AS/NZS 4853:2000

AS/NZS 4853

Australian/New Zealand Standard™

Electrical hazards on metallic pipelines

Standards Australia

STANDARDS NEW ZEALAND
Paerewa Aotearoa

This Joint Australian/New Zealand Standard was prepared by Joint Technical Committee EL/1, Wiring Rules. It was approved on behalf of the Council of Standards Australia on 3 November 2000 and on behalf of the Council of Standards New Zealand on 27 October 2000. It was published on 1 December 2000.

The following interests are represented on Committee EL/1:

The Association of Consulting Engineers Australia
Australian Building Codes Board
Australian Electrical and Electronic Manufacturers Association
Communications, Electrical Plumbing Union
Electrical Contractors Association of New Zealand
Electrical Contractors Association Qld
Electrical Safety Organisation (New Zealand)
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Institution of Engineers Australia
Insurance Council of Australia Limited
Ministry of Commerce New Zealand
National Electrical and Communications Association
New Zealand Council of Elders
New Zealand Electrical Institute
Regulatory authorities (electrical)
Telstra Corporation Limited

Additional interests participating in the preparation of this Standard:

Cathodic Protection Consultants/Installers
Electrical Protection Engineers
Gas Suppliers
Pipe Manufacturers
Pipeline Installers
Pipeline Operators
Railways
Water Authorities

This Standard was issued in draft form for comment as DR 99086.

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First published as AS/NZS 4853:2000.

Jointly published by Standards Australia International Ltd, GPO Box 5420, Sydney, NSW 2001 and Standards New Zealand, Private Bag 2439, Wellington 6020

ISBN 0 7337 3683 1

PREFACE

This Standard was prepared by the Joint Standards Australia/Standards New Zealand Committee EL-001, Wiring Rules.

The objective of this Standard is to provide guidelines on how to limit the electrical hazards which may appear on metallic pipelines, to identify some additional safeguards which may be necessary, and to specify acceptable electrical limits on pipelines.

This Standard also provides a range of informative appendices (which is not intended to be exhaustive) on the following subjects, which have a bearing on the application of the Standard:

(a) Sample methods of calculation of induced and other voltages from high voltage power lines and a.c. electric rail on pipelines.

(b) Methods of controlling or reducing the induced or coupled voltages on pipelines, to achieve the prescribed values.

(c) Precautions available to mitigate hazards due to fault conditions on the high voltage system.

(d) The interaction of cathodic protection systems with protective earthing systems and some suggested means of resolving the resultant problems.

(e) Check lists of data that may be required for calculation of low frequency induction (LFI) from the electricity transmission organization and from the pipeline owner or authority.

(f) Pipeline lightning protection.

(g) A brief bibliography on the technical matters addressed in this Standard.

During preparation of this Standard, reference was made to documentation provided by Brisbane Water and acknowledgment is made of their assistance.

The terms ‘normative’ and ‘informative’ have been used in this Standard to define the application of the appendix to which they apply. A ‘normative’ appendix is an integral part of a Standard, whereas an ‘informative’ appendix is only for information and guidance.

Symbols used in equations in this Standard are defined in relation to the particular equations in which they occur.

CONTENTS

FOREWORD

To utilize land effectively, it is common to use easements for both high voltage power lines and pipelines. This close proximity of high voltage power lines and pipelines can result in voltages being induced onto the pipeline from a number of external influences.

Although overland transmission lines and metallic pipelines have been laid and constructed in the same easements for many years, the continuous growth of energy consumption, with increases in voltages, load currents and fault capacities, has resulted in an increase in the electrical and physical problems. The adoption of modern pipeline insulating coatings has exacerbated these problems.

There is a growing concern about the following aspects:

(a) Safety of people making contact with the pipeline.

(b) Risk of damage to the pipeline coating and metal.

(c) Risk of damage to equipment such as the pipeline cathodic protection (CP) system and telemetry systems.

This Standard considers a number of circumstances which give rise to electrical conditions on pipelines.

(i) Low frequency induction (LFI) due to parallel or near parallel positioning of the pipelines and high voltage power lines or high voltage a.c. traction systems.

(ii) Earth potential rise (EPR) due to pipeline proximity with high voltage power line towers, substation earth mats, and other earthing current discharge points.

(iii) EPR due to lightning current following flash attachment to objects or structures adjacent to the pipelines.

(iv) Capacitive coupling due to the placing, temporarily or permanently, of pipelines sufficiently adjacent to high voltage power lines to intercept a significant proportion of their electric field.

(v) The effects of lightning current introduced to the pipeline, directly or indirectly, and the effects due to the electrical properties of the pipeline and its coating.

(vi) The fortuitous contact of pipelines with other electrical systems such as electricity distribution or traction systems.

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Australian/New Zealand Standard
Electrical hazards on metallic pipelines

1 SCOPE

This Standard specifies voltage limits and corresponding time constraints acceptable on both underground and above-ground pipelines that may be subject to power system influences. Guidance on the mitigation of lightning flash attachments is also provided.

NOTE: The acceptable voltage and time limits are based on the conditions outlined in AS 3859.

This Standard describes the mechanisms which create hazardous electrical conditions on such pipelines and provides guidance on how to calculate and mitigate these hazards.

This Standard does not cover electrical hazards on electricity power plant associated with the construction of pipelines and their coatings. Such hazards are covered by AS/NZS 3000 and its associated Standards.

2 APPLICATION

This Standard is applicable to those pipelines with electrically conducting walls, usually steel, and with an aqueous slurry or hydrocarbon-based product content such as water, oil or gas.

The responsibility for the application of this Standard rests with the owner or operating authority of the pipeline and therefore they should seek competent advice with regards to its content.

It is not intended that this Standard be applied retrospectively to installations existing at the date of publication of this Standard in so far as design, construction, operation, maintenance and testing are concerned. However, this Standard may be used during redesign or upgrading of existing pipelines to achieve conformance.

3 REFERENCED DOCUMENTS

The documents referred to in this Standard are listed in Appendix A.

4 DEFINITIONS

For the purpose of this Standard the definitions listed in Appendix B apply.

5 ACCEPTABLE VOLTAGE LIMITS

5.1 General

This Clause 5 sets out requirements for two categories of acceptable voltage limits for pipelines. Requirements for Category A touch voltage limits are provided in Clause 5.3. Requirements for Category B touch voltage limits are provided in Clause 5.4.

NOTES:

1 The voltage limits are touch voltage limits as defined in this Standard.

2 Pipelines which have touch voltages above those given in Clause 5.4 are outside the scope of this Standard. Some indication of the nature of such voltages is provided in Clause 5.5.

3 Reference in other documents to the acceptable voltage limits given in this Standard may be achieved by the wording 'Category A (or Category B) touch voltage limits in accordance with AS/NZS 4853 (this Standard)' as appropriate.

4 There is a misconception that internationally agreed power and telecommunication induction and earth potential rise (EPR) limits are applicable generally to environmental safety. These limits are as follows:

(a) Voltage withstand for pulse conditions of affected telecommunications equipment is relatively high (≈ 1500 V).

(b) Low risk conditions in telecommunications terminals—clear, dry, insulated floors and very small contact areas.

(c) Very low coincident exposure (based on statistical analysis).

(d) Minute cost to telecom carriers to fit exposed circuits with gas tube protectors, which are often required to protect against lightning surges. Combined with high resistance circuits (50 – 1000 ohm), these offer high protection.

These items are not applicable to pipeline technology.

5.2 Risk assessment

Acceptable Category A maximum touch voltage limits for accessible pipelines are given in Table 5.3. The voltages relate to electrical safety protection from electric shock. However, Category A touch voltage limits may be unnecessarily onerous on pipelines with totally restricted public access (e.g. high pressure gas transmission lines) and a risk assessment should be made to determine whether Category B touch voltage limits (Clause 5.4 and Table 5.4) may be permitted.

NOTE: Guidance on risk management is given in AS/NZS 4360.

Whilst the major point of the risk assessment is to determine the acceptability of Category B touch voltage limits, attention is drawn to the need for a risk assessment also for some aspects of installations with Category A touch voltage limits.

The risk assessment shall be in two parts; one for pipelines accessible by the general public and the other for pipelines only accessible to authorized persons. The risk assessment shall include the following:

(a) Depth of burial of the pipeline.

(b) Protection against loss of pipeline cover.

(c) Electrical isolation of accessible sections of pipelines or other adequate protection.

(d) Protection of cathodic protection (CP) test points by equipotential mats or other appropriate means.

(e) Design and location of any earthing system.

(f) Frequency and duration of power system faults.

(g) The location of the pipeline in relation to power system plant.

(h) The accessibility of the pipeline.

(i) The requirements of the appropriate regulators.

(j) The need for appropriate signs.

(k) Training of authorized personnel.

(l) The need for the use of personal protection equipment such as special footwear or gloves.

In assessing the risks associated with a substantial pipe to soil voltage (e.g. 3000 V), account must be taken of the source and impedances of the origin of this voltage. For example, 3000 V from earth potential rise (EPR) due to a fault to a high voltage power line tower a few metres from a buried pipeline is of little consequence; a pipeline coating in good condition should survive this condition. Minor leakage current from the soil to the pipeline is negligible. However 3000 V from low frequency induction (LFI) on a pipeline is energy imparted to the pipeline, at low impedance, and may travel for many kilometres along the pipeline, unless mitigated by measures described in this Standard. The power level can be hundreds of kilowatts.

Higher voltage short term electrical surges (e.g. 300 V 100 ms) in accordance with Table 5.3 would not normally be electrically hazardous in terms of AS 3859. However they can cause violent muscular reaction which could lead to physical injury (such as falling from a ladder or contact with power tools, etc).

The assumptions, methodology and outcomes of the risk assessment shall be appropriately documented and retained.

The risk assessment shall be revalidated whenever a change to the pipeline or its environment occurs or every five years whichever occurs first. The performance review outlined in Clause 12.4 should also be carried out at this time.

NOTE: Where a section of pipeline is wholly underground, and isolated from all terminals and appurtenances, including CP test points, the voltage limit, under LFI power fault conditions, of this pipe section may rise to any voltage not exceeding the long term voltage withstand of the pipeline coating. This is a Category B—Special condition. The isolation facilities may be adequately rated Monolithic Isolation Joints (M.I.J.) or equivalent. If any appurtenances such as CP test points are connected directly to the section of the pipeline, this would negate the Category B rating in accordance with Clause 5.5, and place the installation outside the scope of this Standard.

5.3 Category A—touch voltage limits for pipelines accessible to the public or unskilled staff

Some pipelines, notably water trunk mains, have many above-ground facilities installed as part of their operational mechanism. These include stop valves, bypass valves, air valves, scour pipes, CP test points and exposed sections across drains or gullies or at changes of direction. Many of these are directly accessible by members of the public, including children.

Direct public access requires the pipeline to have a safety level consistent with the guidance on such safety limits given in AS 3859. The limits are a combination of the current level and the time for which it is applied. The current level may be converted to voltage conditions by assuming the hand-to-hand or hand-to-foot resistance of a human body (AS 3859 gives this as 1000 Ω). This occurs when the skin is broken down, almost instantaneously, above 200 V.

The touch voltage limit and corresponding time of application shall be in accordance with Table 5.3. A value of 32 V r.m.s. a.c. is the maximum continuous voltage that is acceptable.

NOTES:

1 A lower value of voltage may result in a person being unable to release themselves from the object or pipeline. Although not immediately electrically hazardous, the continued exposure to the voltage may lead to serious injury.

2 Continuous induction results from the magnetic field established by the normal load current (no fault) of the high voltage power lines.

3 The protection fault clearance times in Table 5.3 usually relate to the fault operation speed of circuit breakers and associated equipment on the high voltage power lines, which are causing the induced voltage (see also Clause 6).

TABLE 5.3

TOUCH VOLTAGE LIMITS FOR PIPELINE AND ITS ANCILLARIES ACCESSIBLE TO PUBLIC OR UNSKILLED STAFF

Protection fault clearance time		Volts	
		a.c.	d.c.
	≤ 100 ms	350*	500
> 100 ms	≤ 150 ms	300*	450
> 150 ms	≤ 300 ms	200*	400
> 300 ms	≤ 500 ms	100	300
> 500 ms	≤ 1 s	50	200
> 1 s including continuous load current		32	115

* From AS 3859 (with high speed skin breakdown at 200 V and over, on a 1000 ohm person).

5.4 Category B—touch voltage limits (up to 1000 V) for pipelines with restricted public access

Category B touch voltage limits are applicable to accessible parts of pipelines which have restricted public access. They may also be applied when Category A touch voltage limits are technically or economically not achievable or when the pipeline operator or owner deems the hazards to be negligible or controllable.

The pipeline owner or operator shall carry out a risk assessment in accordance with Clause 5.2 prior to applying Category B touch voltage limits. Such touch voltage limits shall only apply to those sections of a pipeline which are accessible without evacuation or similar activity.

Category B touch voltage limits and corresponding time of application shall be in accordance with Table 5.4.

NOTE: Where a section of pipeline is wholly underground, the voltage rise on that section of pipeline should not exceed the long term voltage withstand of the pipeline coating.

TABLE 5.4

TOUCH VOLTAGE LIMITS FOR PIPELINE AND ITS ANCILLARIES FOR NON-PUBLIC-ACCESS CONDITIONS

Protection fault clearance time	Volts	
	a.c.	d.c.
≤ 1 s	1000	1000
>1 s and continuous	32	115

5.5 Voltages in excess of Category B

Voltages in excess of Category B touch voltage limits are outside the scope of this Standard. Such voltages are likely to lead to hazards or failures affecting the following:

(a) Personnel safety.

