APPLICATION GUIDE

CABLE SHEATH BONDING

NZCCPTS

Issue 1

September 1999

Reprinted November 2010

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

The New Zealand Committee for the Co-ordination of Power and Telecommunication Systems was established in 1985 following the increasing need to implement efficient cost-effective measures for the limitation of hazard and interference to power and Telecommunications Systems and Personnel.

Such measures not only require the determination of optimum engineering solutions consistent with minimum national cost, but also necessitate clear guide-lines covering the equitable allocation of responsibilities during all work phases from planning through to in-service operation.

The objective of the New Zealand Committee for the Co-ordination of power and Telecommunication Systems is to meet these needs and, by means of publications and seminars, promote a greater awareness and understanding of the action that must be taken to ensure that Power and Telecommunication Systems coexist satisfactorily.

Membership of the Committee and its Working parties currently comprises representatives for each of the following organizations:

- **Transpower New Zealand Ltd.**
- **Telecom New Zealand Ltd.**
- **Electricity Engineers' Association of New Zealand Inc.**
- **KiwiRail (NZ Railways Corporation)**
- **Energy Safety Service, Ministry of Consumer Affairs**

For further information concerning this Committee and its published guides, refer to the NZCCPTS website at www.nzccpts.co.nz, or contact the NZCCPTS Secretary.

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APPLICATION GUIDE

FOR

CABLE – SHEATH BONDING

for the control of earth potential rise and for the limitation of hazardous induction into telecommunication circuits

Published and issued by:

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

This guide sets out the technical issues and implications for nearby telecommunication network plant of various cable sheath bonding arrangements for high voltage power cables between substations.

NZCCPTS is indebted to the Electricity Engineers' Association of New Zealand, Telecom New Zealand Limited, and Transpower New Zealand Limited, for their contributions in the formation of this guide.

Comments for revision of this guide are welcomed. Any comments or information that may be useful for inclusion in future issues should be forward to:

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A brief description of the objectives and organization of the New Zealand Committee for the Co-ordination of Power and Telecommunication Systems Inc. is printed inside the back cover of this publication.

Contents

1.0 Introduction

Cable sheaths can be used in conjunction with power system earthing systems to assist in controlling earth potential rise and induction to parallel telecommunication circuits during earth fault conditions.

Bonding arrangements should be provided to meet the following objectives:

(a) to limit the magnitude of EPR on the substation earth mats. This

- reduces step and touch voltages on and near the substation site,
- reduces the EPR that telecommunication cabling and equipment terminating in the substation must be designed for, and
- reduces the EPR at the location of nearby telecommunications plant.

(b) to minimize the voltage induced in parallel telecommunication circuits.

Techniques now exist for modelling earthing systems with cable sheaths bonded at either end or both ends, or at cable mid-points. However, for some situations, the implications of various bonding arrangements may be determined without the need for detailed modelling studies.

This guide is intended to help engineers determine appropriate installation arrangements, primarily for the control of EPR, and to recognize when detailed modelling and study should be pursued. Cross bonded single core cables require both ends (and intermediate positions) to be solidly earthed, but this guide does not detail all the studies necessary for such installations. Detailed information on determining induced voltages in telecommunications lines and cable that parallel power cables can be found in both the NZCCPTS Guide for Investigating Power System - Telecommunication System Noise Interference and in the NZCCPTS Application Guide for Single Wire Earth Return High Voltage Power Lines.

This guide forms part of a series of guides, each one dealing with a particular aspect of inter-action between power and telecommunication systems. References to other guides are included in Section 9.0.

1.1 Scope

This guide describes the conditions to be met in power systems that use insulated cables to interconnect various parts of those systems

and

outlines the factors that should be considered when determining the cable sheath bonding arrangements at each end of the cable.

1.2 Definition of Terms

Distribution Substation
A substation within the distribution network that provides 400/230V output.

Earth Potential
The actual voltage of the earth with respect to remote earth.

Earthing System Potential Rise (EPR)
The voltage with respect to remote earth to which the earthing system rises due to the flow of fault current between the earthing system and earth.

National Grid
The bulk power transmission system, owned and operated by Transpower New Zealand Ltd.

Point of Delivery (POD) Substation
A substation forming part of the National Grid that supplies electricity to a local distribution network.

Remote Earth
A body of earth sufficiently free of any influence from the HV Stations of interest or the distribution network under consideration because it is sufficiently far away from any material resistively connected to those HV Stations (generally 1 km+), and outside of their electro-magnetic influence (3 km+).

Transferred Earth Potential Rise (TEPR)
The rise in potential with respect to remote earth to which an earthing system rises as a consequence of being connected via a cable sheath or other conductor to another earthing system on which an Earthing System Potential Rise occurs due to a fault current flowing through that earthing system to earth. (Note: Overhead earth wires on transmission lines provided primarily for shielding purpose usually provide high resistance connections between earthing systems compared to cable sheaths, but should be taken into account as they can significantly affect TEPR).

Zone Substation
A substation embedded within a distribution network and that transforms voltage levels to not less than 6.6kV.

1.3 Background

Early practice appears to have been to simply bond cable sheaths to earth at both ends to distribute fault current as widely as possible in the earthing systems.

About 1970, concerns were raised in New Zealand over the possible implications of exporting earth potential rises under fault conditions via cable sheaths from high voltage transmission substations to lower voltage distribution substations. At that time, the main concern was with possible hazards to personnel and equipment at the distribution site. For some time after 1970, many installations were completed with cable sheaths bonded to earth at one end only and insulated at the other end.

Incidents have since occurred in which damage to telecommunication equipment occurred because the non-bonding of cable sheaths at the delivery station (to avoid export of EPR) resulted in much higher EPR at the receiving station (See Section 5.4). Detailed study showed these incidents could have been avoided if the separate earth mats had been connected together via the cable sheaths; had this been done, minimal telecommunication isolation would have been needed for protection. It has now become clear that cable sheaths can provide a means of controlling earth potential rise wherever it is possible to effectively couple two earth mats together via the cable sheath without subjecting the cable sheath insulation to excessive voltage stress and without overloading individual cable sheaths with circulating currents, eddy currents, or fault currents.

2.0 Outline of Cable Sheath Bonding Systems

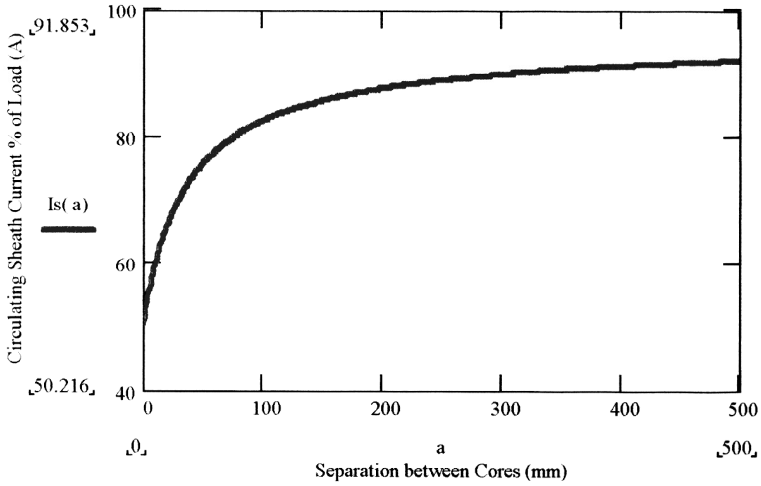
Four bonding systems are available for use. These are:

- solidly bonded system, where the sheaths at both ends of each cable (3 core cable or 3 x single core cable circuit) are solidly connected to the relevant earth mats.
- end-point bonded system, where one end only of each cable is solidly earthed.
- mid-point bonded system, where the sheath bonding to earth is located half way along the cable length (for the same reason as in the end-point bonded system).
- cross-bonded system, where the sheaths at both ends of the cables are solidly bonded to the relevant earth mats and are also bonded together (and possibly earthed) at points along the cable route. Usually used in 33kV and higher voltage systems where single phase cables are used, particularly for higher power levels and for longer routes.

End-point, mid-point, and cross-bonded systems are often referred to as variations of specially bonded cable systems. The main reason for the specially bonded cable systems is to eliminate the heating effects of circulating sheath currents and consequently maximize the single core cable current rating. The main features of each of these bonding systems are described in sections 2.1 to 2.4.

2.1 Solidly Bonded System

This system of bonding involves solidly bonding the cable sheath at both ends to the relevant earth mats. It is very suitable for distribution networks at 11kV and 33kV, particularly where 3 core lead sheath cables are installed. Sheaths solidly bonded at both ends of circuits made up of single core or multicore power cables, will result in circulating currents that are produced in the sheaths by the magnetic flux linking the conductors and the sheaths. If single phase cables are laid in close trefoil formation, the sheath circulating currents can be as high as 40% of the load current. The figure below shows the sheath circulating current as a percentage of the load current, versus the separation between the cores of the three single phase cables in a three phase circuit. The sheath currents are also a function of the sheath resistance. As the sheath resistance increases, the circulating current decreases. Due to internal transposition of cores in three core cables, they usually have no significant sheath circulating currents.



The sheath circulating current as a percentage of the load current vs the separation between cores.

Close trefoil formation of single-phase cables affects the load rating of the cables, because of the heating effect of the cables on each other. However, de-rating as a consequence of installation in trefoil formation is seldom a significant issue in distribution systems because it is usually more economic to use cables of standard manufacturing sizes; these often have a rating substantially in excess of the maximum required.

