF BRANCHES
END  /  OF CAPACITORS
END  /  OF LOADS
END  /  OF TRANSFORMERS
```

H.5.2 Output Results File

The results are listed in the following. Note that these correspond with the manually calculated values in section H.4, allowing for rounding errors and that the computer model has j0.001 ohms to represent short circuits.

FROM	VOLTAGE MAGNITUDE	PHASE ANGLE DEG	TO		CURRENT MAGNITUDE	PHASE ANGLE DEG	LOAD KW KVAR	SOURCE VOLTS MAGNITUDE	PHASE ANGLE DEG
HBYR	2418.7	-19.8							
			GEN	HBYN	4893.3	-33.4		6350.0	0.0
			RL-BRA	CCGR	4893.3	-33.4	$=i_F$		
HBYY	6212.6	-127.2							
			GEN	HBYN	0.0	94.2		6350.0	- 120.0
			RL-BRA	CCGY	0.0	-118.6			
HBYB	7119.1	121.8							
			GEN	HBYN	0.0	-156.1		6350.0	120.0
			RL-BRA	CCGB	0.0	0.0			
HBYS	800.2	135.9							
			RL-BRA	CCGS	3863.6	149.4			
			RL-BRA	HBYE	3863.1	-30.6			
HBYE	799.3	136.2							
			RL-BRA	HBYN	4893.6	-33.4			
			RL-BRA	GRND	1051.7	136.2			
			RL-BRA	HBYS	3863.1	149.4			
HBYN	798.4	136.5							
			GEN	HBYR	4893.3	146.6		6350.0	0.0
			GEN	HBYY	0.0	-85.8		6350.0	- 120.0
			GEN	HBYB	0.0	23.9		6350.0	- 120.0
			RL-BRA	HBYE	4893.6	146.6			
CCGR	1576.6	-43.7							
			RL-BRA	HBYR	4893.3	146.6			
			RL-BRA	CCGE	4893.4	-33.4			
CCGY	6212.6	-127.2							
			RL-BRA	HBYY	0.0	61.4			
CCGB	7119.1	121.8							
			RL-BRA	HBYB	0.0	0.0			
CCGS	1578.4	-44.0							
			RL-BRA	HBYS	3863.6	-30.6	I_{sheath}		
			RL-BRA	CCGE	3863.5	149.4			
CCGE	1577.5	-43.8							
			RL-BRA	GRND	1051.7	-43.8	$= I_g$		
			RL-BRA	CCGS	3863.5	--30.6			
			RL-BRA	CCGR	4893.4	146.6			

H.5.3 Output Results With 20ohm NER Connected Between Transformer Neutral and Earthmat

FROM	VOLTAGE MAGNITUDE	PHASE ANGLE DEG	TO	CURRENT MAGNITUDE	PHASE ANGLE DEG	LOAD KW KVAR	SOURCE VOLTS MAGNITUDE	PHASE ANGLE DEG
HBYR	148.8	11.7						
			GEN HBYN	301.0	-1.9		6350.0	0.0
			RL-BRA CCGR	301.0	-1.9	I_f		
HBYY	10644.6	-150.2	GEN HBYN	0.0	-27.0		6350.0	- 120.0
			GEN HBYN	0.0	-27.0		6350.0	- 120.0
			RL-BRA CCGY	0.0	0.0			
HBYB	10863.7	148.3	GEN HBYN	0.0	-46.3		6350.0	120.0
			RL-BRA CCGB	0.0	0.0			
HBYS	49.2	167.4						
			RL-BRA CCGS	237.7	-179.1			
			RL-BRA HBYE	237.7	1.0			
HBYE	49.2	167.7						
			RL-BRA HBYN	301.0	-1.9			
			RL-BRA GRND	64.7	167.7			
			RL-BRA HBYS	237.7	-179.0			
HBYN	6068.7	178.0						
			GEN HBYR	301.0	178.1		6350.0	0.0
			GEN HBYY	0.0	153.0		6350.0	- 120.0
			RL-BRA HBYE	301.0	178.1			
CCGR	97.0	-12.2	RL-BRA HBYR	301.0	178.1			
			RL-BRA CCGE	301.6	-1.9			
CCGY	10644.6	-150.2						
			RL-BRA HBYY	0.0	0.0			
CCGB	10863.7	148.3						
			RL-BRA HBYB	0.0	0.0			
CCGS	97.1	-12.5						
			RL-BRA HBYS	237.7	0.9	$= I_{sheath}$		
			RL-BRA CCGE	237.5	-179.1			
CCGE	97.0	-12.3						
			RL-BRA GRND	64.7	-12.3	$= i_g$		
			RL-BRA CCGS	237.5	0.9			
			RL-BRA CCGR	301.6	178.1			

Note that the star point, HBYN, voltage rises substantially to 6,069 volts because of the fault current voltage drop across the NER. Further, the yellow and blue phase voltages rise to nearly 11kV with respect to ground causing extra voltage stress on these two phases during the fault.

H.5.4 Summary of Results

Further simulations were run to compare the results if the cable sheath was isolated at the substation end only. All results are summarized in the following table.