(b) Degree of fire risk.

(c) Cathodic protection converters.

(d) Isolation joints (flashovers).

(e) Ancillary electrical equipment (pumps, etc.).

(f) Pipeline telemetry equipment.

(g) Lightning protection equipment.

Management of voltages over 1000 V requires high voltage techniques.

5.6 Construction and maintenance

Excessive voltages may appear on a pipeline or a length of pipe during construction or maintenance activity.

Where a pipeline is exposed for maintenance, modification or replacement, precautions shall be taken to limit the voltages to Category A touch voltage limits for the period of such activity.

If a pipeline has Category B touch voltage limits, equivalent construction/working condition for Category A touch voltage limits may be achieved by the following:

(a) The use of metal equipotential surface mats of adequate size which must be bonded to the pipeline.

(b) The use of maximum safe length of welded or jointed pipeline (a maximum safe length of pipeline would be where Category A touch voltage limits are achievable without the need for protection earthing), laid beside or in a trench. Such use must be advised to the appropriate supervisor for each electrical exposure.

In addition an assessment shall be made of any circumstances particular to Category B touch voltage conditions to identify any risks which may need to be addressed to reduce any hazards to an acceptable level.

If lengths greater than the maximum safe length are to be laid out, temporary appropriate earthing must be fitted and not disconnected until the new section is jointed into the pipeline which has permanent earthing arrangements fitted.

Personnel working on the pipeline shall be advised that the exposed end of the pipeline may possibly be hazardous at times. Precautions listed in Clause 10.3 and Appendix I shall be followed accordingly.

6 LOW FREQUENCY INDUCTION (LFI)

6.1 General

Alternating current on a high voltage power line can induce a voltage on a parallel pipeline. This induction results in a longitudinal voltage over the exposure length due to the electromagnetic field from the current; that is, the voltage appearing on the pipeline, by virtue of its acting as the secondary of a large air core transformer, is from one end to the other. Unlike electricity supply, it is not a voltage to earth. It does have a relationship to earth due to the electrical capacitance caused by the coating on the pipeline allowing some current to flow to earth along its length. This capacitive reactance depends on the wall area of the pipe and the thickness and dielectric constant of the coating material, and is greatly influenced by the properties of the pipeline backfill. Very dry sand, for example, increases the reactance, whereas electrolyte around the pipe reduces it towards the minimum represented by the coating alone. Values of from 1 to 10 microfarads per kilometre are not unusual. This corresponds to a reactance of 3000 to 300 Ω, pipe to earth per kilometre at 50 Hz.

The earth path via capacitive reactance (see Figure 6.1) may represent a personnel hazard in its own right if a very large LFI fault voltage (e.g. 5000 V) is involved. A well-coated pipeline is often protected by CP. Unfortunately, this can result in a much more hazardous LFI condition than exists on the pipeline alone. This occurs due to the reduction of impedance from pipe to earth through the CP anode circuit. Thus the distributed capacitive reactance of perhaps 1000 Ω/km is reduced to perhaps 4 or 5 Ω (resistive) or less. If the CP is applied at one end only, the other end of the pipe will now exhibit the high LFI potential at very low impedance (a dangerous condition).

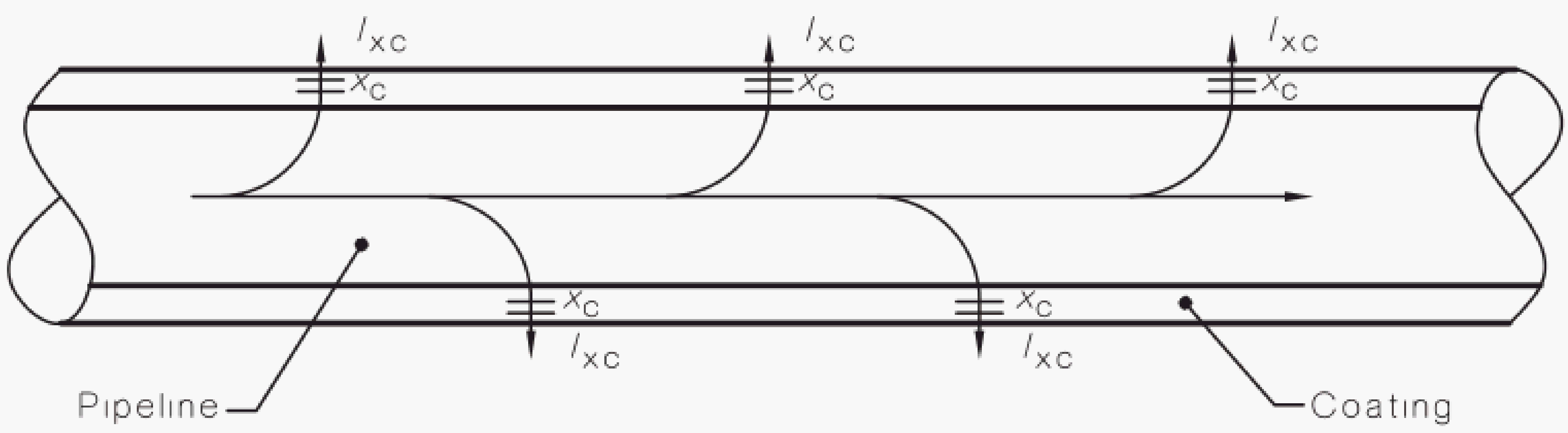


FIGURE 6.1 TYPICAL CURRENT PATH VIA CAPACITIVE REACTANCE

6.2 Load current LFI

In the case of load current LFI, the effect is a differential induction between the current in each of the three phase conductors and the pipeline, which is at differing distances from each conductor. The geometric mean of the induction levels results in a continuous voltage on the pipeline. This is normally a small figure, but in long (100 km) parallels, and for high load currents, it can result in significant voltages. Mitigation is by a similar process to fault current LFI, and usually action taken for this condition will be adequate to control load current effects.

NOTE: A sample calculation for load current LFI is shown in Appendix C.

6.3 Fault current LFI

In a transformer action similar to that described in Clause 6.2, a fault current on a high voltage power line can induce a large voltage on a parallel pipeline.

This is usually the major concern for an electrical hazard.

NOTE: A sample calculation for fault current LFI is shown in Appendix D.

6.4 A.C. traction LFI

The effect of a.c. rail traction is similar, in principle, in its induction effects to fault current induction (see Clause 6.3).

There are two significant differences as follows:

(a) The initiating current has a variable location, due to the traction car movement.

(b) The current varies with the degree of acceleration of the car.

Item (b) is caused by variation in the a.c. waveform to provide greater or lesser acceleration. In addition, this gives rise to a rich source of harmonics in the power system. This is of no consequence to the pipeline condition, but may impact on some pipeline telemetry systems.

NOTE: Calculation of LFI voltage on a pipeline subject to the foregoing condition is difficult. Guidance is given in Appendix E. Several different power arrangements may exist in the traction system. They include the following:

(a) Booster transformers (BT), whereby rail current is 'collected' by transformers at about 3 km intervals, and returned by non-earthed conductors.

(b) Auto-transformers (AT), whereby higher powered auto-transformers supply rail current at about 10 km intervals.

(c) Direct feed, with no correction effect on rail return.

6.5 Mitigation

Mitigation of LFI may take several forms, or a combination of forms. Reducing the modular lengths of the exposure by insertion of isolating pipeline joints will make voltage control more manageable, and usually of lower total cost. However, this might be unacceptable for pipeline operation reasons (pressure, product safety, lightning protection, segmenting CP designs, telemetry requirements). If the pipeline and its ancillaries (valves, scour valves, CP test points, CP converters, ground bed terminations) are made inaccessible to the general public, it may be tolerable to allow momentary high induced voltages that can be subject to controlled work practices by authorized persons. See Clauses 5.3 and 5.4.

A single electrode (or anode) shall not be fitted to an isolated, exposure affected pipeline as it will merely reduce the impedance of the LFI voltage thus increasing the hazard; except where the mitigation design uses the electrode as part of a voltage divider to reduce the voltage to levels in accordance with Clause 5.3 (e.g. at a pipeline terminal often in conjunction with an isolation joint).

Partial shielding by other pipelines or conductors will reduce the voltage induced, but this is rarely a stand-alone design option.

When the foregoing arrangements are impracticable or unacceptable, it is necessary to devise a means of reducing the voltage on exposed or accessible parts of the pipeline. This may be done by converting the pipeline 'transformer' to a dynamic condition, and relying on the effects of Kirchoff's law to present only a portion of the voltage on the ends of the pipeline, as a voltage divided network. This also may be carried out on several modular lengths of the pipeline, if the overall voltage is too high to be met with one overall design.

Acceptable values of induced voltage are given in Clause 5. Guidance on the measurement of the resistance of earth electrodes is given in AS/NZS 1768 and AS/NZS 2832.1. The only other parameter needed for dynamic mitigation of the LFI condition is the pipeline loop reactance. This is the reactance due to the self inductance of the pipeline, forming a loop path to and via earth at each end. Its value will depend mainly on resistivity of geological strata forming the return path. The deeper the path, the higher the inductance. It is also affected by the nature of the enclosed minerals and electrolyte. These conditions should not be confused with pipeline admittance studies, which refer to the conductance properties of coatings. The earth electrodes virtually supplant all other conductive paths. In addition, the resistance of almost any pipeline is negligible (typically in the range of 3 to 30 mΩ/km).

NOTE: A sample calculation for pipeline loop impedance (including inductive reactance) is given in Appendix F.

7 CAPACITIVE COUPLING

7.1 General

Capacitive coupling, often inaptly termed 'electrostatics', is the condition whereby the (electrostatic) capacity between the lowest phase conductor on a high voltage power line forms an electrical path to earth. A small current flows continuously in this way, distributed along the transmission line. The interposition of a metallic object, such as a length of pipeline, when suspended above the earth, but more or less under the lowest conductor, will intercept a portion of this current (typically 5% to 10%), and re-transmit it to earth either by metallic contact of tracked vehicles or by its own capacity to earth if the mechanical handling vehicle has rubber or similar insulating tyres.

In the event of a vehicle with insulating tyres being used, a person in contact with earth and with the vehicle will cause the current to flow through the body to ground, this being a much lower impedance than via the pipe capacity.

To determine the effect on personnel, in order to comply with Clause 5.3 the effect of capacitance current for a suspended pipe length may be used.

NOTE: A sample calculation is shown in Appendix G.

Example:

A 20 m pipe length of 1 m diameter suspended 10 m longitudinally under a 275 kV transmission line (phase to earth of 159 kV), has a capacitance current of approximately 0.58 mA.

Contact by a person with both the pipeline and earth would result in this 0.58 mA passing through the person's body. The resultant body voltage would be:

$$V_{(body)} = IR \qquad \text{. . . 7.1}$$

where

$I = 0.58$ mA

R with skin perforated (AS 3859) ≈ 1,000 Ω

R with skin unperforated (average figure) ≈ 10,000 Ω

Thus

$V_{(body)}$, skin perforated = 0.58 V

$V_{(body)}$, skin unperforated = 5.8 V

Neither of these conditions is of any consequence, as the effect would be barely perceptible.

However, if the pipe length was metallically connected to earth, any tiny spark would be sufficient to ignite a concentration of fuel (such as petrol) vapour nearby.

7.2 Mitigation

Examples of mitigation procedures for capacitive coupling are given in Paragraph G4 of Appendix G.

8 EFFECTS OF LIGHTNING

8.1 The electrical nature of lightning

Lightning may range from a small amount with a charge of less than 1 coulomb up to, in rare cases, over 200 coulombs. These are small quantities, but the charge is delivered in a few microseconds, at voltages over 100 000 000 V and peak currents ranging from several thousand amperes to over 200 000 A. The concept of the peak energy (volts by amperes by time) is difficult to grasp because of the magnitude.

The current is so large and the electrical pressure driving it so immense that the only practicable protection solution is to accept the charge via an earthing system and to conduct it by as short a path as possible to earth. If this path is too tortuous, or too long, or the resistance of the earthing system too high, a very large voltage is developed between the earthing down conductor (or structure) and all surrounding earthed objects. This leads to a secondary or side flash from the down conductor to nearby objects. This side flash is more often than not the source of pipeline lightning problems.

A direct strike to a pipeline would destroy part of any pipe coating in its path to earth. Also, it might possibly cause some metal damage to the pipe itself through gross overheating of the pipeline at the entry or exit points. These are very rare conditions.

The side flash energy is of much lower value than a direct flash attachment to the pipeline. It is a parallel path and the pipeline electrical properties need to be considered to determine the effects. (See Clauses 8.3 and 8.4.)

8.2 The electrical properties of coated pipelines

A modern high-performance pipeline coating has insulation as good as or superior to that of electrical power cables. A near holiday-free coating has an insulation resistance to ground in the order of MΩ/km. In addition, it has a remarkably high voltage withstand capacity.

NOTE: A fused/sintered polyethylene coating of 1 mm thickness has a withstand in the order of several tens of thousands of volts.

The presence of insulating or dielectric material produces an electrostatic capacity. This property stores electrical energy in the dielectric itself. The value of the electrostatic capacity will depend on the area of pipe surface, the thickness of the coating and its dielectric constant.

NOTE: A value of electrical capacity in the order of 1 to 10 microfarads per kilometre of pipeline may be expected. However, the precise value of this is modified by the effect of very dry backfill, which increases the thickness of the dielectric material, thus reducing the capacity.