2.2 End-Point Bonded System

This system of bonding involves earthing the cable sheaths at one termination and insulating the cable sheaths from ground at the other end. In single phase cable systems, the magnetic flux linking the conductors and the sheaths will result in a standing 50Hz voltage between the sheaths and the ground at the insulated end. For cable lengths of over 0.5 km, it may be necessary to use cables with a higher sheath insulation level than normally provided, or else provide sheath voltage limiting protectors. Where short lengths of cables are used between overhead line terminations and substations, it may be more economic to directly connect the line terminal earth mat (to which the cable sheath would normally be bonded), to the substation earth mat via a separate suitably rated conductor to avoid expensive cable requirements. Section 7.0 provides further detail on short cables for overhead line terminations.

End point bonding at the remote end away from the substation can avoid the export of EPR. However, the implications of this arrangement need careful consideration.

A short length of control/instrumentation cable running across a station earth mat may need to be end-point bonded to avoid having the cable sheath (which is unlikely to have a significant current rating) become a parallel path within the earth mat.

2.3 Mid-Point Bonded System

In this system, the cable is earthed midway along the cable route, and both ends of the cable are insulated from ground. The mid point bonded system effectively doubles the length of cable that can be installed without requiring either a higher level of sheath insulation or sheath voltage limiting protectors.

2.4 Cross-Bonded System

This bonding system is necessary for long sub-transmission and transmission system installations comprising long lengths (greater than 300m) of single core cables. Without cross bonding, heating from sheath/screen circulating currents in long cables may necessitate a significant derating of the cable capacity. Where single phase cables are used in very long runs, cross bonding is also essential to protect the outer insulation against standing and impulse voltages.

The route length is divided into a number of minor sections, with this number being a multiple of 3. The sheaths are insulated from ground at the cross bond joints between each minor section. At each set of minor section joints, the sheaths are cross connected between cables of different phases so that the standing voltages on the sheaths of 3 minor sections in series comprise 3 vectors 120° apart, which sum to zero voltage.

The cable sheaths are bonded to earth at both cable ends, and also at every third set of joints (at the end of major sections). Sheath voltage limiters are installed at all other minor section cross bond joint positions, or alternatively a higher rated (and more expensive) sheath/screen insulation can be provided.

For cables longer than 1 km, or with sheaths that are not rated for high fault currents, the impedance of the cable sheaths is often substantially greater than the earth mat resistances, and this limits the fault current (and hence TEPR) transferred through the sheaths between the delivery and receiving stations' earth mats. Long, high MVA capacity 110 kV and 220 kV cables, necessitating the use of single core cables, are good examples of this.

2.5 Cable Sheath Insulation

This section has been included to provide some understanding of the significance of metallic cable sheaths in cable construction, and of the need to protect cable sheaths in turn by further insulation.

Metallic sheaths are essential for paper insulated cables to exclude moisture from the insulation. Extruded insulation cables (XLPE etc) are usually manufactured with copper wire screens over the outer semi-conducting insulation layer for use at 11kV and 33kV, while metallic sheaths are mainly specified for cables at 66kV and above. A metallic sheath/screen also reduces the electric field (but not the magnetic field) around the cable to zero at the outer surface of the cable insulation when the sheath is bonded to earth.

The layers surrounding the sheath are primarily to protect the metallic sheath/screen against damage or corrosion. Any puncture of the sheath will eventually allow moisture to penetrate the insulation and consequently lead to insulation failure. While moisture can lead to corrosion of screens (aluminum being more susceptible), damage to XLPE insulation may take many years to arise.

Usually a combination of materials is provided over the sheath/screen, occasionally including steel wire or steel tape armouring to provide longitudinal mechanical strength for installation handling and for impact protection.

Because the materials that are normally used for sheath protection do not provide high quality electrical insulation, they in turn need to be protected against transient and steady state voltages of magnitudes that may puncture the sheath protection and thereby allow corrosion of the sheath to proceed. In the UK, the standard practice is to limit the standing sheath voltage on cable sheaths, relative to ground, to 65V and to protect against sheath damage by installing sheath voltage limiters between sheath and earth wherever cable sheaths are not able to be bonded to earth to prevent such sheath voltages occurring. In long submarine power cables, the cable sheath is bonded to the external armouring at intervals along the length of the cable; the intervals are chosen to ensure that the cable sheath protection cannot be overstressed by any voltages developed between the sheath and the armouring, which is considered to be effectively at earth potential.

While manufacturers may sometimes provide sheath insulation with higher than standard sheath insulation protection levels, the costs of doing so can be significant. This is a situation often encountered with XLPE cables.

3.0 Electrical Interference on Nearby Telecommunication Network Plant

The following sections 3.1 to 3.5 provide a brief summary of aspects relevant to the causes and magnitude of hazardous electrical interference to nearby telecommunication plant, together with a summary of the legislative requirements on interference hazard limits and notification of the construction of new electrical works in the vicinity of telecommunication plant.

3.1 Interference Mechanisms

Hazardous voltages can be impressed on nearby telecommunication network plant by the following means:

(1) induction of a hazardous voltage onto a telecommunication cable, caused by the **earth return** (fault) current carried by a parallel HV power line.

(2) hazardous EPR at the location of telecommunication plant. This includes EPR in the soil surrounding a buried telecommunication cable, EPR at the location of telecommunication network ready access points, and EPR at premises in which telecommunication circuits terminate (e.g. the substation itself, and neighbouring houses/buildings).

These hazardous voltages can cause hazard to telecommunication customers and personnel, and damage to telecommunication plant.

Non-hazardous “noise” interference voltages can also be impressed on telecommunication network plant.

3.2 Legislative Requirements

Sections 24 and 25 of the Electricity Act 1992 require that, before an Electricity Operator can start constructing or altering a works, it must first provide details of the work involved to any Telecommunication Network Operator (TNO) whose plant might be affected. The TNO then has 15 working days to notify the Electricity Operator of any “reasonable” conditions it imposes on that work.

Electricity Regulation 58 further requires that any Electricity Operator constructing a works in the vicinity of telecommunication plant must ensure that the works cannot cause an induced voltage or EPR that is likely to cause a hazard to persons, or damage to telecommunication plant. Induction hazard voltage limits of $650V_{rms}$ for faults with a duration of $\leq 0.5s$, and $430V_{rms}$ for faults with a duration $> 0.5s$ and $\leq 5s$, are prescribed. There is a reciprocal requirement on TNOs constructing a works in the vicinity of HV power plant.

3.3 Typical Effects of Cable Sheath Bonding on Electrical Interference on Nearby Telecommunication Network Plant

Cable sheath bonding, particularly between an urban POD Substation (e.g. 110/33kV Grid substation) and a Zone Substation (e.g. 33/11kV substation), **typically** has the following effects:

- substantial reduction in induced voltages on telecommunication cables parallelling the HV (e.g. 33kV) power cable.
- usually a substantial reduction in the maximum EPR on the Zone Substation earth mat
- usually a reduction in the maximum EPR on the POD Substation earth mat.

Cable sheath bonding in these cases **usually** has a substantial net benefit in terms of its effect on nearby telecommunication network plant.

If the Zone Substation is in turn effectively bonded to an extensive urban MEN system (plus various HV earthing systems), then the consequential maximum EPRs at the POD Substation and the Zone Substation (and any downstream distribution transformers) are rarely a problem.

However, since it is possible for cable sheath bonding to worsen some induction or EPR hazards, as shown in the next section, this needs to be evaluated on a case by case basis.

3.4 Maximum Short Circuit Power, Current and Fault Clearance Times

Both the magnitude and time duration of voltages, either induced in or impressed on telecommunication equipment, are taken into account in determining hazard limit values.

The relevant Transpower maximum available short-circuit MVA, 3 phase current values and fault clearance times for points of delivery from the national grid to the distribution system, are tabulated below:

Nominal Voltage (kV)	Maximum Short-Circuit	
	Power (MVA)	3 Phase Current (kA)
220	12,000	31.5
110	6,000	31.5
66	1,800	16
50	1,350	16
33	1,400	25
22	950	25
11	475	25

Fault Clearance times for Feeders	
Nominal Voltage (kV)	**Design Maximum Fault Clearance Time* (ms)**
220	120
110	200
66	200
50	200
33	1,000
22	1,000
11	1,000

* Final back-up fault clearance times are longer and are not shown.

Source of data –Transpower Grid Operating Security Policy 1997, Appendix 5 p 26-27.

Zone substations, which are normally supplied from the national grid and have an earthed neutral 11kV (or other distribution voltage) secondary, provide a neutral earthed source for faults which arise within the 11kV distribution system. An indication of the magnitude of (3 phase) fault currents for various fault ratings within 11kV and 33kV distribution systems are shown in the following table:

11kV Short-circuit		**33kV Short-circuit**	
Power (MVA)	**3 Phase Current (kA)**	**Power (MVA)**	**3 Phase Current (kA)**
500	26.2		
350	18.5	1500	26.2
250	13.2	1000	17.5
150	8.0	750	13.0
100	5.35	500	8.7
50	2.67		

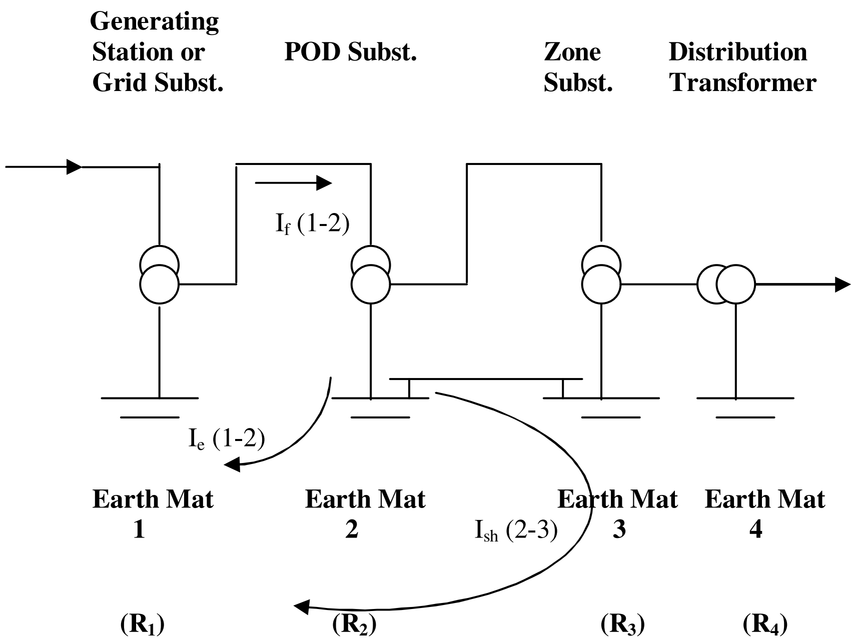
The currents listed are balanced 3 phase values. Single phase fault values may be slightly higher.