Conditions		Fault Currents			MEN Voltage At CCG	Voltage at Supply Transformer			
						Phase - Ground			Star Point (V)
20 ohm NER	Sheath Bonded	I_f (A)	I_g (A)	I_{sheath} (A)	V_{EPR} (v)	Red (v)	Yellow (V)	Blue (V)	
N	Y	4,893	1,052	3,864	1,578	2,419	6,213	7,119	798
N	N	2,025	2,025	0	3,038	3,618	6,709	7,638	1,539
Y	Y	301	65	238	97	149	10,645	10,864	6,069
Y	N	277	277	0	416	495	10,319	10,645	5,753

H.6 Conclusions and Comments

The worked example has shown that the calculations of a reasonably straight-forward case is quite complicated. It is clear that the aid of software is needed in order to obtain reliable results. A more complicated configuration could not reasonably be solved by manual means.

PSSUI provides a good tool for solving the network. It is very flexible in terms of setting up a network, is appropriate for the 'utilization' level and handles data in convenient power system terms. However, the complexity is largely in the preparation of component values and formulating a valid model. There will always be uncertainty in data on earthing resistance or mutual coupling value, which will introduce some uncertainty in calculated results. However, software is needed to ensure a valid model and correct derivation of component values. It is hoped that this will be developed or found in the future.

The tabulated results show the value of bonding the cable sheath. The consumer MEN voltage is substantially reduced.

The tabulated results also show the advantages of using the NER. The fault currents and MEN voltage are all substantially reduced. Of concern, though, is the higher voltage stress on the unfaulted phases which also gives rise in practice to a significant charging current back to the transformer star point if a significant amount of cable is connected. Earth leakage protection can respond to an apparent earth fault on unfaulted feeders. By careful design, a compromise can be reached.

For more complicated cases, the approach to take would be to derive component values as best you can, derive the model and use PSSUI.

H.7 Derivation of Cable impedances

The unit length phase impedances for the 185mm^2 A1 cable are derived from the sequence impedances per Westinghouse formulae. These take the earth resistivity and influence of the earth return path into account.

H.7.1 Positive and Negative Sequence Impedances

R_c	=	Cable Resistance per phase	= 0.1648 ohms/km
$GMD3_c$	=	Geometric Mean Distance	= 23.24 mm
$GMR1_c$	=	Geometric Mean Radius, 1 conductor	= 6.774 mm
k	=	7.5% reduction in reactance for sectored cables	= 0.925

$Z_1 = Z_2$ = R_c + jk x 0.1447 log $\left|\frac{GMD3_c}{GMR1_c}\right|$ ohms / phase / km,

= 0.1648 + j0.925 x 0.1447 log $\left|\frac{23.24}{6.774}\right|$

= 0.1648 + j0.0717 ohms / phase / km;

H.7.2 Zero Sequence Impedance

R_e = ac resistance of earth return path

= 0.6214 km/mile x 0.286 ohm (converting Imperial data)

= 0.1777 ohm/km (from the Westinghouse Electrical Transmission and Distribution Handbook)

Depth of earth return

D_e = 658.4 $\sqrt{\frac{p}{f}}$ where ρ = oil resistivity = 200 ohm.m; f = frequency = 50 Hz

= 1316.8 metres

Geometric Mean Radius, 3 conductors

$GMR3_c$ = $\sqrt[3]{[GMR1_c(GMD3_C)]^2}$

Z_0 = $R_c + R_e$ + j0.4341 log $\left|\frac{D_e x\ 10^3}{GMR3_c}\right|$

= 0.1648 + 0.1777 + j0.4341 log $\left|\frac{1.316.8\ x\ 10^3}{15.4}\right|$

= 0.3425 + j2.141 ohm / phase / km

H.7.3 Phase Impedance

Z_{ph} = $\frac{Z_1 + Z_2 + Z_0}{3}$

= $\frac{[2(0.1648 + j0.717) + 0.0325 + j2.14]}{3}$

= 0.224 + j0.761 ohm / phase / km

H.7.4 Sheath Impedance

r_o = outer radius of sheath = 24.7 mm
r_1 = inner radius of sheath = 22.6 mm
R_{sh} = sheath resistance

$$= \frac{80.2}{\left[(r_0 + r_i)(r_0 - r_i)\right]} \text{ ohms / km for lead sheaths}$$

$$= 0.807 \text{ ohms / km}$$

$$Z_{sh} = \frac{\left[3R_{sh} + R_e + j0.4341\ log\left(\frac{2D_e x 10^3}{r_0 + r_1}\right)\right]}{3} \text{ ohms / km}$$

$$= \frac{\left[\mathbf{3x0.808 + 0.1777 + j04341\ log\left(\frac{2x1316.8x10^3}{24.7 + 22.6}\right)}\right]}{\mathbf{3}}$$

$$= 0.866 + j0.687 \text{ ohms / km}$$

H.7.5 Mutual Impedance, Core - Sheath

$$Z_m = Z_{sh} - R_{sh}$$

$$= 0.059 + j0.687 \text{ ohm per km}$$

APPENDIX I Historic Substation Protection Practices (pre 1989)

I.1 Transpower Substations

A Transpower substation usually has voice and data communications with links to other Transpower substations and facilities, and sometimes with Electrical Supply Authorities.