8.3 The combination of lightning current with the pipeline

Lightning current or its resultant effects can enter the pipeline in several ways. These include the following:

(a) By lightning electromagnetic pulse (LEMP), from a lightning flash direct to earth some distance from the pipeline.

(b) By direct flash attachment to the pipe, if it is exposed on the surface of the ground, or to ancillaries that are thus exposed. Such ancillaries include valves, valve spindles, CP test points, CP converters, pump stations, scraper stations, telemetry installations and the like.

(c) By conduction, through the earth itself, following a flash attachment to some adjacent tree, structure or equipment, not directly connected to the pipeline. This is EPR and includes flash attachment to high voltage power lines adjacent to the pipeline. It also includes direct, over or near the pipeline, flash attachments to the earth. EPR is described in Clause 9.

(d) By shared flash conditions with some other structure that is essentially earthed, but which has metallic connection to the pipeline. For example, electrically powered equipment such as CP converters or pump station equipment or telemetry equipment will receive substantial current from a flash attachment to the low voltage power lines serving this plant. The connection to the pipeline will cause a Kirchoff division of current, depending on the respective pulse impedances.

(e) Side flash, which is the process by which some earthed object (tree or structure) suffers a flash attachment. Then, due to its high impedance to earth and the length of the flash current path, it re-transmits a portion of the flash current by an arc to the adjacent pipeline.

The incidence of direct flash attachments described in Items (b), (d) and (e) is relatively rare; it ranges from 2 to 10 episodes/1000 km/annum depending on earth flash counts for the location. The incidence of longitudinal induction referred to in Item (d) is around 100 times greater due to the ‘catchment’ area being much greater; in the order of ±0.5 km from the pipeline. EPR episodes may be considered as about 10% of LEMP incidents in number.

8.4 Lightning mitigation

The process of lightning mitigation is one of providing a path to earth from the pipeline to discharge the surge energy in such a way as to minimize the risk to personnel and the damage to pipeline and ancillary equipment. In general, the lower the resistance of these paths, the lower will be the voltage on the pipeline during the discharge period.

An electrode resistance of 5 Ω to earth at each end of a pipeline section (typically 10 to 100 km) is recommended. This will remove a stored charge in the case of Clause 8.3(b), (c), (d) or (e) in approximately 10 ms, and an even shorter time in the case of Clause 8.3(a). An even lower earth resistance may be required to protect CP convertors and telemetry equipment.

It will usually be necessary to review the effects of lightning protection on CP design (See Clause 11). Low firing voltage, high current surge protection devices (SPDs) may be needed in series with the lightning earth conductors.

9 CONDUCTIVE EFFECT—EARTH POTENTIAL RISE (EPR)

When current is discharged to earth from an external source, such as lightning or a faulted tower, it will flow into the general body of earth in a radially outwards manner. The uniformity of this flow will depend on earth resistivity, in particular relating to the various geological layers. If the earth were of uniform resistivity, the electric field pattern would be made up of a series of concentric hemispheres. This is illustrated in Figure 9.1.

NOTES:

1 Guidance on the mitigation of EPR is provided in Appendix H.

2 A sample calculation for a phase to earth fault on a 50 Hz high voltage installation is shown in Appendix H.

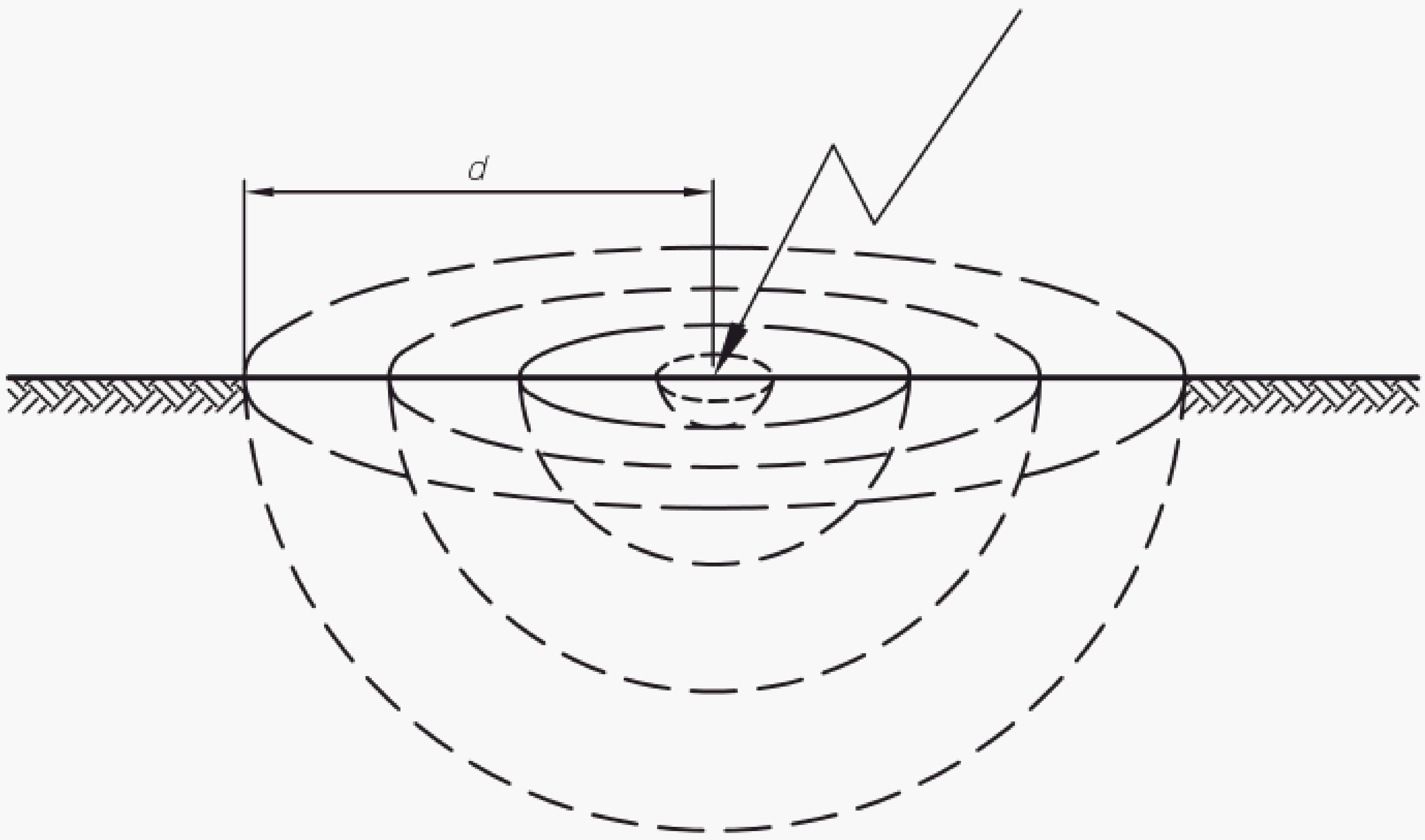


FIGURE 9.1 EQUIPOTENTIAL SHELLS FOR AN EARTH DISCHARGE

10 OTHER HAZARDS

10.1 Open-circuited neutrals

Water pipelines are usually connected to the electrical installation earth bar and then to the neutral bar (via the MEN link) at all premises, via equipotential bonding arrangements in accordance with AS 3000. This means an open circuit neutral conductor may cause a rise of voltage on the water pipeline system. In general, voltage limits given in Clause 5.3 will be exceeded. This condition is caused by a fault occurring on the electricity installation, and is not subject to any controls except by isolation of the water pipes. If the pipeline owner considers the risk unacceptable, isolating spacers can be fitted at the water pipe junctions with the main water pipeline.

10.2 D.C. traction systems

10.2.1 *General*

Pipelines in urban areas often cross or are buried alongside railway tracks which carry the return current from d.c. traction (rail) systems.

Drainage bonds designed to mitigate the effects of traction return currents on pipeline CP systems bring conductors from the pipeline and the rail into close proximity.

Although the drainage bonds are enclosed and are thus protected against accidental contact, this does not exclude the possibility of personnel working on the pipeline CP system being exposed to the rail potential, referenced to the pipeline.

NOTE: Voltages in the order of 150 V d.c. may occur for a significant time. Therefore protection such as equipotential mats may need to be used at CP terminals or testing points.

The calculation of rail voltage requires considerable knowledge and experience in electrical d.c. traction systems. Voltage limits are given in Clauses 5.3 and 5.4.

10.2.2 *Voltage exposure*

Hazardous voltages may appear from time to time in and around CP drainage bonds between the following three structures:

(a) *The pipeline connection* The pipeline connection will conduct any potential which exists on the pipeline to the drainage bond.

(b) *The rail line connection* The rail line connection will conduct any rail potential to the drainage bond. In the absence of any concurrent dangerous electrical condition on the pipeline, the pipeline potential will be close to the local earth potential, and the two may (for the purpose of this analysis) be considered to be equipotential.

Voltages on the rail result from the return currents of the traction system. Typically, the voltage is within ±70 V d.c. of earth, but can rise due to faults.

NOTE: The State Rail Authority of NSW (SRA) has installed rail voltage monitors linked to rail-earth contactors, which will connect the rail to earth should the rail potential become excessive. The effectiveness of this strategy in limiting rail to earth potential depends on local conditions, such as soil condition.

This system works to a rail to earth potential/time relationship as follows:

(i) For potentials below 100 V................................no trip.

(ii) For potential equal to 100 V ....500 ms.

(iii) For potentials between 100 V and 400 V........... reduction from 500 ms to under 20 ms.

An examination of this relationship within AS 3859 (time/current zones for d.c.) indicates that there is little risk of serious physiological effects. However, there appears to be the possibility of reversible disturbances of formation and conduction of impulses in the heart for lengthy periods of contact, which should therefore be avoided.

(c) *The local earth* The local earth may be subject to EPR. This situation is discussed in Clause 9.

With a supply of 1500 V d.c. at many hundreds of amperes, d.c. traction systems obviously have the potential to impose hazardous voltages on rail tracks.

In the context of pipelines, this appears to be only a hazard to personnel with access to CP drainage bonds, where the potentials on the pipeline, earth and rail are accessible.

NOTE: Electrical potentials on the pipeline (caused by LFI or power line EPR) or earth (caused by EPR) are covered in Clauses 6 and 9.

Electrical potentials on the rail are monitored by automatic systems which will earth the rail should they become hazardous. In addition, other systems will isolate the electrical supply in case of train faults, which will in turn reduce the rail-earth potential to zero.

The automatic systems will not necessarily protect against intermediate level potentials which can cause noticeable but reversible physiological effects. It should be possible to deal with these potentials by using proper operating procedures (e.g. gloves, or instructions to not touch two structures simultaneously).

10.3 Storage and handling of pipe lengths

During construction and maintenance of pipelines, with coated surfaces, in close proximity to high voltage power lines it may be necessary to—

(a) use mechanical handling equipment;

(b) store pipe lengths;

(c) connect long strings of pipe lengths during construction;

(d) remove pipe lengths during maintenance; and

(e) physically touch uncoated parts of pipe lengths.

This may result in electrical hazards due to excessive induced voltages or mechanical handling equipment touching overhead conductors.

Where conductors are used to earth pipe lengths or bond between pipe lengths during construction and maintenance, they shall be not less than the equivalent of 2 by 16 mm^2 copper conductors in parallel.

NOTE: Guidance on the handling of pipe lengths and the use of personal protective equipment such as insulating gloves, insulating footwear and equipotential mats is given in Appendix I.

11 INTERACTION BETWEEN PROTECTIVE EARTHING SYSTEMS ON PIPELINES AND CATHODIC PROTECTION SYSTEMS

Some CP systems may be compromised by the protective earthing systems used.

There are several reasons for fitting 'earthing' systems to pipelines. The most important are as follows:

(a) LFI protection for personnel protection in situations where pipelines are installed along high voltage power line corridors. LFI may have ramifications on the pipeline hardware and ancillary equipment survival.

(b) Lightning protection (LP) primarily for personnel protection, also for ancillary equipment survival.

(c) CP anodes for corrosion control.

NOTE: Information on the interaction of the protective earthing systems on pipelines with the CP systems is given in Appendix J.

12 COMMISSIONING AND MAINTENANCE OF PIPELINE EARTHING SYSTEMS

12.1 General

Pipeline earthing and associated equipment maintenance and refurbishment comprise the following three aspects as outlined in Clauses 12.2 to 12.4:

(a) Initial commissioning testing.

(b) Periodic integrity checks.

(c) Performance review.

12.2 Initial commissioning

12.2.1 *General*

An earthing system, earth mats and mitigation equipment should be checked and inspected immediately after construction. This is required to—

(a) validate that construction complies with the system design and also statutory safety requirements; and

(b) set initial performance guidelines, as a basis for future comparison.

The commissioning checks involve both physical inspections and electrical tests.

12.2.2 *Physical inspection*

The physical inspection should include assessment of the following:

(a) Design layout compliance.

(b) Earth connections integrity.

(c) Bonds to structures and equipment.

(d) Mitigation equipment and procedures.

The condition of any crushed rock, earth mats or mitigation equipment associated with any associated electrical installations and above ground facilities should be inspected for integrity.

12.2.3 *Electrical performance*

During the initial commissioning tests, impedances of current-carrying protective devices (e.g. polarization cells) of the earthing systems and performance of decoupling devices should be confirmed.