4.0 Summary of Impact of Cable Sheath Bonding

The impact of bonding the sheath of the HV cable between a POD Substation and a Zone Substation, to the respective substation earth mat at each end of the cable, can be considered as set out below. The situation considered is illustrated in the diagram below.

The following three phase-to-earth fault situations need to be separately considered.

(1) Phase-to-Earth Fault to Earth Mat 2 (from incoming line)



$I_f(1\text{-}2) = I_e(1\text{-}2) + I_{sh}(2\text{-}3)$

NETT **earth return** currents

1 - 2 $I_e(1\text{-}2) + I_{sh}(2\text{-}3) = I_f(1\text{-}2)$

2 - 3 $I_{sh}(1\text{-}2)$

$EPR_1 = R_1 \times I_f(1\text{-}2)$

$EPR_2 = R_2 \times I_e(1\text{-}2)$

$TEPR_3 = R_3 \times I_{sh}(2\text{-}3) = TEPR_2$

where $I_e(1\text{-}2)$ = net **earth return** fault current, that passes through earth mats **1** and **2**, for a phase-to-earth mat fault on the incoming feeder to POD substation (**2**)

I_f(1-2) = total fault current for a phase-to-earth mat fault at the downstream substation (**2**)

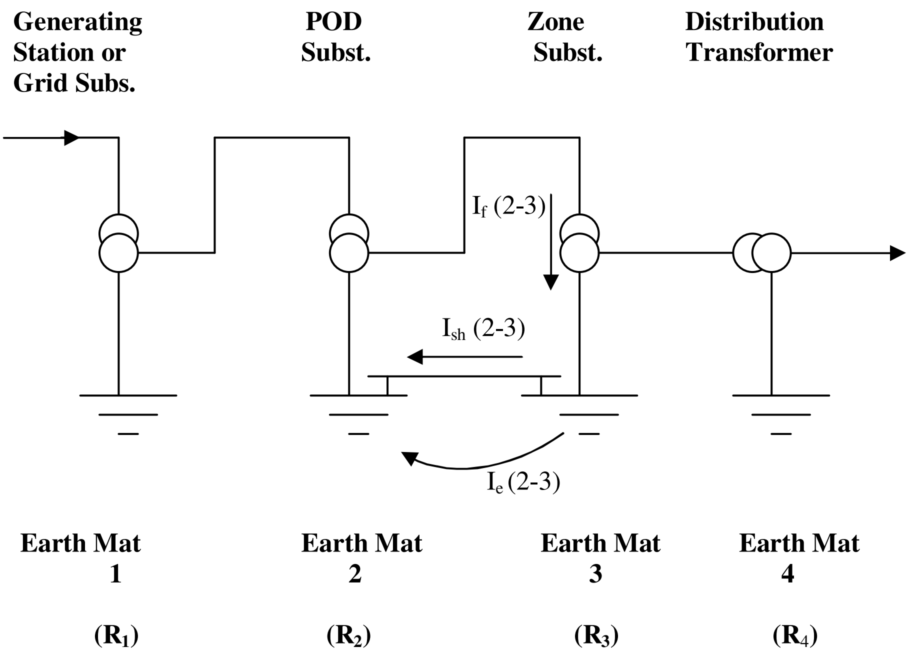
I_{sh}(2-3) = that portion of the total fault current I_f(1-2) that returns to earth mat **1** via the cable sheath bond between earth mats **2** and **3**

EPR_2 = EPR on earth mat **2**

$TEPR_3$ = that portion of EPR_2 that is **transferred** via the cable sheath to the substation earth mat **3** on the other end of the cable

Because any current flow through the cable sheath will result in a voltage drop along the sheath, the "received" transferred EPR (e.g. $TEPR_3$) will always be less than the original "source" EPR (e.g. EPR_2).

(2) Phase-to-Earth Fault to Earth Mat 3 (assumes fault just upstream of zone transformer)



I_f(2-3) = I_e(2-3) + I_{sh}(2-3)

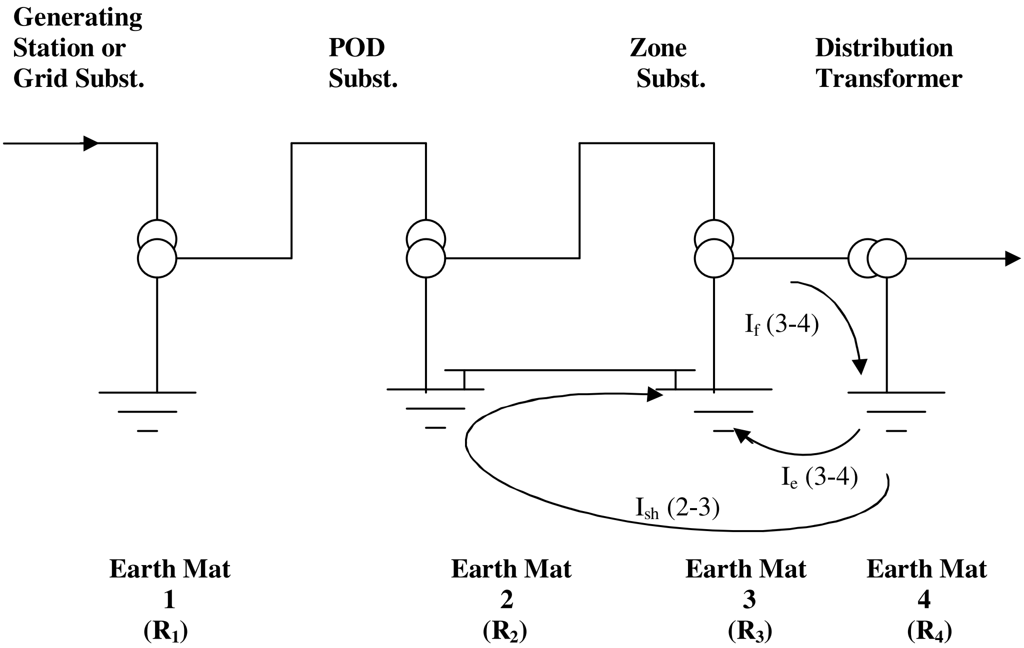
NETT **earth return** currents

2 - 3 I_e(2-3)

EPR_2 = R_2 x I_e(2-3)

EPR_3 = R_3 x I_e(2-3)

(3) Phase-to-Earth Fault to Earth Mat 4



$I_f(3\text{-}4) = I_e(3\text{-}4) + I_{sh}(2\text{-}3)$

NETT **earth return** currents

2 - 3 $I_{sh}(2\text{-}3)$

3 - 4 $I_e(3\text{-}4) + I_{sh}(2\text{-}3) = I_f(3\text{-}4)$

$TEPR_3 = R_2 \times I_{sh}(2\text{-}3)$

$EPR_3 = R_3 \times I_e(3\text{-}4)$

$EPR_4 = R_4 \times I_f(3\text{-}4)$

NETT EFFECTS OF CABLE SHEATH BONDING

(1) Total fault currents

$I_f(1\text{-}2)$	increases (usually only slightly)
$I_f(2\text{-}3)$	increases (often substantially)
$I_f(3\text{-}4)$	increases (usually only slightly)

(2) Maximum nett **earth return** fault currents

1 - 2	increases (usually only slightly)
2 - 3	usually reduces (often substantially) - see below Note
3 - 4	increases (usually only slightly)

Note

The maximum **earth return** fault current between earth mats 2 and 3 may NOT be the "reduced" $I_e(2\text{-}3)$, but rather one of the "transferred EPR" fault currents ($I_{sh}(2\text{-}3)$ for a phase-to-earth fault to earth mat **2**, or $I_{sh}(2\text{-}3)$ for a phase-to-earth fault to earth mat **4**). If this is the case, the maximum earth return fault current between earth mats 2 and 3 **may** increase as a result of cable sheath bonding.

(3) Maximum substation earth mat EPRs

EPR_1		increases (usually only slightly)	
EPR_2	=	maximum of	
		$R_2 \times I_e(1\text{-}2)$	decreases
		$R_2 \times I_e(2\text{-}3)$	decreases (often substantially)
		$TEPR_2$	new
EPR_3	=	maximum of	
		$TEPR_3$	new
		$R_3 \times I_e(2\text{-}3)$	decreases (often substantially)
		$R_3 \times I_e(3\text{-}4)$	decreases (usually only slightly)
EPR_4		increases (usually only slightly)	

While bonding the two substation earth mats 2 and 3 together via the cable sheath will lower the effective resistance of both substations, thereby reducing any **existing** EPRs at each substation, the transferred EPRs may still result in the "worst case" EPR at one of these substations **INCREASING**.