I.1.1 General Aspects

These communications links may be by way of:
- Radio links
- Power line carrier systems
- Transpower or Electrical Supply Authority owned physical circuits
- Telecom's public subscriber dialing network
- Telecom leased direct circuits

The latter three types of communications links are usually physical circuits. Transpower substation prospective EPR's are usually greater than 430V. Therefore physical circuits extending outside the earthmat perimeter are provided with electrical isolation against 50Hz common-mode voltages, thereby eliminating transferred voltages due to EPR to equipment or persons at remote earth potential.

Electrical isolation for physical circuits is achieved by the use of:
- Barrier relays for pulsed dc signals
- dc/dc transducers for continuous dc signals
- Isolation transformers for ac signals
- Optical fibre communications links for digital analogue signals

Isolation equipment is normally rated to withstand 25kV rms for 1 minute.
Optical fibre links are a relatively recent innovation. They are highly effective in providing electrical isolation because the signals travel along a non-conducting "wire". No special equipment or construction/maintenance practices are required to achieve electrical isolation.

In the case of metallic physical circuits, the special isolation equipment, can be located:
- At or outside the 430V contour of the highest prospective EPR situation.
- Within the 430V contour and outside the perimeter of the substation Earthmat.
- Inside the Earthmat perimeter.

As many substations it is impractical to site the isolation equipment outside the hazard zone, especially if it is outside the substation site.

I.1.2 Housing of Isolation Equipment

The isolation equipment may be housed in a purpose-built building, a separate room in a substation main or ancillary building, or in a special cubicle in the relay room of the substation control building.

The isolation equipment building, room or cubicle is designed and constructed so that a person working on the equipment cannot make simultaneous contact with anything that is "earthed" locally and any metallic connection extending inside/outside the earthmat. This is achieved by shrouding exposed metalwork and by the use of insulating panels and insulated standing platforms or floor coverings.

The isolation area is provided with isolated power supplies, whether 230V ac for potable tools, etc. or dc for the isolation equipment and circuits. All metallic fittings are earth-free.

Communications cables extending both inside and outside the earthmat are rated at 25kV between conductors and the surrounding earthmat. Cables are laid in separate trenches or ducts at least 1m away from parallel substation primary cable routes and with at least 1m away from parallel substation secondary cable routes and with at least 0.3m separation at crossings. One additional situation is where substation staff housing has power supply from the substation local service 400/230V transformer(s). It is Transpower practice to use isolating transformers with isolation of 15kV rms between windings and from each winding to earth. Special earthing and maintenance practices are applied.

I.2 Electrical Supply Authorities

Electrical Supply Authorities usually have their own communications facilities for data and voice transfer between depots and substations. Since there is an electrically hazardous environment and a requirement for high security, special precautions are taken and appropriate equipment is used.

I.2.1 Communication Cables

Within distances of up to 10km, multipair communication cables are usually used. These are generally configured to Telecom standards (e.g. 7, 10 or 15 pair), but have a higher voltage insulating outer sheath and armouring and/or screens. It is common to test the cable with 10kV dc between wires, and from all wires to the metallic outer cover (armouring or screen).

For greater distances, UHF links or leased Telecom circuits are usually used.

Within substation boundaries, multicore control cables or multipair communication cables are used. These are generally not armoured but many have screens. They must also have a high voltage withstand capability (10kV or greater).

I.2.2 Earthing of Communication Cable Armouring/Screens and Fibre-Optic Cable Metallic Strength Members

Communication cables often go from one hazard zone to another, and can be in parallel with power circuits. Hence, without adequate protection practices, they can carry earth return fault current which may damage the cable. They can also transfer earth potential rises which could become a hazard to personnel or plant at a point remote from the hazard zone.

In an overhead power system environment, the armouring/screen or metallic strength member is earthed at one end only. The end chosen is usually the one with the lower EPR.

In an underground power cable environment it is usual to bond all armouring, screens and steel strength members to earth at both ends. This is because cable sheath bonded power systems are usually not subject to hazardous EPR.

I.2.3 Termination/Isolation Equipment

EPR must be prevented from being applied to the cable pairs along the length of the cable (a common mode voltage). The recommended practice to achieve this is:

- Terminate each pair with an isolation transformer with 1:1 turns ratio and suitable rating (typically 5kV or 25kV). These usually have an electrostatic shield that should be connected to the local earth.
- Mount isolating transformers on a suitably protected high voltage insulation board and ensure that the cable is insulated from the local earthed environment to at least the transformer's voltage rating. Generally, the closer the termination to the point of entry to the building, the better.
- Label the line (cable) side plant as hazardous and ensure that maintenance staff take suitable precautions.
- Where dc has to be transmitted, use a barrier relay or optical isolation unit for single ended isolation.
- Where double ended isolation is used, a suitably isolated dc power supply is required on each circuit pair. This is not a common technique.

APPENDIX J References

Conferences, Seminars and Guides on Co-ordination

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