12.3 Periodic integrity checks

The response of earthing systems, earth mats and mitigation equipment may progressively degrade as their conductors and connectors deteriorate. Therefore, periodic integrity tests are required to detect and repair damaged equipment or corroded conductors. Buried conductors should be insulated both for durability and to avoid dissimilar metal corrosion with steelwork.

The frequency and type of periodic checks required are to be determined in conjunction with the risk assessment, statutory requirements and the earth system vulnerability. Areas of high frequency of access or fault occurrence should be inspected at least once a year.

12.4 Performance review

In many cases earthing systems are last ‘seen’, or have their performance tested during the construction stage. In addition to the development of a strategy for the ongoing maintenance of new systems, a critical review and refurbishment program is needed for older earthing systems. This should include safeguards to detect unexpected damage such as vandalism.

Earthing systems are often ignored or even ‘actively disregarded’. It is considered that such a philosophy is quite dangerous in view of the maintenance and refurbishment experience of many countries.

A responsible review strategy is needed to ensure the correct operation of protection systems and compliance with safety criteria. The review process is aimed at satisfying professional responsibilities related to duty of care, whilst controlling expenditure by targeting hazardous sites and providing economical designs.

APPENDIX A

LIST OF REFERENCED DOCUMENTS

(Normative)

The following documents are referred to in this Standard:

AS	
ISO1000	The international system of units (S1) and its application
3859	Effects of current passing through the human body
AS/NZS	
1768	Lightning protection
2832	Cathodic protection of metals
2832.1	Part 1: Pipes and cables
3000	Electrical installations (known as the Australian/New Zealand Wiring Rules)
4360	Risk Management
ESAA	
EG1(97)	ESAA Substation Earthing Guide

APPENDIX B
DEFINITIONS
(Normative)

B1 DEFINITIONS

B1.1 General

Throughout this Standard, unless the context otherwise requires, the terms below have the meanings given as listed.

In an individual clause where an additional term is defined, such a term has, unless the context otherwise requires, the meaning as defined.

Words or terms not specifically defined are to be interpreted as commonly understood.

Where the terms voltage and current are used, they imply r.m.s. values unless otherwise defined.

B1.2 Accessible

Capable of being reached easily without climbing over or removing obstructions or using a movable device such as a ladder.

B1.3 Anode

An electrode, placed in the electrolyte, to apply cathodic protection to a structure, accessed by that electrolyte.

B1.4 Authorized person

The person in charge of the premises, or the person appointed or selected by the person in charge of the premises, to perform certain duties associated with the pipeline.

B1.5 Cathodic protection

The prevention or reduction of corrosion of metal by making the metal the cathode in a galvanic or electrolytic cell. Galvanic systems use a directly earthed anode. Other systems use impressed current. (*see* Paragraph B1.12.)

B1.6 Converter

A device that converts electrical energy to extra-low voltage (ELV) direct current.

NOTE: A rectifier is considered to be a converter.

B1.7 Diameter

The outside diameter nominated in the consideration of the pipeline.

B1.8 Drainage bond

A return conductor system from affected structures to return stray current to the traction rail.

B1.9 Earth (noun)

The conducting mass of the general body of the earth.

B1.10 Earth (verb)

To connect any conductor to earth.

B1.11 Electrode

An electronic conductor that allows current to flow either to or from an electrolyte with which it is in contact, generally for pipeline LFI and lightning protection.

B1.12 Electrolyte

A liquid, or the liquid component in a composite material such as soil, in which electric current may flow by ionic charge transfer.

B1.13 Equipotential mats

A conducting metal mesh or structure at or below ground level at test points or other pipeline facilities and connected electrically to the pipeline, to avoid differences of electrical potential across the body of a person.

B1.14 Fluid

Any liquid, vapour, gas or a mixture of any of these.

B1.15 Gas

Any hydrocarbon gas or mixture of gases, possibly in combination with liquid petroleum condensates or water.

B1.16 Holiday

Any flaw, discontinuity in a coating, or a thinning out of coating.

B1.17 Impressed current

Direct current supplied by an external power source to cathodically protect a structure.

B1.18 Isolating joint

A joint that breaks electrical continuity in a structure, but does not affect the mechanical integrity of the structure.

B1.19 May

Indicates the existence of an option.

B1.20 Polarization cell

An electrochemical device which, at potential levels typical of cathodically protected structures, has low impedance to alternating current but high impedance to direct current of lower voltages used in cathodic protection systems. Some electronic devices have been developed which are not electrochemical but are also referred to by this title.

B1.21 Shall

Indicates that a statement is mandatory.

B1.22 Should

Indicates a recommendation.

B1.23 Structure

A metal surface in contact with an electrolyte, usually being a pipeline and its ancillary fittings.

B1.24 Test point

A nominated point on a structure (pipeline) for electrical contact. This may also include protection earthing terminals.

B1.25 Touch voltage

A voltage appearing between accessible metalwork and a point on the earth surface (or other accessible metalwork) separated by a distance equal to a person's normal maximum horizontal reach (approximately 1 m), loaded by the human body impedance (typically 1000 Ω), measured with a high impedance voltage meter.

APPENDIX C

LOAD CURRENT LFI EXAMPLE CALCULATION

(Informative)

C1 GENERAL

When a pipeline passes in close proximity to a high voltage power line, LFI in the pipeline can be due to the load current in the high voltage power line. This LFI will be a continuous condition for as long as the high voltage power line is carrying the load current. The induced voltage in the pipeline is the resultant vector sum of the voltage induced by each high voltage power line phase current. Since the high voltage power line load current can be considered as a balanced set of currents in the three phases, in which case their vector sum is zero, the LFI may be minimal and is always much less than the LFI under fault conditions. The magnitude of the induction is dependent on both the magnitude of the load current and the relative distances between each of the phases and the pipeline. Generally, the higher the voltage of the power line, the further will the phases be separated and the greater will be the induced voltage.

C2 LFI CALCULATION—NO OVERHEAD EARTHWIRES

A simple high voltage power line construction will be considered as an example. This example assumes that there are no overhead earthwires and no adjacent high voltage power lines to interfere with the LFI in the pipeline. The resultant induced voltage, V_p, can be expressed in equation form as follows:

$$V_p = I_a.Z_{ap} + I_b.Z_{bp} + I_c.Z_{cp} \qquad \ldots \text{C1}$$

where

I_a, I_b and I_c are the vector phase currents in the high voltage power line;

Z_{ap}, Z_{bp} and Z_{cp} are the mutual impedances between the respective a, b and c phase conductors and the pipeline.

The equation used for the calculation of the mutual impedances, Z_{ap}, Z_{bp} and Z_{cp}, is Equation D1 of Appendix D, where the variables are as defined in Appendix D.

Typical 275 kV high voltage power line phase spacings together with a pipeline layout are shown in Figure C1.

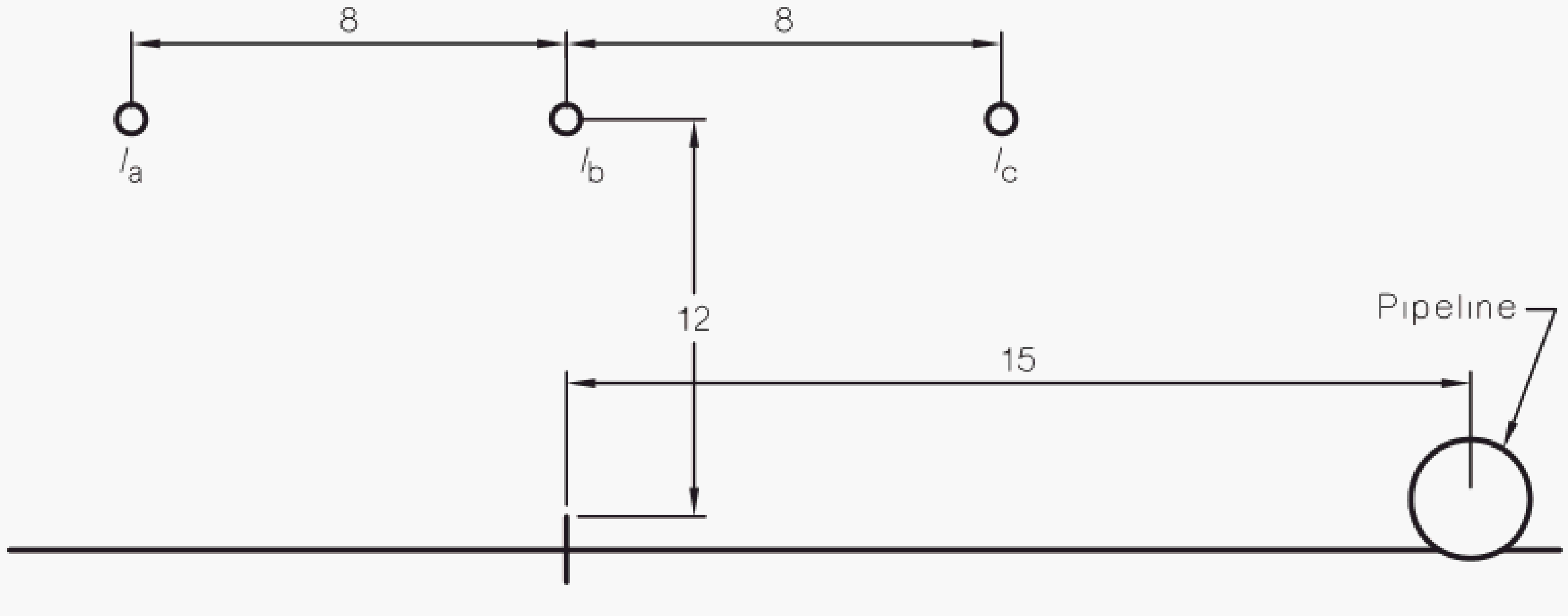


FIGURE C1 TYPICAL 275 kV HIGH VOLTAGE POWER LINE– PIPELINE RELATIONSHIP

Let the high voltage power line phase currents be—

$I_a = 500\angle 0$ amps; $I_b = 500\angle -120$ amps; $I_c = 500\angle 120$ amps

The distances between the phases and the pipeline are given by—

$$D_{ap} = \sqrt{23^2 + 12^2} = 25.94 \text{ m}$$

$$D_{bp} = \sqrt{15^2 + 12^2} = 19.21 \text{ m}$$

$$D_{cp} = \sqrt{7^2 + 12^2} = 13.89 \text{ m}$$

And the mutual impedances become (assuming $\rho = 100$ ohm metres and $f = 50$ Hz, which gives $D_e = 931.08$, using equation D2)—

$$Z_{ap} = 0.04935 + j0.14468.\log_{10}\left(\frac{D_e}{D_{ap}}\right) = 0.04935 + j0.2250 \ \Omega/\text{km}$$

$$Z_{bp} = 0.04935 + j0.14468.\log_{10}\left(\frac{D_e}{D_{bp}}\right) = 0.04935 + j0.2439 \ \Omega/\text{km}$$

$$Z_{cp} = 0.04935 + j0.14468.\log_{10}\left(\frac{D_e}{D_{cp}}\right) = 0.04935 + j0.2642 \ \Omega/\text{km}$$

Therefore—

$$V_p = I_a.Z_{ap} + I_b.Z_{bp} + I_c.Z_{cp}$$
$$= 112.5\angle 90.0 + 121.95\angle -30 + 132.1\angle 210$$
$$= 16.98\angle -121.2 \text{ V/km}$$

A voltage of 17 V/km would be induced into the pipeline.

For an exposure of say 10 km, the induced voltage is 170 V. This voltage is significantly less than the induced voltage due to fault current as calculated in Appendix D, but the voltage so developed is a continuous condition.

Usually high voltage power lines of the higher voltages are transposed. Any pipeline exposed to such a power line will result in the cancellation of the induced voltage over the pipeline length. But the voltage induced in the pipeline for the exposure length between the power line transposition points may be sufficiently high to exceed the voltage limits specified in this Standard. It is therefore important to determine the positions of transpositions along the power line.

C3 LFI CALCULATION—WITH OVERHEAD EARTHWIRES

Most high voltage power lines have overhead earthwires in their construction. These overhead earthwires have a shielding effect on the pipeline which reduces the LFI in the pipeline.

In this case the resultant induced voltage, V_p, can be expressed in similar fashion to equation C1 as follows:

$$V_p = I_a.Z'_{ap} + I_b.Z'_{bp} + I_c.Z'_{cp} \quad \text{. . . C2}$$

where

I_a, I_b and I_c are as defined for equation C1;

Z'_{ap}, Z'_{bp} and Z'_{cp} are corrected depending on the number of overhead earthwires involved.

Consider a high voltage power line with one overhead earthwire, 'w', then Z'_{ap}, Z'_{bp} and Z'_{cp} are defined by:

$$Z'_{ap} = Z_{ap} - \frac{Z_{aw} . Z_{wp}}{Z_{w}}$$

$$Z'_{bp} = Z_{bp} - \frac{Z_{bw} . Z_{wp}}{Z_{w}}$$

$$Z'_{cp} = Z_{cp} - \frac{Z_{cw} . Z_{wp}}{Z_{w}}$$

where

Z_{ap}, Z_{bp} and Z_{cp} are defined above for Equation C1

$$Z_{aw} = 0.04935 + j0.14468.\log_{10}\left(\frac{D_{e}}{D_{aw}}\right)\ \Omega/\text{km}$$

$$Z_{wp} = 0.04935 + j0.14468.\log_{10}\left(\frac{D_{e}}{D_{wp}}\right)\ \Omega/\text{km}$$

$$Z_{w} = r_{w} + 0.04935 + j0.14468.\log_{10}\left(\frac{D_{e}}{GMR_{w}}\right)\ \Omega/\text{km}$$

and D_{aw} is the distance between the phase 'a' and the earthwire 'w'

D_{wp} is the distance between the earthwire 'w' and the pipeline

r_{w} is the a.c. resistance in ohms/km of the earthwire 'w'

GMR_{w} is the geometric mean radius of the earthwire 'w'.