Also, because the lower effective earth resistance of both substations (**2** and **3**) will result in higher **earth return** fault currents from the next upstream substation (**1**), and to the next downstream substation (**4**), the maximum EPRs at both the next upstream and next downstream substations will increase (usually only slightly).

4.1 Impact on Telecommunication Network Operator's Network

Any Telecommunication Network Operator (TNO) with plant near substation earth mats 1, 2, 3 or 4, should be sent details of

- all the above **increased** nett earth return fault currents
  i.e. $I_f(1\text{-}2)$ and $I_f(3\text{-}4)$ (and the greater $I_{sh}(2\text{-}3)$ (for a phase-to-earth fault to either earth mat **2** or earth mat **4**) if it is more than the former "unbonded" $I_e(2\text{-}3)$)
- all the above **increased** maximum substation earth mat EPRs
  i.e. EPR_1, EPR_4 and possibly EPR_2 and/or EPR_3.

These details should be sent to the TNO's Power Co-ordinator (see Appendix C for contact details) so he/she can evaluate:

(i) what increased voltages may be induced into nearby parallel telecommunication cables,

(ii) what increased EPR hazards may be impressed onto nearby telecommunication plant (both entering the substation, and located near the substation),
(iii) if these induced or EPR hazard voltages require mitigation,
(iv) what mitigation options there are, and
(v) the cost of these mitigation options.

Any increased hazard to nearby telecommunication plant (and the cost of mitigating this hazard) must be taken into account in the decision on whether to bond the HV cable sheath.

4.2 Impact on Power Network

The impact of any **new** or **increased** fault currents, earth return currents and cable sheath return currents, needs to be evaluated with respect to the current ratings of power network plant.

The impact of any **increases** in the maximum EPR on any substation earth mat (i.e. EPR_1, EPR_4 and possibly EPR_2 and/or EPR_3) needs to be evaluated with respect to the consequential touch and step voltages on the earth mats.

5.0 Advantages and Disadvantages of Cable Sheath Bonding

The following sections 5.1 to 5.4 describe the typical consequences of cable sheath bonding for a range of situations. The simplified calculation procedure in section 6.1 illustrates with calculated examples many of the points raised in this section.

5.1 Advantages of Cable Sheath Bonding

(1) Cable sheath bonding provides a metallic return path for a significant portion of a phase-to-earth fault current at the downstream substation and, consequently the portion of the fault current that returns through the earth (the earth return current) over the HV cable section, will usually be substantially reduced. This will result in a corresponding substantial reduction in the voltages induced on any parallel telecommunication cables.

- in urban areas, with low “effective” zone substation earth mat impedances, the resultant earth return fault current without cable sheath bonding is usually very high (with corresponding very high levels of hazardous induced voltage on any parallel telecommunication cables).
- in urban areas, the telecommunication cables are often high pair count cables, so any mitigation adopted in the telecommunication network is likely to be very expensive.

(2) The maximum EPRs at the upstream (POD) Substation and the downstream (Zone) Substation are often reduced.

- this can result in a significant reduction in the costs of mitigating the associated EPR hazard to nearby telecommunication plant, especially if the upstream POD Substation is located in an urban area - large numbers of customers premises might otherwise be within the “unbonded cable sheath” EPR hazard voltage contour (i.e. require mitigation).
- lower maximum EPRs will result in lower step and touch potentials on the upstream (POD) and downstream (Zone) Substation earth mats.
- where cable sheath bonding is being considered for a new substation at the design stage, lower earth return fault current may enable a lower cost earth mat to be installed (e.g. Appendix A).

5.2 Disadvantages of Cable Sheath Bonding

(1) The maximum **earth return** fault current over the bonded cable sheath section could actually increase if any of the new “transferred EPR” fault currents in the cable sheath (for faults to upstream or downstream earth mats) is greater than the original “unbonded” **earth return** fault current over that section. Corresponding voltages induced on any parallel telecommunication cables could similarly increase.

(2) The maximum EPRs at the upstream (POD) Substation or the downstream (Zone) Substation could actually increase, if any of the new "transferred EPR's" via the cable sheath (for faults to upstream or downstream earth mats) is greater than the original "unbonded" EPRs. This would result in:
- increased step and touch voltages
- increased EPR hazard to nearby telecommunication plant
- increased power plant insulation levels.

(3) The maximum EPRs at the next upstream and/or the next downstream substations may increase. This would result in:
- increased step and touch voltages
- increased EPR hazard to nearby telecommunication plant

Normally, any increase in EPR would only be minor, and would probably require no further mitigation.

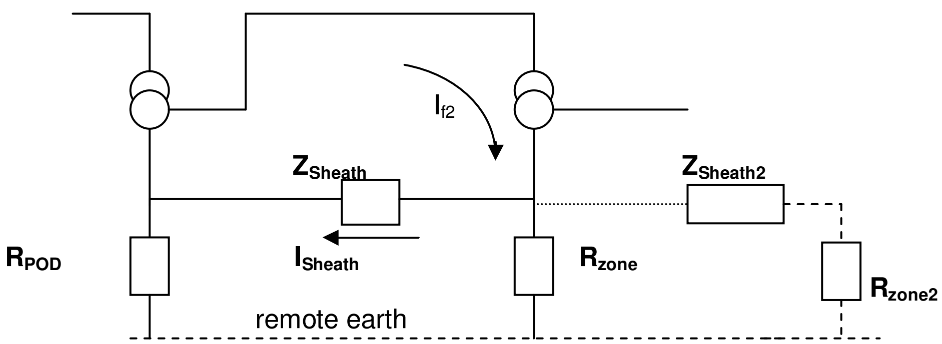
(4) The sheath of the HV cable, or an associated earth connection, may not be rated for the maximum fault current that could pass through it.

5.3 Typical Consequences Of Cable Sheath Bonding

The consequences of cable sheath bonding depend primarily on the fault path impedances, of which earth mat resistances form part, and on the single phase to earth fault currents flowing through the earth mats of concern. Because the major source of fault duty is the national grid, it is possible to summarize typical cable-sheath bonding consequences in terms of interconnecting POD and zone substation earth mats, zone and distribution substation earth mats, or POD and zone and distribution substation earth mats, as follows:

5.3.1 POD and zone substation earth mats

A very simple method of assessing the consequences of bonding is to consider the impedances of the interconnected networks and the cable sheath as a simple voltage divider network as shown below:



The current flowing via the cable sheath will be

$$I_{sheath} = \frac{R_{POD} + R_{zone}}{R_{POD} + R_{zone} + Z_{sheath}} \times I_f$$

If Z_{sheath} is small in relation to $R_{POD} + R_{zone}$, then I_{sheath} will be a large proportion of I_{f2}.

The transferred EPR will be determined by the voltage divider effect of the cable sheath impedance in series with the connected earth mat impedance, that forms a parallel path across the source EPR earth mat.

i.e. $$TEPR_{POD} = \frac{R_{POD}}{R_{POD} + Z_{sheath}} \times EPR_{zone}$$

and $$TEPR_{zone2} = \frac{R_{zone2}}{R_{zone2} + Z_{sheath2}} \times EPR_{zone}$$

Also $$TEPR_{zone} = \frac{R_{zone}}{R_{zone} + Z_{sheath}} \times EPR_{POD}$$ for a fault at the POD substation

EPR_{zone} is reduced below that of the unbonded case because the parallel resistance of the interconnected earth mats (and MEN system if also connected via bonded cable sheaths) more than offsets the increased fault current.

Note: The smaller the cable sheath impedance is in relation to the zone substation earth mat resistance, the closer the $TEPR_{zone}$ will be to the POD earth mat EPR. Therefore a zone substation in a rural location fed by cables with sheaths bonded to earth at both ends with an earth mat resistance in the order of 5 to 6 ohms, and with a cable sheath impedance in the order of 1 ohm, can be expected to experience TEPR values very close to the POD substation EPR. In detailed calculations, cable sheath zero sequence self impedance and mutual impedance will be taken into account. For first approximations, mutual impedances can be ignored as consequently calculated currents will be conservative values (i.e. on the high side).

5.3.2 Zone substation and distribution substation earth mats

Normal practice is to bond these substations together as the overall benefits are normally considered by Distribution Companies to exceed any disadvantages. If it is desired to make a quick assessment of TEPR arising from fault currents passing through each earth mat, the method set out in 5.3.1 can provide a good first approximation.

5.3.3 POD and zone and distribution substation earth mats

Where cable sheath bonding progressively interconnects POD and zone substation earth mats and then zone and distribution substation earth mats, the consequences as set out in 5.3.1 and 5.3.2 apply, but because of the increased number of earth mats involved the benefits of reduced EPR increase. This is illustrated in the worked example that is included in the assessment procedure in Section 6.1.

Progressively bonding from POD to zone to distribution substations may prevent high TEPR values being impressed on distribution substations from zone substations with high earth mat resistance values.

5.4 An Example of Cable Sheath Bonding Showing Clear Advantages

The national grid 220/11kV substation at Tangiwai supplies power to a paper-pulp mill sited only a few hundred metres away.

Without any interconnection between the two earth mats, the separate EPR values were –

Tangiwai substation	-	approximately 2.8kV
Pulp mill	-	approximately 7.0kV

With the two earth mats interconnected, both station EPR values and TEPR values reduced to approximately 1.4kV.

The close proximity between the two sites resulted in negligible impedance in the interconnection between the two, and in nearly equal EPR and TEPR values. While this is a special case, it confirms the benefits/expected results set out in Section 5.3 above.

6.0 Calculation of EPR and TEPR for Earth Mats Connected Together Via Bonded Cable Sheaths

Section 6.1 sets out a simplified calculation process for determining those cases where bonding can be adopted without the need for detailed study. Sections 6.2 and 6.3 provide some guidance on techniques available for determining EPR and TEPR values for proposed installations where detailed study is necessary.