Similar expressions can be derived for the other values involving the 'b' and 'c' phases with the earthwire 'w'.

For the consideration of more than one earthwire or other continuously earthed conducting mediums for shielding purposes, the expressions Z'_{ap}, Z'_{bp} and Z'_{cp} must be expanded to include their effects. The expressions must also include the inter-reaction between the earthwires, and or other conducting mediums, which increases the complexity of the formulae.

The determination of the induced voltage, *V*p, in the pipeline as a consequence of the presence of shielding effects has increased the calculations required to include those effects. Since these shielding mediums reduce the LFI in the pipeline, they need only to be considered in the calculation if the voltage limits are exceeded and measures to reduce the LFI warrant their inclusion.

APPENDIX D

FAULT CURRENT LFI EXAMPLE CALCULATION

(Informative)

D1 GENERAL

Low frequency induction (LFI) in pipelines in close proximity to high voltage power lines is due to the time-varying magnetic fields produced by the current in the high voltage power line phases. In this calculation example the currents in the phases will be those flowing as a result of a fault occurrence. Because balanced currents have a cancellation effect, the currents to be considered in the phases will be the zero sequence current values. The zero sequence current has a return path through the earth and forms an inductive loop enclosing the pipeline.

D2 CALCULATIONS USING ρ = 100 ohm metres

The most commonly used method for calculation of LFI involves the use of Carson's equations, which define the mutual impedance between the pipeline under consideration and the current carrying phases. The mutual impedance is calculated from the physical relationship of the phases and the pipeline and the separation between them.

The mutual impedance has the general form (see Figure D1) of—

$$Z_{\mathrm{lp}} = 9.869 f \times 10^{-4} + j\,2.8935 f \times 10^{-3} \log_{10} \frac{D_{\mathrm{ep}}}{D_{\mathrm{lp}}}\ \Omega/\mathrm{km} \qquad \ldots \text{D1}$$

At 50 Hz frequency (f) this becomes—

$$Z_{\mathrm{lp}} = 0.04935 + j\,0.14468 \log_{10} \frac{D_{\mathrm{ep}}}{D_{\mathrm{lp}}}\ \Omega/\mathrm{km}$$

NOTE: This is an approximate equation, but is sufficiently accurate for parallel exposure occurring for separations up to 1 km. For greater separations and extreme variations in soil resistivity, guidance may be obtained from CIGRE (ref. (f), Appendix K).

The value D_{e} is given by the equation—

$$D_{\mathrm{e}} = 658.37 \sqrt{\frac{\rho}{f}}\ \mathrm{m} \qquad \ldots \text{D2}$$

where

ρ = the earth resistivity in Ω.m

f = frequency in hertz.

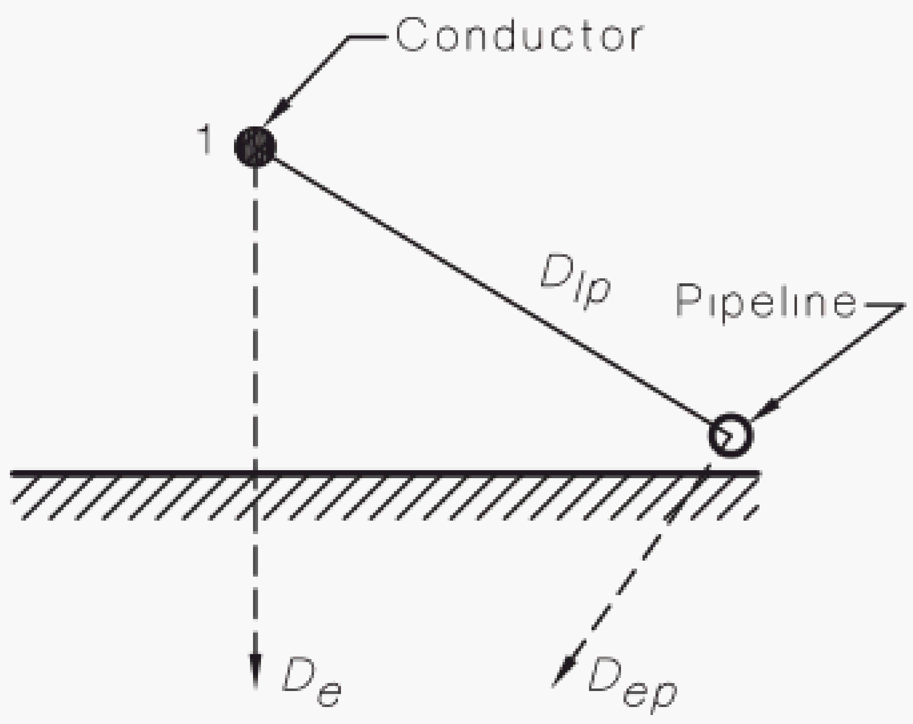


FIGURE D1 CONDUCTOR—PIPELINE RELATIONSHIP

At 50 Hz and for a value of ρ, at the usual value of 100 Ω.m the values of D_e and D_{ep} are relatively large.

D_{ep} is therefore taken as equal to D_e and, in all the following calculations, D_e is used instead of D_{ep}.

The low frequency induced voltage is then given by—

$$V_{LFI} = I_1 Z_{lp.} \quad \text{. . . D3}$$

where

I_1 = the current in the conductor 1

In order to examine these effects more closely, a number of high voltage power line configurations will be considered as follows:

(a) The conductor 1 can be a single conductor as in a single wire earth return (SWER) line, in which case the LFI is produced for both load and fault current, with the fault current producing the highest value but for only a limited time, until the fault is cleared.

The equations used are then as defined above.

(b) The conductor 1 can be replaced by a group of conductors, such as exists for a three phase high voltage power line.

Then the geometric mean separation distance D_{lp}, for a feeder with phases a, b and c, is defined in terms of the distances D_{ap}, D_{bp} and D_{cp} between the pipeline and the respective phases as follows—

$$D_{lp} = \sqrt[3]{D_{ap} D_{bp} D_{cp}} \quad \text{. . . D4}$$

In this case the current I_1, becomes the high voltage power line $3I_0$ current value where I_0 is the zero sequence current.

(c) When a high voltage power line has overhead earthwires in its construction (see Figure D2), these act as a shield for the high voltage power line fault current, with the result that some of the current returns via the overhead earthwires. This in effect reduces the magnetic coupling with the pipeline. Most power authorities calculate the factor known as the shielding factor (K_{SF}), which is the ratio of current in the ground to the current in the high voltage power line.

If we let D_{wp} be the distance from the pipeline to the earthwire group then, for the situation where D_{lp} and D_{wp} are equal (or their effect is the same), the value of voltage as determined for the three phase high voltage power line case above is multiplied by the factor K_{SF}, giving a LFI voltage of—

$$V_{LFI} = 3I_0 K_{SF} Z_{lp} \quad \text{. . . D5}$$

The value of D_{wp} is calculated in a similar manner to D_{lp}. Suppose there are two earthwires w_1 and w_2 then—

$$D_{wp} = \sqrt{D_{w1p} D_{w2p}} \quad \text{. . . D6}$$

(d) When D_{lp} and D_{wp} are sufficiently different the factor K_{SF} is corrected to the new value K^1_{SF} as follows—

$$K^1_{SF} = 1 - (1 - K_{SF}) \frac{Z_{wp}}{Z_{lp}} \quad \text{. . . D7}$$

where

$$Z_{wp} = 0.04935 + j\,0.14468 \log \frac{D_e}{D_{wp}}$$

It is to be noted that K_{SF} is a vector and should be used as such in the above equation.

Generally the difference between K^{1}_{SF} and K_{SF} can be ignored but it must be remembered that Z_{wp} is always less than Z_{lp}, so that K^{1}_{SF} will always be larger than K_{SF} and may need to be allowed for if the value of induced voltage is critical.

(e) For a double circuit constructed high voltage power line the LFI effect can be calculated by considering the double circuit construction as if it were one high voltage power line. If we let one set of phases be a_1, b_1 and c_1 and the other set be a_2, b_2 and c_2 then D_{lp} becomes—

$$D_{lp} = 6\sqrt{D_{a1p} D_{b1p} D_{c1p} D_{a2p} D_{b2p} D_{c2p}} \qquad \text{. . . D8}$$

from which we calculate Z_{lp} as previously. Also the value of V_{LFI} is calculated as in Item (c) where in this case the value of $3I_0$ used is the vector sum of the individual $3I_0$ currents of each of the parallel high voltage power lines.

The values of total $3I_0$ (easement) current and high voltage power line shielding factors are obtainable from the appropriate power authority and generally these provide a sufficient calculation of V_{LFI}. A more accurate calculation can be obtained by considering each of the high voltage power lines in turn as outlined in Item (c) and vectorially adding the LFI voltages due to the individual high voltage power line $3I_0$ current values.

Example calculation for a single circuit high voltage power line is as per Item (c).

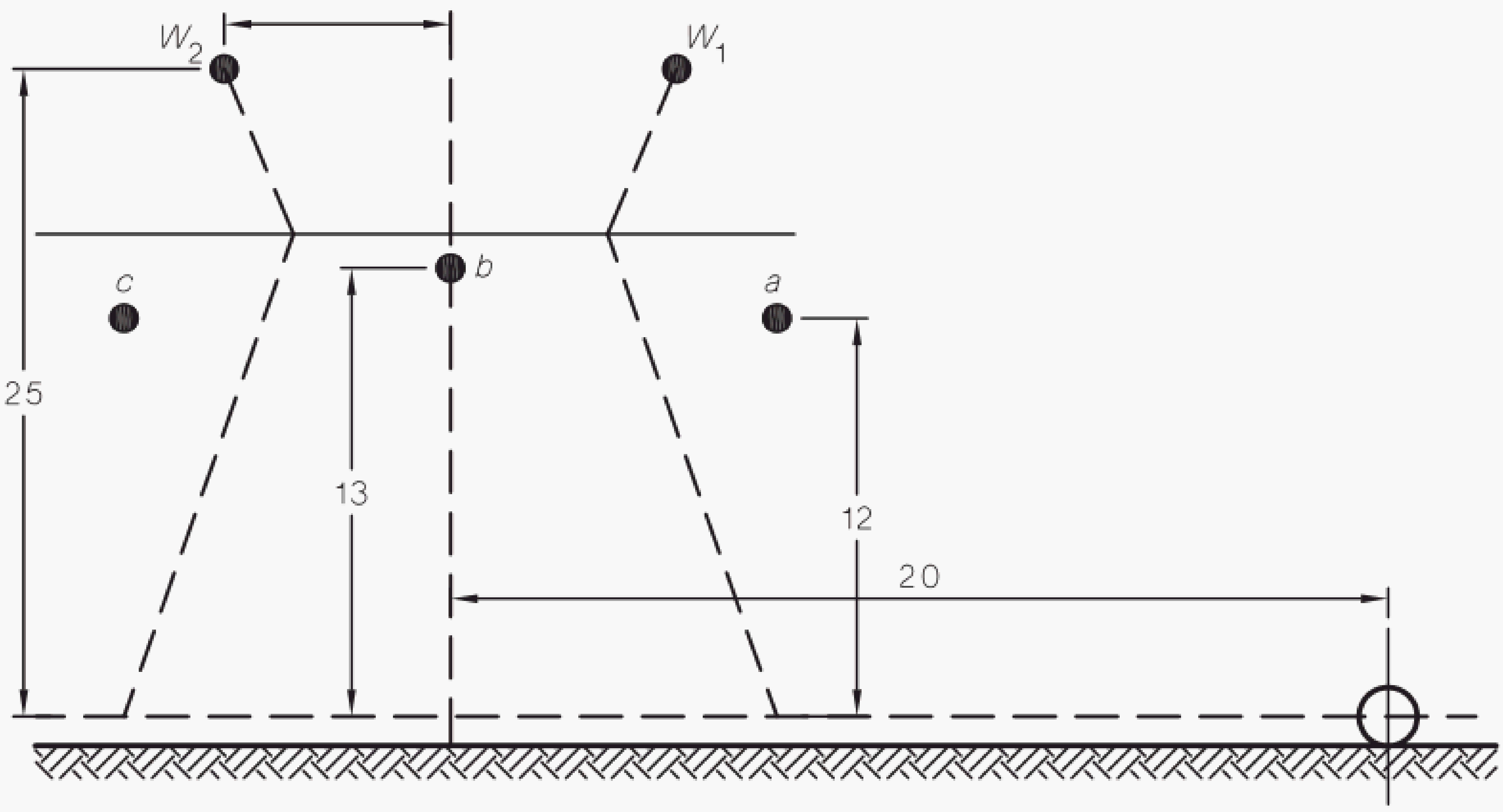


FIGURE D2 SINGLE CIRCUIT HIGH VOLTAGE POWER LINE—PIPELINE RELATIONSHIP

High voltage power line fault current, $3I_0$ = 1500 A

$$K_{SF} = 0.912 \angle -7.4$$

and ρ = 100 Ω.m

$$D_e = 658.37 \sqrt{\frac{\rho}{f}} = 658.37 \sqrt{\frac{100}{50}} = 931.08 \text{ m}$$

$$D_{ap} = \sqrt{12.5^2 + 12^2} = 17.33 \text{ m}$$

$$D_{bp} = \sqrt{20^2 + 13^2} = 23.85 \text{ m}$$

$$D_{cp} = \sqrt{27.5^2 + 12^2} = 30.00 \text{ m}$$

$$D_{lp} = 3\sqrt{D_{ap} D_{bp} D_{cp}} = 23.15 \text{ m}$$

$$Z_{lp} = 0.04935 + j\,0.14468 \log_{10} \frac{931.08}{23.15}$$

$$= 0.04935 + j\,0.2321$$

$$= 0.2373 \angle 78.0\ \Omega/\text{km}$$

For $3I_0$ = 1500 A and K_{SF} = 0.912

Then V_{LFI} = 1500 × 0.912 × 0.2373

= 324.6 V/km

For an exposure of say 10 km then total

V_{LFI} = 3246 V

Consider correction for true K^1_{SF}, we need to calculate—

$$D_{w1p} = \sqrt{13.5^2 + 25^2} = 28.41 \text{ m}$$

$$D_{w2p} = \sqrt{26.5^2 + 25^2} = 36.43 \text{ m}$$

$$D_{wp} = \sqrt{D_{w1p} D_{w2p}} = 32.17 \text{ m}$$

and

$$Z_{wp} = 0.04935 + j\,0.14468 \log_{10} \frac{931.08}{32.17}$$

$$= 0.04935 + j\,0.2115$$

$$= 0.2172 \angle 76.87\ \Omega/\text{km}$$

From which

$$K^1_{SF} = 1 - (1 - 0.912 \angle -7.36) \frac{0.2172 \angle 76.87}{0.2373 \angle 78.0}$$

$$K^1_{SF} = 0.917 \angle -6.59$$

Then

V_{LFI} = 1500 × 0.917 × 0.2373

= 326.4 V/km

In this case there is a negligible difference between the two values 324.6 and 326.4 V/km, due to insufficient difference between D_{wp} and D_{lp}.

D3 MUTUAL IMPEDANCE WHEN ρ VARIES FROM 100 OHM METRES

In some exposures, where considerable variations in geomorphology exist, ρ may vary over several orders of magnitude. In addition, the pipeline/high voltage power line separation may also vary continuously, e.g. where a pipeline follows a roadway which only basically lies adjacent to the high voltage power line. In this event a large number of calculations is required. This necessitates either the adoption of a computer program, or reference to a nomogram or chart corresponding to Equation D1. The nomogram or chart will be less precise, but nevertheless adequate for this purpose. Such a chart is shown as Figure D3, covering the separation range from 1 m to 1 km. Generally, 1 km is about the limit of separation for the application of Equation D1.

It is essential to derive a value for ρ at some depth to validate any calculation. Correlation of ρ readings with known geological data for the areas will often produce a viable result. Testing instruments to read ρ at depth will require a more sophisticated earth resistivity device than those normally used for corrosion testing. ρ should be read at intervals of 2 km to 4 km, or more frequently if required by changes in earth formation.

D4 MAXIMUM TOTAL COUPLING

The phase to earth fault current may need to be calculated at different locations along an exposure, in order to find the maximum total coupling. The electricity distributors will normally be able to supply a fault current profile for the high voltage power line under consideration. A profile of a high voltage power line fed from both ends is reproduced in Figure D4.

Not all exposures will cause a minimum LFI voltage when the fault on the high voltage power line is at or beyond the end of the exposure. The induction depends on the product *IL* in Equation D9. Consequently, the impedance of the high voltage power line causing the fault profile in Figure D4 may result in a point on the profile curve where *IL* diminishes with distance.

The induced voltage for the exposure will be derived from—

$$E = C.I.L. \qquad \ldots \text{D9}$$

where

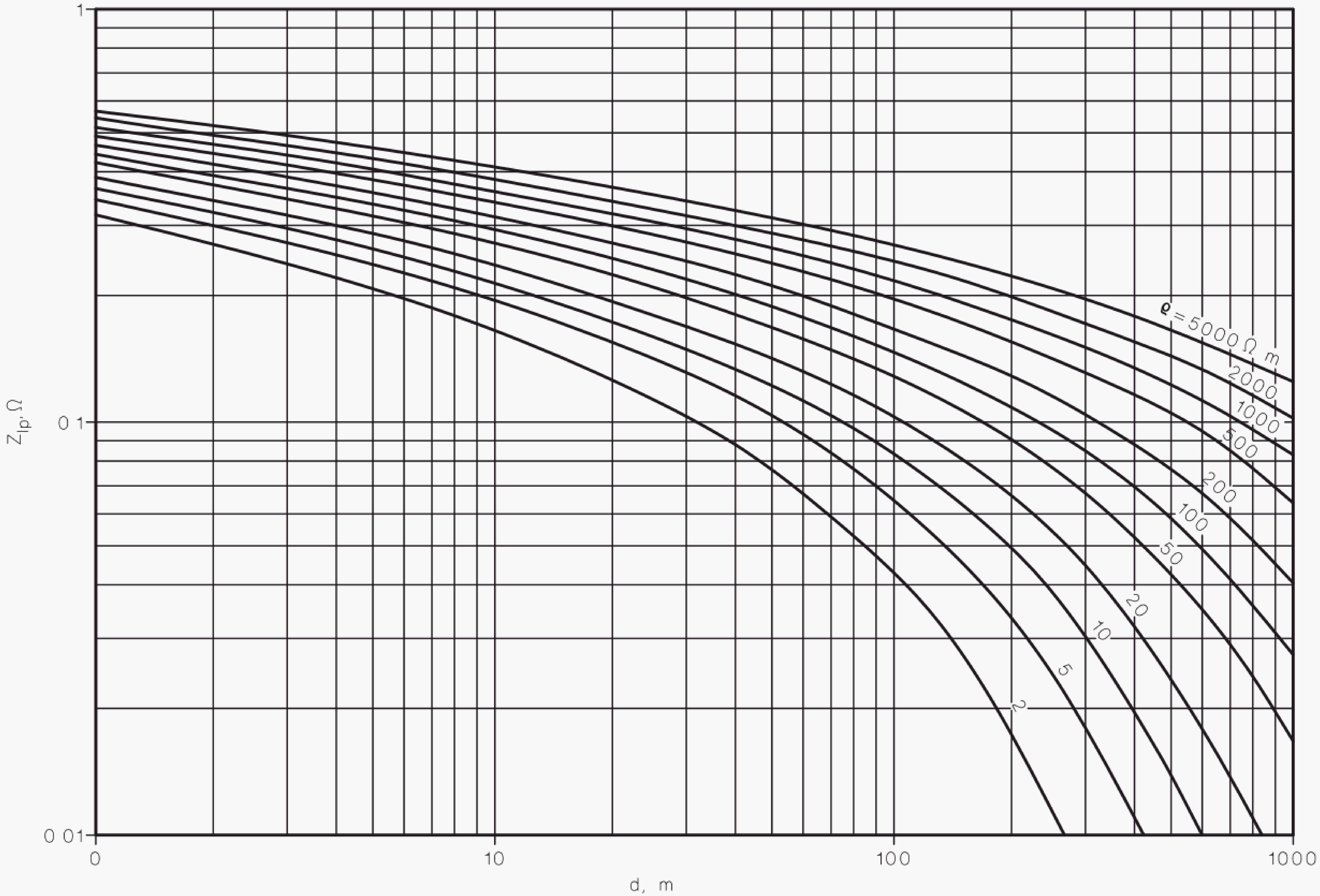
E = the pipeline induced voltage (V)

C = the coupling factor (from the chart in Figure D3)

I = the fault current (from the current profile in Figure D4)

L = the length, in km, of the exposure.

In some cases, a shielding (moderating) factor *k* may be involved. This is added to the Equation D9. It is the reducing component caused by either an overhead earth wire carrying a proportion of the fault current, or metallic infrastructure (other pipelines, traction rails, etc., parallel to the pipeline) causing a reduction of induction electromagnetic field. It is typically in the range of 0.7 to 0.9, when applicable.



NOTE: Figure D3 provides the coupling factor C (mutual impedance Z_{lp}) at 50 Hz between high voltage power lines and a pipeline with earth return, as a function of their geometric mean separation distances (d_{lp}) in metres at varying values of ρ (Ω.m).

FIGURE D3 COUPLING FACTOR, C (MUTUAL IMPEDANCE) AT 50 HZ

D5 PARAMETERS REQUIRED TO ASSESS POSSIBLE HAZARDS

D5.1 High voltage power line

To evaluate the extent of a hazardous voltage on pipelines, it is necessary to collect a substantial amount of data regarding the high voltage power line. This data may be divided into three basic categories as follows:

(a) *High voltage power line location* It is necessary to obtain plans for the high voltage power line route showing the location of the easement and, for close separations, the location of the high voltage power line within the easement. The plans should also show the location of towers and substations. These plans are necessary to enable separations and length of exposures to be determined.

Considerable time and cost savings may be achieved if a coordinated plan showing power lines and pipeline on one drawing is arranged.

(b) *High voltage power line operational parameters* The operational parameters of the high voltage power line which may need to be assessed include the following:

(i) Phase to phase voltage.

(ii) Maximum load current.

(iii) Configuration of conductors and supports.

(iv) Transposition scheme—location of cross points and estimation of balance.

(v) Fault clearance time.

(vi) Fault current profile—from both ends if part of a grid system. (See Figure D4).

(vii) Overhead earth wires—number of, shielding factor, extent of (e.g. for all or part of route).

(viii) Average height of lowest conductor from ground.

(ix) Magnetic field under phase conductors at ground level (due to load current).

(x) Average tower footing resistance, and radial extent of tower earthing system.

(xi) Soil resistivity—relatively shallow for EPR calculations near towers, deeper for LFI calculations.

(c) *High voltage power line 'life cycle'* Many of the parameters listed in Item (b) may be affected by changes to the high voltage power system that may happen some time in the future. Therefore when assessing parameters, it is useful to obtain long-term plans where available.

Items that require consideration include the following:

(i) Changes of voltage.

(ii) Changes of load current.

(iii) Changes of fault current.

(iv) Extensions to route.

Notwithstanding the above, it may in some cases be more economical to mitigate for present hazards and address future hazards at the appropriate time.

D5.2 Metallic pipelines

The data required for the pipeline may be divided into the following categories:

(a) *Pipeline*

(i) Material.

(ii) Diameter.

(iii) Pipeline wall thickness.

(iv) Length of pipeline—between isolating joints.

(v) Working pressure.

(vi) Distance pipeline parallels high voltage power line.

(b) *Jointing mechanism*

(i) Welded.

(ii) Rubber ringed joint (cross bonding cables).

(iii) Other.

(c) *Coating system*

(i) Pipeline.

(ii) Field joints.

(iii) Ancillary fittings.

(iv) Resistivity.

(v) Thickness.

(d) *Off takes (quantity & locations)*

(i) Third party.

(ii) Scours.

(iii) Air valves.

(iv) Monitoring/flow equipment.

(v) Pits.

(e) *Other underground utilities* In vicinity of easement

(f) *Easement plan*

(g) *Site information*

(i) Soil data—resistivity.

(ii) Other.

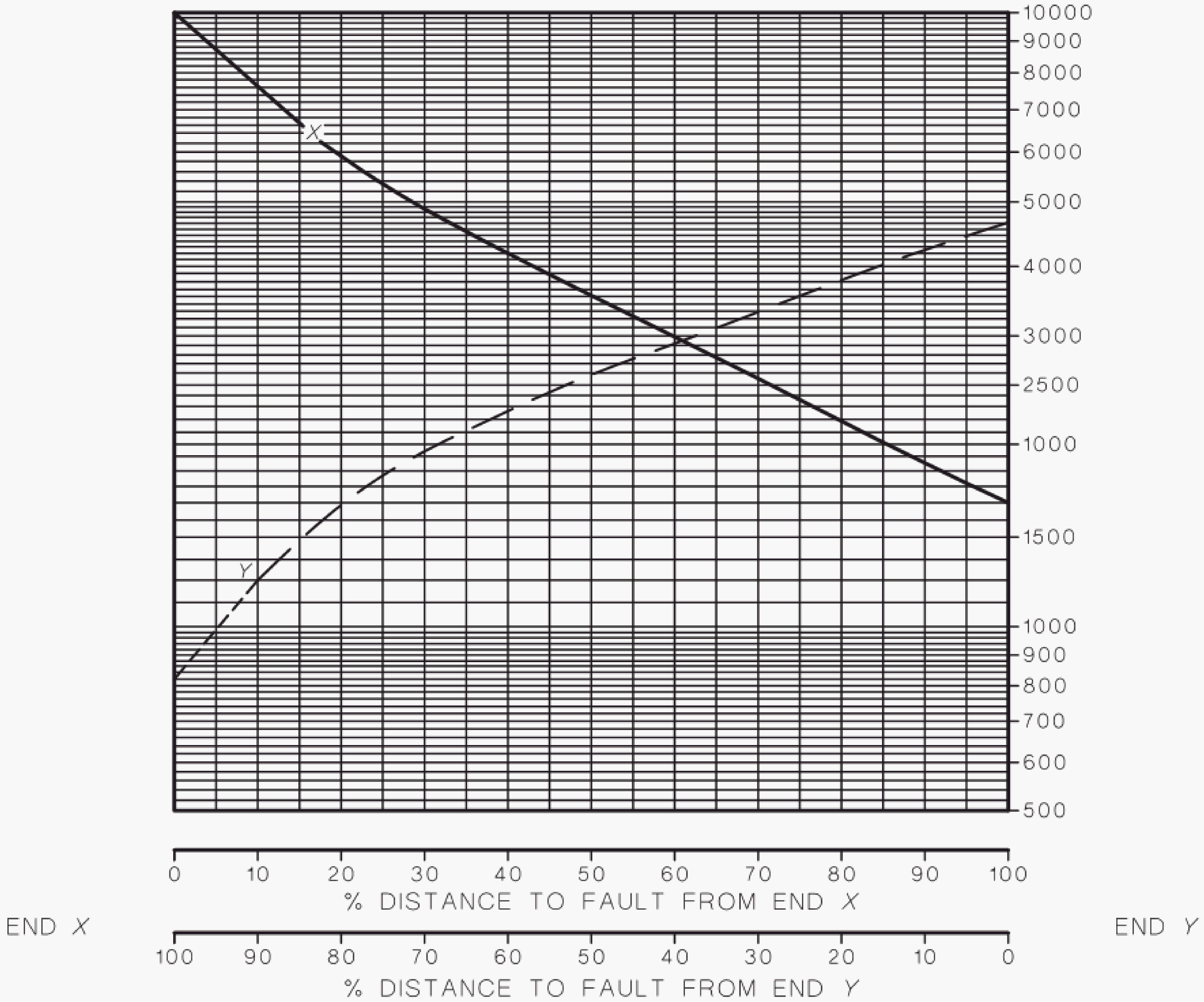
(h) *Cathodic protection*

(i) Details of proposed cathodic protection.