6.1 Calculation Process for Cable Sheath Bonding

The following process has been developed to either:

(a) confirm that bonding is appropriate in those cases where the benefits clearly favour such action.

or

(b) identify those exceptional cases where detailed study is necessary to evaluate the possible disadvantages of bonding so that appropriate action can be determined.

The key steps in the calculation process are:

1. Assemble all relevant data or, if not readily available, choose values considered typical of similar installations and locations.

2. Develop a single line circuit diagram to represent fault current sources, likely fault current paths and all relevant impedances and earth mat resistances (either actual or assumed values).

3. Consider prospective fault current locations and estimate EPR and TEPR values for each earth mat for the highest fault currents likely to pass through the relevant earth mats.

4. Compare estimated EPR and earth return fault current values for each earth mat without cable sheaths bonded, against the estimated EPR, TEPR and earth return fault current values with cable sheaths bonded.

5. Use the results of the comparisons to determine one of the following:

   i) cable sheaths can be bonded at both ends without further study where it is apparent that both telecommunication plant interference limits and acceptable step and touch potentials will not be exceeded

   ii) cable sheaths cannot be bonded at both ends without further study

iii) more accurate cable sheath impedance values and/or earth mat resistance values are required for re-calculation and possibly more detailed modelling
iv) field measurements are required

The following notes are intended to provide further suggestions and help in working through an assessment:

1) Data Assembly

Assemble the following data for all relevant substations likely to be affected by, or contribute to, the EPR and TEPR values at the substation of concern:

- earth mat resistances to ground
- maximum expected single phase to earth fault currents
- sheath impedance of proposed interconnecting power cable
- ratings, leakage impedances (%), and voltage ratios of zone and distribution transformers.

Where data are not readily available, the following approximations may be useful:

Point of Delivery earth mat resistances are normally 0.5 ohm or less, and typically lie between 0.15 and 0.3 ohm for earth mats on very large sites.

Zone substation earth mats at high soil resistivity locations, such as on the shingle plains of Canterbury, may be as high as 6.0 ohms. (Average for the thirteen central Canterbury rural zone substation earth mats was 2.17 ohms).

Urban zone substations, without interconnections to the earth mats of other substations, usually cover smaller site areas than POD substations and are therefore likely to have earth mat resistances in the order of 0.5 ohms to 1.5 ohms. (Five urban zone substation earth mats in Christchurch range from 0.23 ohm to 0.70 ohm, averaging 0.53 ohm. Four urban zone substation earth mats in the Gisborne area range from 0.60 ohm to 1.5 ohm, averaging 1.23 ohm). Where interconnections to other substation earth mats exist, the earth mat resistances are likely to be in the order of 0.3 to 0.5 ohm. In rural locations, cable feeders are less likely to be used and therefore interconnections to other substation earth mats in such locations are less likely.

Distribution substations connected to an extensive 400V MEN system are likely to have earth mat resistances in the range 0.1 to 0.3 ohm, but rarely below 0.2 ohm.

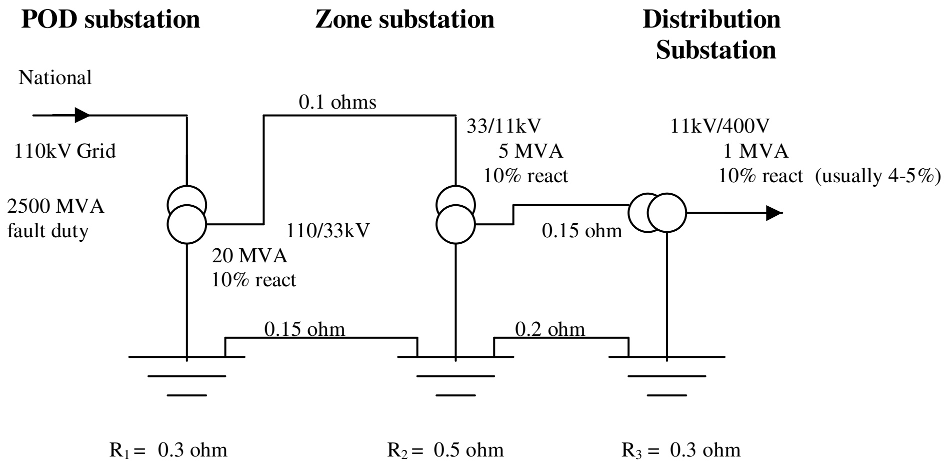
2) Circuit Diagrams

The circuit shown below is used to illustrate the calculation process. A diagram is a very useful aid, as all the relevant data can be shown, ensuring that all appropriate values have been included.

The purpose of the calculations that follow in (3) is to assess the consequences of using cable sheath bonding between the POD and zone substation earth mats.

The fault current (or fault duty) for a single phase-to-earth (66kV, 110 or 220kV bus) fault at the relevant POD substation should be obtained from consultation between the distribution network owner and the grid operator (i.e. Transpower). If the fault current value is not available, it can be calculated from the fault duty.

Common practice within distribution companies is to interconnect zone and distribution earth mats by cable sheath bonding, except perhaps in rural networks. This bonding arrangement is included in the circuit diagram. Only one distribution substation is shown, but in most situations a number would be supplied from one zone substation; with this arrangement the effective earth mat resistance for single phase faults onto the zone - distribution earth would be in the order of 0.2 ohm rather than the 0.25 ohm used below for the case of a single bonded distribution substation.



<u>Preliminary diagram showing known and estimated data</u>

3) Calculations

A relatively straightforward method of calculation is the 'per unit' method in which the positive, negative and zero sequence impedance components are converted to per unit (p.u.) values on a common base, and the calculations are performed accordingly.

To begin, it is necessary to determine impedances in p.u. (per unit) values relative to a chosen reference base (in this case a reference base of 100 MVA is used):

i) source impedance (of the 110kV grid) on a 100 MVA base

= Z_{IG} (positive sequence impedance, which is assumed to be equal to the negative sequence impedance Z_{2G})

$$= \frac{100\,(\text{base MVA})}{2500\,(\text{fault duty MVA})}$$

= 0.04 p.u.

ii) impedance of POD substation on a 100 MVA base

= $Z_{IP} = Z_{2P}$

$$= \frac{100\,(\text{base MVA})}{20\,(\text{transformer rating MVA})} \times 0.1\,(\text{transformer reactance of } 10\%)$$

= 0.5 p.u.

iii) impedance of Zone substation on a 100 MVA base

= $Z_{IZ} = Z_{2Z}$

$$= \frac{100}{5} \times 0.1$$

= 2 p.u.

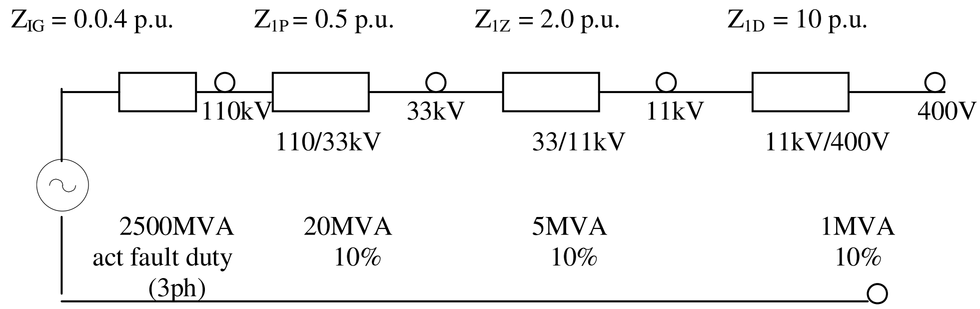
iv) impedance of Distribution substation on a 100 MVA base

= $Z_{ID} = Z_{2D}$

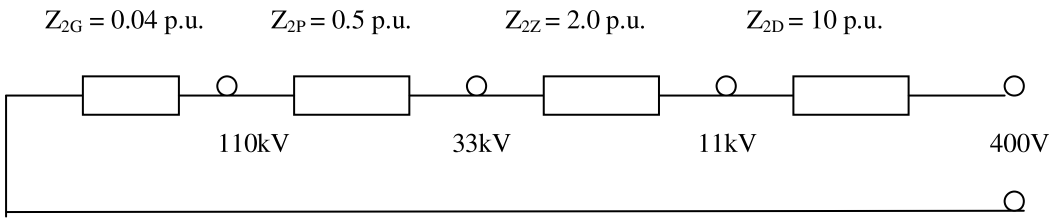
$$= \frac{100}{1} \times 0.1$$

= 10 p.u.

The circuit diagram above can now be re-drawn as equivalent positive and negative sequence diagrams. These are shown below:



Positive sequence impedance diagram



Negative sequence impedance diagram

It is also necessary to determine base impedance in ohms at each voltage level as follows:

i) Z_{base} @ 110kV $= \dfrac{V^2}{MVA_{base}} = \dfrac{(110\times10^3)^2}{100\times10^6}$

$= 121$ ohm

ii) Z_{base} @ 33kV $= 10.89$ ohm

iii) Z_{base} @ 11kV $= 1.21$ ohm

iii) Z_{base} @ 400V $= 0.0016$ohm

and to determine current p.u. values at 100MVA base for each voltage level as follows:

i) I_{base} @ 110kV $= \dfrac{100MVA}{\sqrt{3}\times110kV} = 525A$

ii) I_{base} @ 33kV $= \dfrac{100MVA}{\sqrt{3}\times33kV} = 1750A$

iii) I_{base} @ 11kV = $\frac{100MVA}{\sqrt{3}\times 11kV}$ = 5250A

It is now possible to determine zero sequence impedances for single phase faults on the primary side of each substation as follows:

i) for the grid $Z_{OG} = Z_{IG} + \frac{3\times Z_{neutral}}{Z_{base}\ @110kV}$

where $Z_{neutral}$ = neutral impedance of the source

Therefore $Z_{OG} = 0.04 + \frac{3\times 0.5}{121}$

= 0.052 p.u.

ii) for the POD substation $Z_{OP} = 0.5 + \frac{3\times 0.3}{10.89}$

= 0.583 p.u.

iii) for the Zone substation $Z_{oz} = 2.0 + \frac{3\times 0.25}{1.21}$

= 2.62 p.u.