(ii) Test points.

(iii) Cathodic protection type.

(iv) Other.



Circuit single phase to earth fault current at rated voltage (AMP)

(Where there is more than one circuit on the same easement, this profile represents the net $3\ I_0$ of the faulted and healthy circuits)

FIGURE D4 AN EXAMPLE OF A FAULT CURRENT PROFILE

APPENDIX E

EFFECTS OF A.C. TRACTION SYSTEM ON A NEARBY PIPELINE

(Informative)

E1 TYPES OF A.C. TRACTION SYSTEM

The level of current induction from the traction line into an adjacent pipeline depends largely on the number of operating trains in the section, the train load and the traction system arrangement.

There are three basic types of a.c. traction supply system used world wide. The selection of a suitable a.c. supply system depends on many factors, including train loads, frequency of train traffic, and remoteness from supply points. The three types are as follows:

(a) Simple 25 kV system with overhead earth wire (see Figure E1).

(b) (25 kV) booster transformer (BT) system with—

  (i) no overhead earth wire (see Figure E2); and

  (ii) overhead earth wire (see Figure E3).

(c) (25 kV — 0 — 25 kV) auto-transformer system (AT) (see Figure E4).

E2 ASSESSMENT OF THE INDUCTION LEVEL INTO ADJACENT PIPELINE

E2.1 General

The mutual impedance and EMF induction are calculated using Haberland's Equation which is quoted in the CIGRE guide (Ref (f), Appendix K), as follows:

$$|Z_m| = \omega \ln\left(1 + \frac{6\times10^5\times\rho}{fd^2}\right)10^{-7}\ \Omega/\mathrm{m}$$

where

Z_m = the mutual impedance of parallel earth return conductors

ω = $2\pi f$

ln = natural logarithm

ρ = soil resistivity (Ω.m)

f = frequency (Hz)

d = geometrical distance between conductors (m)

The minimum distance between the traction overhead wires and the pipeline used in the calculation is 5 m. This represents the minimum distance (vertical) between the traction overhead wire and the rails (ground). Distances of up to 100 m from the traction overhead wires are considered in this Appendix. A soil resistivity of ρ = 100 Ω.m is considered for simplicity. Other values may be assumed. (See Appendix D).

During normal load conditions, a typical train load current that would produce the highest induction, for a critical length of parallel pipeline (exposure), is used in the calculations of the voltage induced along the pipeline during normal load on the high voltage line, EMF_n.

Under fault conditions the highest fault current, which occurs near the supply station, and which would be expected to provide the worst induction along the critical exposure, is used in the calculations of the voltage induced along the pipeline during a fault on the high voltage line, EMF_f.

NOTE: An extrapolation to longer exposures is expected to give a very conservative estimate for the induced EMF.

E2.2 Simple 25kV system with overhead earth wire

The traction system feeding arrangement and the pipeline critical exposure is shown in Figure E1. The pipeline is assumed to be parallel with the traction overhead system over the length of the exposure. This arrangement provides the highest induction per unit length from the traction line.

Table E1 displays a sample of calculations for the mutual impedances and EMF induction from the traction line into a nearby parallel pipeline.

TABLE E1

SIMPLE 25 kV SYSTEM WITH OVERHEAD EARTH WIRE
(exposure = 600 m, I_{normal} = 300 A per train)

Local parameters				Normal condition		Fault condition	
d m	ρ Ω.m	|Zm| mΩ/m	L km	I_{normal} A	EMF_n V	I_{FAULT} A	EMF_f V
5	100	0.339	0.6	300	61	10 000	2 032
20	100	0.252	0.6	300	45	10 000	1 509
50	100	0.194	0.6	300	35	10 000	1 164
100	100	0.151	0.6	300	27	10 000	904

NOTE: If the pipeline exposure extends further towards the traction feeder station (for a distance greater than 600 m) the effective load current in the overhead wire can be approximated to 60% of the load current assumed in this Table. This applies to all systems with overhead earth wire that is connected to the track at short intervals (500 m to 600 m).

For normal conditions the number of trains on the feeding section must also be taken into account.

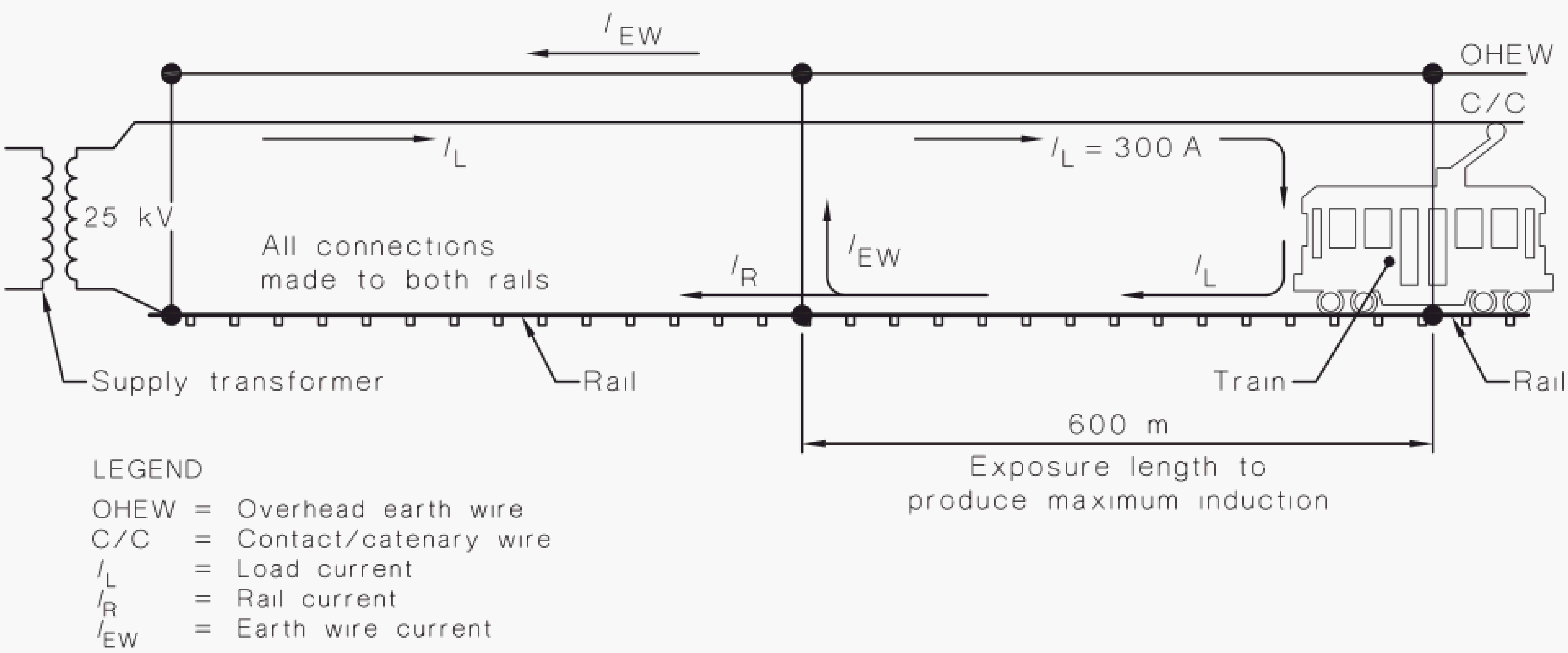


FIGURE E1 SIMPLE 25 kV SYSTEM, WITH OVERHEAD EARTH WIRE

E2.3 (25kV) booster transformer system (BT)

E2.3.1 *With no overhead earth wire*

Circuit arrangement and the influence between the traction system and an adjacent pipeline are shown in Figure E2. Results of calculating the expected mutual impedance and induction between the two systems are shown in Table E2.

TABLE E2

BT SYSTEM WITH NO OVERHEAD EARTH WIRE
(max exposure = 1.5 km, I_{normal} = 160 A per train)

Local parameters				Normal condition		Fault condition	
d m	ρ Ω.m	|Zm| mΩ/m	L km	I_{normal} A	EMF_n V	I_{FAULT} A	EMF_f V
5	100	0.339	1.5	160	81	10 000	5 079
20	100	0.252	1.5	160	60	10 000	3 773
50	100	0.194	1.5	160	46	10 000	2 910
100	100	0.151	1.5	160	36	10 000	2 260

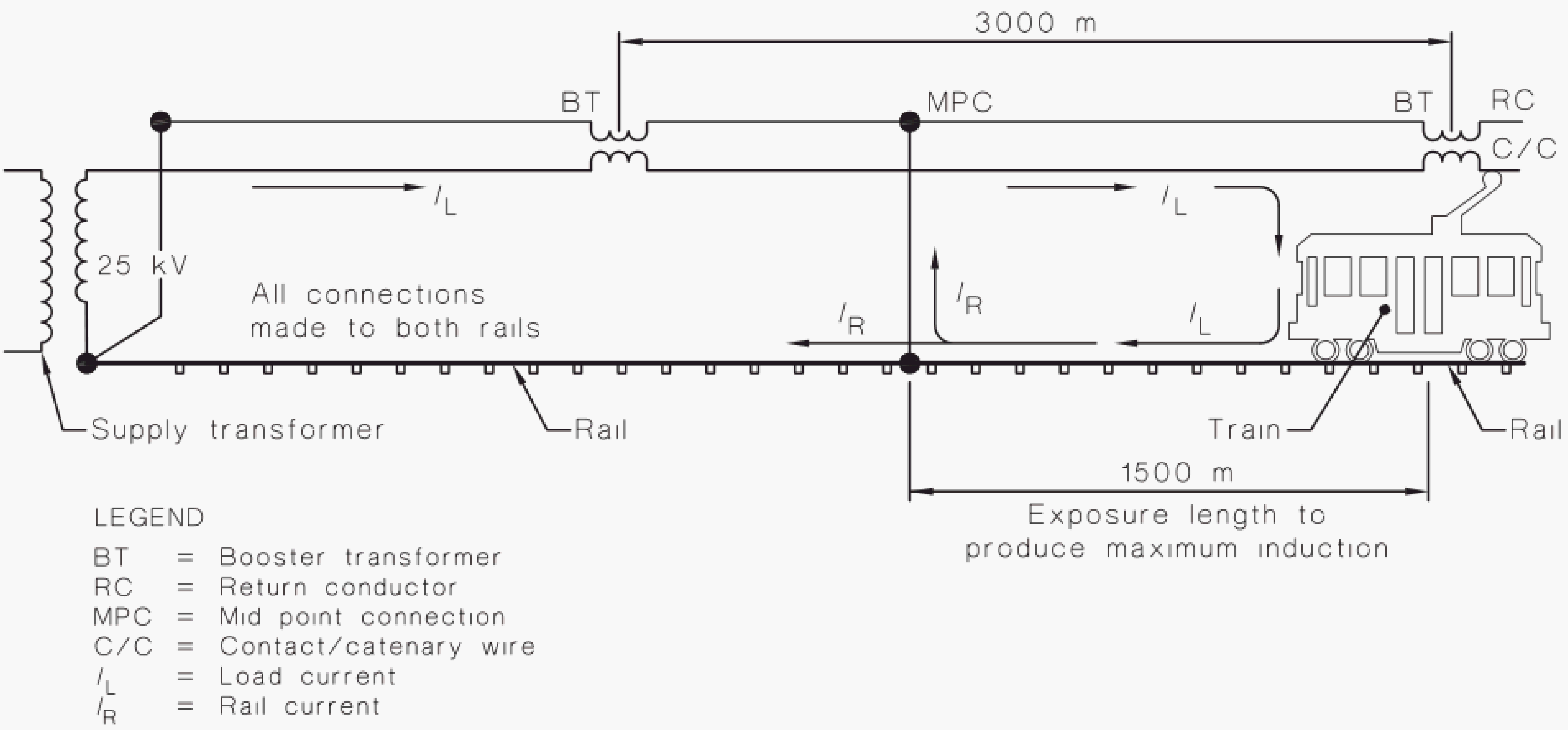


FIGURE E2 BT SYSTEM WITH NO OVERHEAD EARTHWIRE

E2.3.2 *With overhead earth wire*

Circuit arrangement and the influence between the traction system and the pipeline are shown in Figure E3. The result of calculating the expected mutual impedance and induction between the two systems is shown in Table E3. (Also see Note to Table E1.)