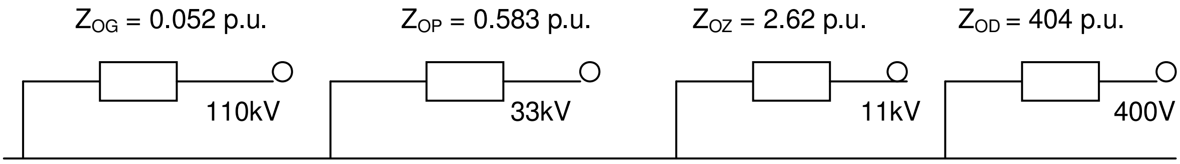
where 0.25 ohms is the effective earth mat impedance of the zone substation earth mat in parallel with the cable sheath impedance in series with the distribution substation earth mat (0.5Ω in parallel with (0.2Ω + 0.3Ω)).

iv) for the Distribution substation $Z_{OD} = 10 + \frac{3\times 0.21}{0.0016}$

= 404 p.u.

where 0.21 ohms is the effective earth mat impedance of the distribution substation earth mat in parallel with the cable sheath impedance in series with the zone substation earth mat (0.3Ω in parallel with (0.2Ω + 0.5Ω)).

The equivalent zero sequence impedance diagram can now be drawn as follows:



Zero sequence impedance diagram

Calculation of fault currents and corresponding EPR values

In order to determine all the relevant EPR and TEPR values with and without cable sheath bonding between the POD and zone substations, a total of 5 separate fault current cases are considered below:

Case 1: The fault current from the 110kV grid into the POD substation earth mat, without cable sheath bonding to the zone substation earth mat, is determined as follows:

The zero sequence impedance of the fault

$$Z_{of} = Z_{OG} + \frac{3Z_f}{Z_{base} @ 110kV}$$

$$= 0.052 + \frac{3 \times 0.3}{121}$$

$$= 0.059 \text{ p.u.}$$

where Z_f = POD substation earth mat impedance

The fault current

$$I_f = \frac{3}{Z_{1G} + Z_{2G} + Z_{of}} \times I_{base} @ 110kV$$

$$= \frac{3}{0.04 + 0.04 + 0.059} \times 525A$$

$$= 11{,}330\text{A}$$

The POD substation EPR for this fault current

$$= 0.3\Omega \times 11{,}330\text{A}$$

$$= 3{,}399\text{V}$$

There is no TEPR at the zone/distribution substation earth mat.

Case 2: The 33kV fault current at the output of the POD 110/33kV transformer, which will circulate within the earth mat, and cannot cause EPR or TEPR, is

$$I_f = \frac{3}{(Z_{1G} + Z_{1P}) + (Z_{2G} + Z_{2P}) + Z_{OP}} \times I_{base} \ @\ 33kV$$

$$= \frac{3}{(0.04 + 0.5) + (0.04 + 0.5) + 0.5} \times 1750A$$

$$= 3{,}323A$$

(Note Z_{OP} at the transformer terminals excludes the neutral impedance and therefore equals 0.5 ohms)

Case 3: The 33kV fault current at the input to the zone substation, without cable sheath bonding between POD and zone substation earth mats, is as follows:

$$Z_{of} = Z_{OP} + \frac{3Z_f}{Z_{base} \ @\ 33kV}$$

where Z_f is the circuit impedance between the POD and zone substations of 0.1 ohm plus the effective resistance of the zone substation earth mat of 0.5 ohm in parallel with the cable sheath bonding impedance of 0.2 ohm in series with the distribution substation earth mat of 0.3 ohm, and which therefore gives Z_f = 0.1 + 0.25 = 0.35 ohm. Z_{OP} is the value at the terminals of the transformer, and excludes the zone substation earth mat to avoid including it twice.

$$Z_{of} = 0.5 + \frac{3 \times 0.35}{10.89}$$

$$= 0.596 \text{ p.u.}$$

$$I_f = \frac{3}{(Z_{1G} + Z_{1P}) + (Z_{2G} + Z_{2P}) + Z_{of}} \times I_{base} \ @\ 33kV$$

$$= \frac{3}{(0.04 + 0.5) + (0.04 + 0.5) + 0.596} \times 1750A$$

$$= 3{,}132A$$

The EPR at the POD substation will be

= 0.3Ω x 3132A

= 940V

and at the zone substation

= 0.25Ω x 3,132A

= 783V

From the voltage divider network established by the interconnected zone and distribution substation earth mat it is apparent that the EPR in the distribution substation will be

$$= \frac{0.3}{0.2 + 0.3} \times 783V$$

= 470V

Case 4: The 110kV fault current from the grid into the POD substation earth mat, with cable sheath bonding between the POD and zone substation earth mats, is considered as follows:

The zero sequence impedance of the fault

$$Z_{of} = Z_{OG} + \frac{3Z_f}{Z_{base} @ 110kV}$$

Z_f has now reduced to 0.17 ohms, which is the cable sheath impedance of 0.15 ohm in series with the zone/distribution substation earth mat of 0.25 ohms, all in parallel with the POD substation earth mat impedance of 0.3 ohms.

$$Z_{of} = 0.052 + \frac{3 \times 0.17}{121}$$

= 0.056 p.u.

$$I_f = \frac{3}{Z_{1G} + Z_{2G} + Z_{of}} \times I_{base} @ 110kV$$

$$= \frac{3}{0.04 + 0.04 + 0.056} \times 525A$$

= 11,582A

The POD substation EPR for this current

$$= 0.17\Omega \times 11,582A$$

$$= 1,969V$$

and the TEPR at the zone substation

$$= \frac{0.25}{0.15+0.25} \times 1969V$$

$$= 1,231V$$

and the TEPR at the distribution substation

$$= \frac{0.3}{0.3+0.2} \times 1231V$$

$$= 738V$$

If 0.2 ohms is used for the effective earth mat resistance of the zone/multiple distribution substation earth mats combined, then very little change occurs to Z_{0f} and hence to I_f, but there is a small reduction in the POD substation EPR because the effective earth mat resistance is now 0.16 ohms, lowering the EPR slightly to = 1,848V.

However, the TEPR at the zone substation reduces more as it becomes only

$$= \frac{0.2}{0.15+0.2} \times 1848V$$

$$= 1,056V$$

and the TEPR at the distribution substation in turn reduces to

$$= \frac{0.3}{0.5} \times 1056V$$

$$= 637V$$

Case 5: The 33kV fault current at the input to the zone substation, with cable sheath bonding between POD and zone substation earth mats, is as follows:

$$Z_{of} = Z_{OP} + \frac{3Z_f}{Z_{base} @ 33kV}$$

$$= \quad 0.5 + \frac{3 \times 0.22}{10.89}$$

$$= \quad 0.561 \text{ p.u.}$$

$$I_f \quad = \quad \frac{3}{(Z_{1G} + Z_{1P}) + (Z_{2G} + Z_{2P}) + Z_{of}} \times I_{base} \ @\ 33kV$$

$$= \quad \frac{3}{(0.04 + 0.5) + (0.04 + 0.5) + 0.561} \times 1750A$$

$$= \quad 3{,}199\text{A}$$

The return path impedance of 0.22 ohm comprises the circuit impedance of 0.1 ohm in series with the cable sheath impedance of 0.15 ohm, which is in parallel with the zone/distribution earth mat impedance of 0.25 ohm in series with the POD substation earth mat impedance of 0.3 ohm.

This fault current will divide between the parallel cable sheath and the earth mat paths in the inverse ratio of the path impedances. The cable sheath current will be

$$= \quad \frac{0.25 + 0.3}{0.25 + 0.3 + 0.15} \times 3199A$$

$$= \quad 2{,}514\text{A}$$

and via the earth mats

$$= \quad \frac{0.15}{0.25 + 0.3 + 0.15} \times 3199A$$

$$= \quad 686\text{A}$$

This 686A will be divided equally between the zone and distribution earth mats, and consequently the individual earth mat currents will be

I_{POD} = 686A

I_{zone} = 343A

I_{dist} = 343A

The corresponding EPRs are

E_{POD} = 0.3Ω x 686A

$= 206V$

$E_{zone} = 0.5\Omega \times 343A$

$= 172V$

$E_{dist} = 0.3\Omega \times 343A$

$= 103V$

4) Insert the relevant calculated values in the circuit diagrams as follows to help assess the results.

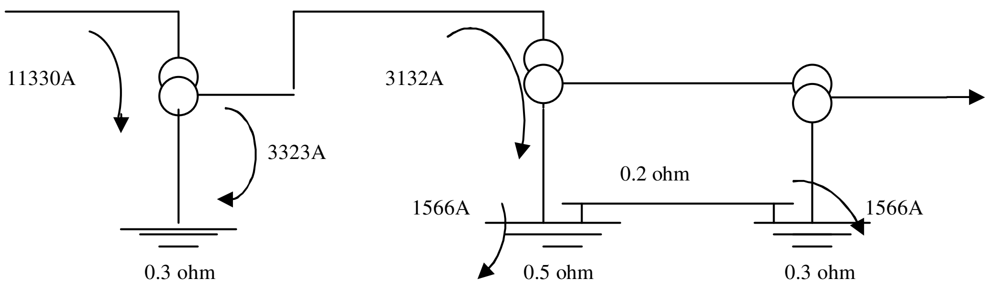
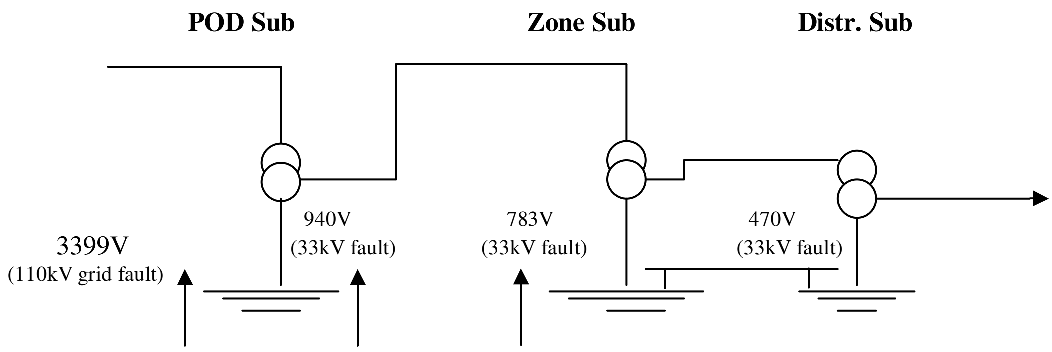
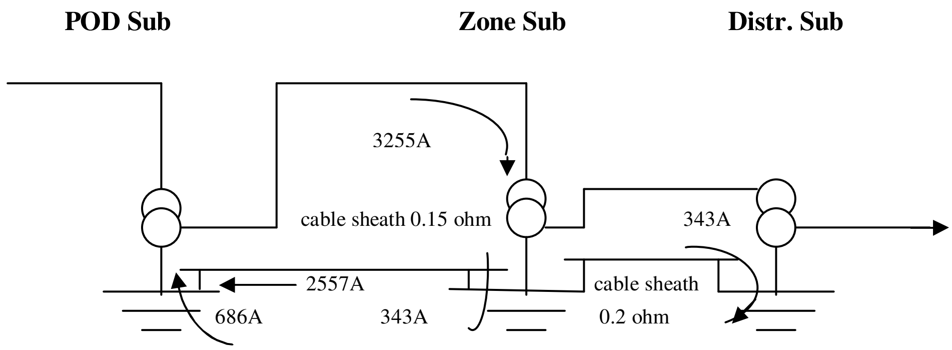


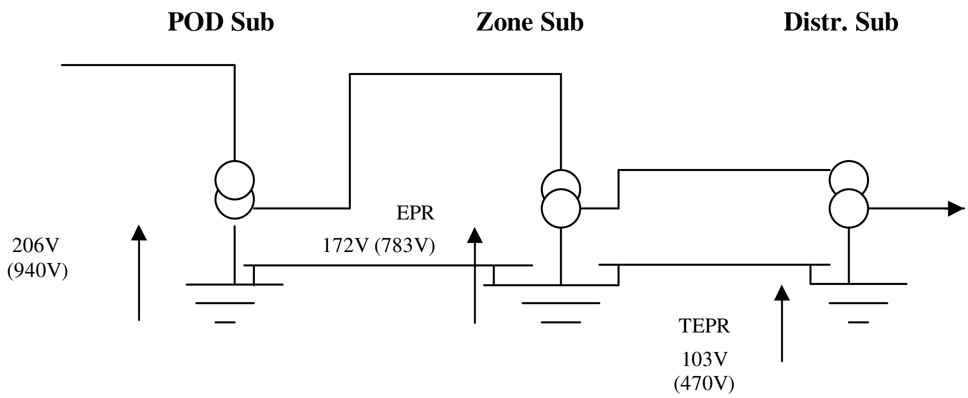
Diagram showing fault currents and earth mat resistances with no cable sheath bonding between POD and zone substations



Max EPR values before cable sheath added between POD and zone substations



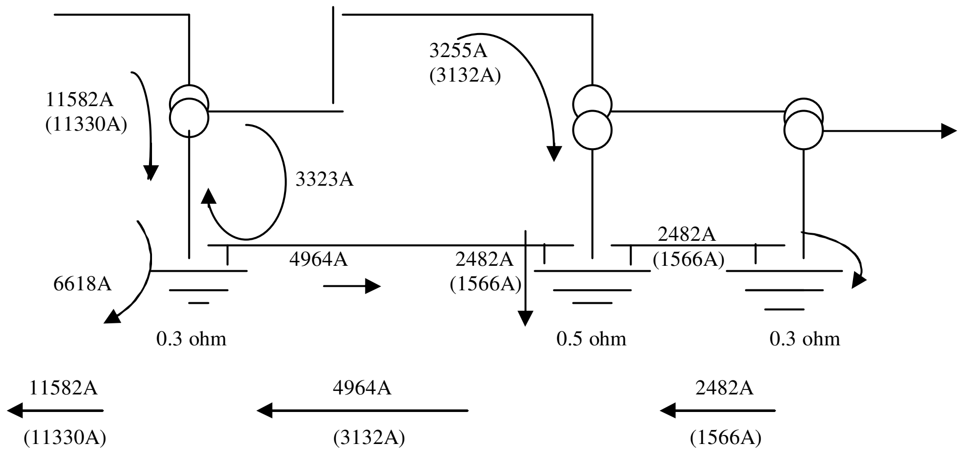
33kV Fault: Fault currents re-calculated with cable sheath bonding included



33kV Fault: New EPR & TEPR values vs original EPR values

Note:

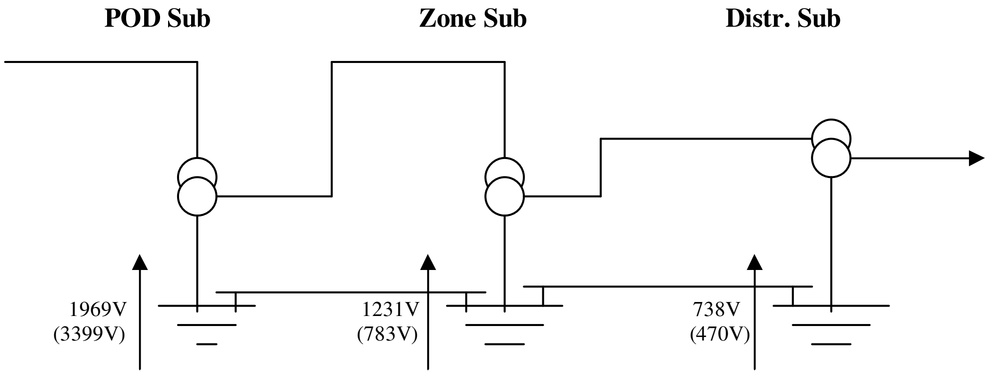
1. Values in brackets are the original EPR and TEPR values.



Maximum fault current values AFTER cable sheath bond is added between POD and Zone substations

Notes:

1. Values in brackets are the maximum fault currents without any cable sheath bond added.
2. The value of maximum **earth return** current between the POD substation and the Zone substation (4,964A) assumes that ALL of the Distribution substation-to-POD substation earth return current flows via the Distribution substation - Zone substation - POD substation route (i.e. it follows the line/cable route). This may be a somewhat conservative assumption.



Maximum EPR values AFTER cable sheath bond is added between Zone and Distribution substations

Note:

1. Values in brackets are the maximum EPRs without any cable sheath bond.

All the above EPRs and currents are higher (possibly much higher) than they will be in reality, since they have been calculated assuming low impedance line and cable circuits between the substations, and the total neglect of the mutual impedance between cable conductors and the sheath which pushes more current through the sheath and less through the earth mat.

5) Consider action

The impacts of the above changes in EPRs and currents on the power network and any nearby telecommunication network plant must be considered as described in 5.1 and 5.2.

1. **Power plant ratings**
   So long as the proposed cable sheath is rated for a short term 7.5kA current, the above increases in currents are unlikely to have any impact.

2. **Substation earth mat touch and step voltages**

   The possible impact of the slight increase in EPR at the Zone substation (from 783V to 1,231V) and the substantial increase in EPR at the Distribution substation (from 470V to 738V), on touch and step voltages at these substations, needs to be considered.

3. **Nearby Telecommunication Plant**

   The increased **earth return** currents between the POD substation and the Zone substation (3,132A increases to 4,964A) and between the Zone substation and the Distribution substation (1,566A increases to 2,482A), will cause a corresponding increase in voltages induced along parallel telecommunication cables. The increased EPRs at the Zone substation (783V increases to 1,231V) and the Distribution substation (470V increases to 738V) may also put nearby telecommunication plant at risk.

   Details of the increased **earth return** currents, the power line/cable routes and the increased EPR's, should be sent to any TNOs with plant in the area, so that the level of induction and EPR hazard to their network can be evaluated.

   These levels of earth return currents and EPRs are likely to cause EPR and induction hazard to nearby telecommunication plant.

If consideration of the above calculated currents and EPRs shows up any significant problems, then more detailed calculations of the current(s) and EPR(s) of concern will normally need to be done. These will include actual line and cable impedances, including mutual impedance between cable conductors and sheath, and actual earth mat resistances.

Field measurements may need to be done to check these calculated parameter values.

6.1.1 Additional Issues

Cable sheath bonding is usually considered as a possible means of

(1) reducing high substation EPR(s), or
(2) reducing induced voltages along parallel telecommunication cables.

Normally cable sheath bonding assists with both these problems. However, in some cases, the end result is worse than the original problem. In these cases, alternative solutions such as neutral earthing resistors/reactors (NERs) should be considered. These can be implemented with or without cable sheath bonding (refer to Section 9.0).

6.2 Computer Modelling

Computer programs are increasingly used in the design of earthing systems and are also very suitable for re-design studies when modifications, such as interconnecting earthing systems via cable sheaths, are proposed.

Power systems analysis programs such as PSS/U (available from the N.Z. agents Worley Consultants Ltd, New Zealand) can be used for fault current analysis to determine the division of current between the individual earth mats forming the earthing system under study.

PSS/U is a set of general purpose programs for power system simulation. It has the ability to calculate fault currents at any point in the power network. The independent phase analysis of PSS/U allows mutual coupling between branches to be included to enable all network voltages to be calculated with respect to remote earth. PSS/U requires accurate cable impedance information which can be calculated using the Alternate Transients Programme (ATP), or manually using established methodologies. The ATP programme can be used to calculate series self impedance and shunt capacitance/admittance of cables of any chosen configuration. A worked example using PSS/U can be found in Appendix B4.5 of the NZCCPTS "Application Guide for Earth Potential Rise".

The results of PSS/U can then be used in earthing system design programs to calculate the earth mat EPR and TEPR contours.

Established programs with the capability to include cable sheath bonding arrangements between earth mat systems include –

SAFEARTH (Safearth Systems, Energy Australia, Australia)
C-DEGS (Safe Engineering Services and Technologies, Canada)

6.3 Companion Document for Application Guide

The symmetrical components method of analysis is a very suitable mathematical tool for the analysis of networks under fault (unbalanced) conditions. The unbalanced network parameters are converted into three separate, but balanced and symmetrical components, that are known as positive, negative and zero sequence components.

The technical paper 'Fundamentals of Calculation of Earth Potential Rise in the Underground Power Distribution Network' by Ashok Parsotam provides detailed guidance for calculating fault currents in a distribution network and is issued as a companion document to this Cable Sheath Bonding Guide. This companion document covers calculation of sequence impedances to model overhead lines and underground cables, and calculation of EPR and TEPR in the cable network. In addition, several fault scenarios are modelled, together with numerical examples outlining all the steps required to calculate EPR and TEPR.

7.0 Typical Network Configurations Involving Insulated Cables

Cables are used in a variety of circuit configurations. The five mostly commonly encountered in New Zealand are:-

(a) a continuous length of cable laid between the source substation and a receiving substation. The cable sheath is usually bonded to earth at both substation earth mats.
(b) a length of cable laid from the source substation to a pole outside the substation earth mat, and terminating on the pole where conductors are connected to an overhead line. The cable sheath is usually bonded to earth at the source substation and at the pole.
(c) a length of cable commencing on an overhead line pole and terminating at a receiving substation. The cable sheath is usually bonded to earth at both the pole and the substation.
(d) a combination of both (b) and (c) on the same circuit.
(e) a length of cable from one pole to another pole within an overhead line between two substations.

In cases involving short lengths of cable where one end terminates on an overhead line pole near a substation, and the pole is located in a high resistivity area (making a low resistance to earth difficult to achieve) it may be economically attractive and beneficial to EPR and TEPR control to use a high conductivity earth continuity conductor from the pole to the nearby substation earth mat.

If the cable sheath is not adequate for the fault current likely to pass between the pothead and the originating substation, then either a buried conductor should be installed back to the earth mat, or alternatively, the cable should be end point bonded at the pothead for the line terminating structure. This will ensure that any exposed metal associated with the cable pothead remains at earth potential while any live line work is in progress on the overhead line. However, because such a situation will require all the fault current to return via the general mass of earth, it will cause higher EPR and the cable insulation will need to be sufficient for this. Also, the higher EPR contours in the vicinity of the pothead earthing system could pose a hazard to nearby telecommunications network plant.

Note: Where a high conductivity earth conductor is used between a line termination and the nearby substation earth mat, it should be recognized that while a bare conductor will reduce the substation earth mat resistance, it will also distort and extend the EPR contours away from the earth mat. If a lightly insulated conductor is used, insulation puncture may occur.

8.0 Summary

Designers should plan for bonding cable sheaths to earth at both ends of each cable installation unless analysis shows bonding would result in an unsatisfactory value of calculated (or modelled) TEPR or the export of substation EPR to situations where it may cause a local hazard.

Economic alternatives, such as using cables with standard rated screens and the direct interconnection of earth mats via separate conductors, should always be a secondary or subsequent consideration.

The overall preference of the designer should always be to improve the effectiveness of the total interconnected earthing system.

9.0 References

1. "Substation Earthing Guide" Electricity Supply Association of Australia Ltd. 1995

2. "Symmetrical Components as applied to the analysis of unbalanced electrical circuits", Wagner C.F. and Evans R.D

3. "Fundamentals of Calculation of Earth Potential Rise in the Underground Power Distribution Cable Network" by Ashok Parsotam (Power and Telecommunications System Co-ordination Conference, Melbourne 1997)

4. "Electric Cables Handbook", E.W.G. Bungay and D. McAllister (BICC)

5. NZCCPTS "Application Guide for Earth Potential Rise"

6. NZCCPTS "Application Guide for Neutral Earthing Resistors/Reactors"

7. NZCCPTS "Application Guide for Single Wire Earth-Return High Voltage Power Lines"

8. NZCCPTS "Guide for Investigating Power System - Telecommunication System Noise Interference"

Copies of any of the NZCCPTS documents (see references 5 to 8) can be obtained from the Secretary, NZCCPTS (see the inside back cover for contact details).

APPENDIX A

KAIWHARAWHARA EARTHING SYSTEM – A RECENT CASE

In 1997, Transpower commissioned a 110/11kV substation in an industrial area at Kaiwharawhara, Wellington, to supply power via 11kV cable feeders to Capital Power's distribution network.

Because of the constrained site at Kaiwharawhara, considerable expenditure was foreseen in achieving an acceptable earth mat resistance to control EPR and step and touch potentials.

Without connection via cable sheaths to Capital Power's zone substation, an initial earth mat design resistance to ground of 0.6 ohm was calculated which would have resulted in unacceptable EPR and step and touch potentials unless long earth rods were added at considerable expense to keep the earth mat potentials within EPR and step and touch potential limit values. Bonding the 11kV cable sheaths at both ends reduced the effective earth mat resistance to 0.17 ohms. This enabled less copper to be used, as well as obviating the need for long earth rods. The 430V EPR contour was also kept close to the site as a result of cable sheath bonding.

110kV cables were installed for 500m from the Kaiwharawhara Substation along the nearby road to a suitable location where access to overhead 110kV transmission was possible. The 110kV XLPE copper sheath cables were end-point bonded to earth at the station end, and a small earth mat at the 110kV cable to line junction was bonded to the Kaiwharawhara Substation earth mat via two 240mm² copper conductors laid in parallel.

In this case, the use of separate copper conductors was chosen for economic reasons. 110kV cables with adequately fault rated cable sheaths would have resulted in a higher cost installation. The solution adopted achieved the benefits determined for cable sheath bonding at both ends, by an alternate approach.

Because the 11kV zone substation was only a very short distance from the POD substation and two high capacity feeder circuits with very low impedance cable sheaths interconnected the two earth mats, the resulting EPR and TEPR values (similar for both earth mats) were within the hazard limit values.

APPENDIX B

WORKED EXAMPLE

Consider the case of the following two substations, located in a city and connected together via 33kV cable(s). A decision needs to be made on whether to bond the two substation earth mats together via the 33kV cable sheath(s).

(1) a Transpower substation, with incoming 220kV and 110kV lines (from Generating Stations about 100km away), and outgoing 33kV cables and lines

(2) a Power Distribution Company zone substation, with incoming 33kV cables and outgoing 11kV cables and lines.

The EPR's at all voltage levels, for both the bonded and unbonded cases, need to be calculated. Some values for one case follow (1.3Ω Transpower Substation earth mat resistance, two 500m 33kV cables (300mm^2 Al PILCA) in parallel, 0.2Ω Distribution Company Zone Substation earth mat resistance).

Type of Earth Fault	EPR's Without Bonding		EPR's With Bonding	
	Transpower	Dist. Co.	Transpower	Dist. Co.
220kV phase-to-earth fault at Transpower Substation	8.9kV	-	1.9kV	1.1kV
110kV phase-to-earth fault at Transpower Substation	11.0kV	-	2.4kV	1.4kV
33kV phase-to-earth fault at Distribution Co. Substation	12.5kV	1.9kV	1.9kV	287V
11kV phase-to-earth fault at downstream distribution transformer	-	287V	230V	270V

Bonding decreases the "worst case" EPR's on both earth mats. However if the Distribution Company substation is extensively bonded to the urban LV MEN system (via the 11kV cable sheathes), the resultant "reduced" EPR may still represent a major hazard to the telecommunications network that is very costly to mitigate. It may instead prove more economic to:

(i) leave the 33kV cable sheathes unbonded,

(ii) install NER's at the 33kV point of supply (in the Transpower Substation) to reduce the EPR on the Distribution Company Substation earth mat below the 650V hazard voltage limit (this will also reduce the EPR on the Transpower Substation for a 33kV phase-to-earth fault to less than 4.3kV), and

(iii) mitigate for the new "worst case" EPR level at the Transpower Substation of 11.0kV - if the Transpower Substation is an "isolated" substation (e.g. just outside the city), this may not be a big problem.

APPENDIX C

CONTACT DETAILS FOR TELECOMMUNICATION POWER CO-ORDINATORS
(refer Section 4.1)

1. **Telecom NZ Ltd. (**as at November 2010)

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