TABLE E3

BT SYSTEM WITH OVERHEAD WIRE SYSTEM
(max exposure = 500 m, I_{normal} = 160 A per train)

Local parameters				Normal condition		Fault condition	
d m	ρ Ω.m	|Zm| mΩ/m	L km	I_{normal} A	EMF_n V	I_{FAULT} A	EMF_f V
5	100	0.339	0.5	160	27	10 000	1 693
20	100	0.252	0.5	160	20	10 000	1 258
50	100	0.194	0.5	160	16	10 000	970
100	100	0.151	0.5	160	12	10 000	753

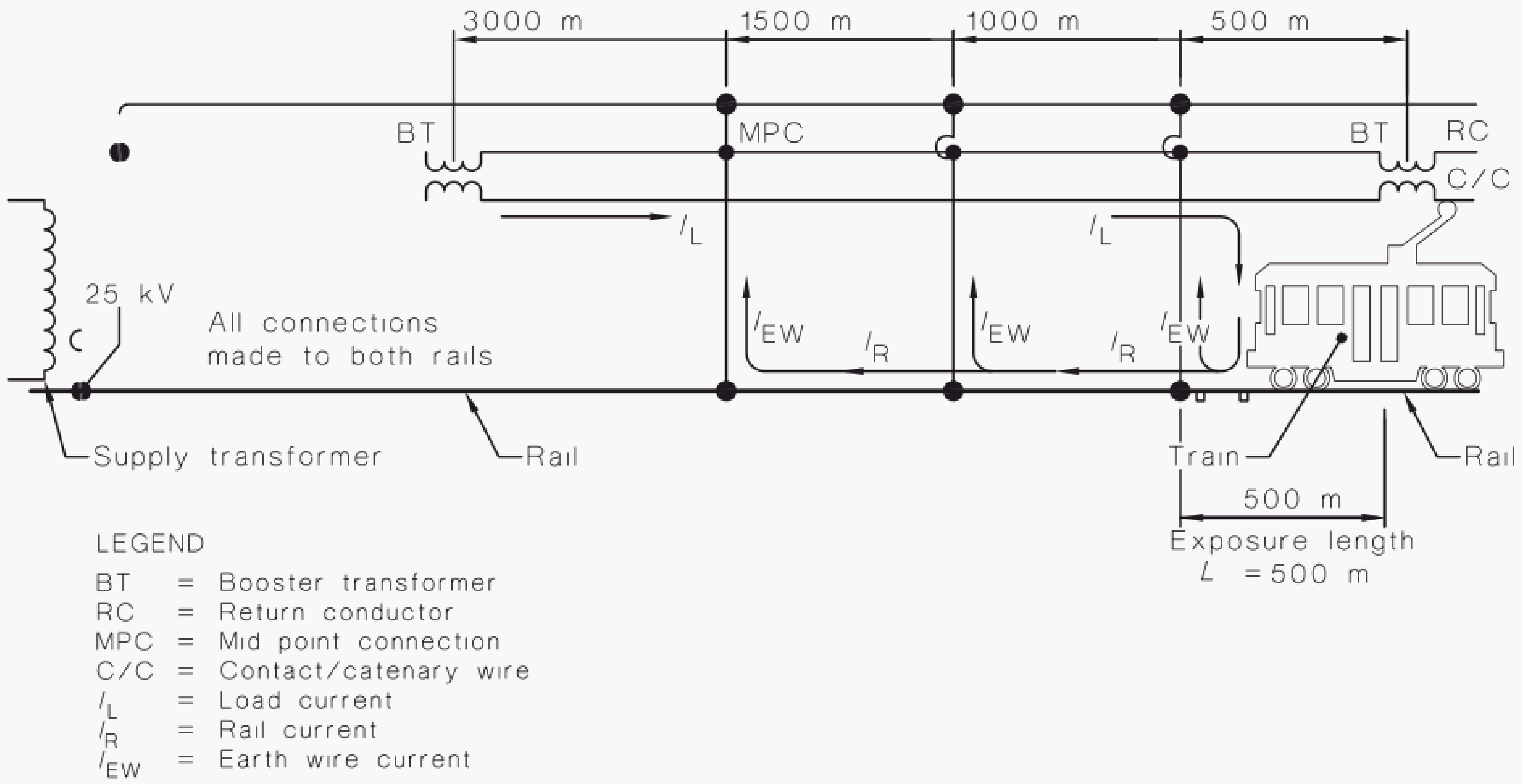


FIGURE E3 BT SYSTEM WITH OVERHEAD EARTH WIRE
(Connected to the rail at 500 m intervals)

E2.4 (25kV – 0 – 25kV) auto-transformer system (AT)

The overhead earth wire is a vital part of an AT traction supply system. Circuit layout indicating the maximum induction between the traction system and an adjacent parallel pipeline is shown in Figure E4. The calculated mutual impedance and induction between the two systems is shown in Table E4. (Also see Note to Table E1.)

TABLE E4

AT SYSTEM
(max exposure = 600 m, I_{max} = 300 A)

Local parameters				Normal condition		Fault condition	
d m	ρ Ω.m	|Zm| mΩ/m	L km	I_{normal} A	EMF_n V	I_{FAULT} A	EMF_f V
5	100	0.339	0.6	300	61	10 000	2 032
20	100	0.252	0.6	300	45	10 000	1 509
50	100	0.194	0.6	300	35	10 000	1 164
100	100	0.151	0.6	300	27	10 000	904

NOTE: For AT system, in some cases, one train can take load current from the overhead wire at locations 1 km apart.

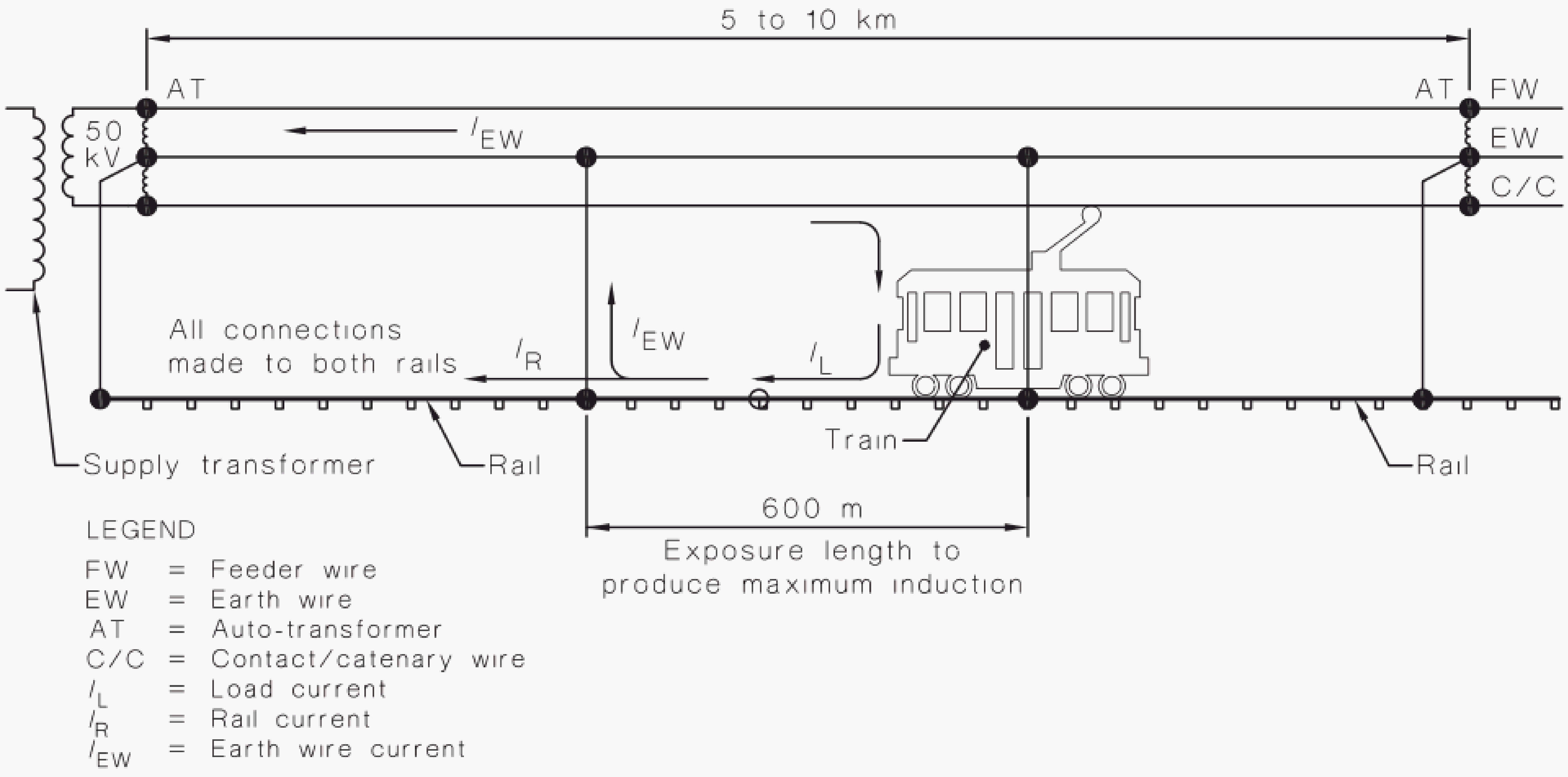


FIGURE E4 AT SYSTEM

APPENDIX F

PIPELINE LOOP IMPEDANCE

(Informative)

F1 INTRODUCTION

A pipeline under LFI coupling develops a longitudinal voltage (end to end) in the manner described in Appendices D and E, the latter case being of more frequent concern. The pipeline becomes the secondary single loop of a large 'air' core transformer, and it in turn acts as a source of a.c. voltage. The reduction of this voltage for safety reasons is usually achieved by installing an earth electrode of designed value and rating at each end of the exposure. This causes current to flow via earth path between the electrodes, and reduces the voltage at the exposed ends of the pipeline by the process described in Ohm's law.

In order to calculate the current under various earth electrode resistances, to determine the value of such resistances required, it is necessary to know the series inductive reactance of the pipeline, electrically looped through the earth.

This reactance may be determined by one of the following methods:

(a) For an existing pipeline, it may be measured as a loop impedance to 50 Hz via two end section earth electrodes (temporary, if necessary). If the LFI condition exists, the 'polarity' should be reversed and an RMS value derived, to avoid load current induction error.

Thus the inductive reactance is as follows:

$$|X_L| = \sqrt{|X_{L1}| \times |X_{L2}|} \quad \ldots \text{F1}$$

where

X_L = Inductive reactance

X_{L1} = Inductive reactance with polarity one way

X_{L2} = Inductive reactance with polarity reversed.

It is advisable to check also with a d.c. measurement to ensure no extraneous earth conditions exist. For example, trunk water mains usually are connected to scour pipes and occasional service lines which mask the earth loop measurement.

(b) If the pipeline does not yet exist, the measured value on a similarly dimensioned pipeline in a similar resistivity environment may be used. If this information is not available, a benchmark figure of $|X_L|$ = 2 Ω/km (the values usually range from 0.2 to 10 Ω) may be used for provisional calculation. In such case, an as-installed measurement should be made after construction. The main caution necessary is to ensure that the geological conditions relating to resistivity are indeed similar between the previous installation and the new project.

(c) It is feasible to derive an approximate maximum value of reactance by calculation, from virtual first principles. This is less accurate than the methods of Items (a) or (b), but will serve as a starting point when nothing else is available.

The process is to derive an inductance based on the work of Carson (Ref. (c), Appendix K) and others. Although such calculations were made for metallic copper conductors, the geometry for pipeline conductors is sufficiently similar.

Carson's work indicated that an equivalent current return path could be postulated for the three-dimensional spread of current through the earth. This would be in accordance with Thevenin's theorem. This equivalent path would be at depth *De*:

$$De = 658.37\sqrt{\frac{\rho}{f}} \text{ metres} \qquad \ldots \text{F2}$$

where

ρ = earth resistivity in ohm metres

f = the current frequency in Hertz (50)

Thus

ρ = 1	*De*	=	92 m
ρ = 10	*De*	=	296 m
ρ = 100	*De*	=	922 m
ρ = 1000	*De*	=	2962 m

It will be observed that as ρ rises to higher figures, the equivalent return depth becomes considerable.

Next, the inductance for a single vertical loop may be calculated from one of the various published equations. These invariably relate to copper wires of regular geometric pattern. The pipeline loop, however, is roughly rectangular with substantially radiused lower corners and the geometry of the pipeline and earth electrodes vary rather considerably from conventional copper conductors. The equivalent current return path cross-section through the earth is also arbitrary. The assumption is made that all current returns at the equivalent depth *De*.

If an inductive loop for a 1 m pipeline is considered with a 1 m diameter return path, through $\rho = 100\ \Omega$.m earth (for which *De* = 922 m), the inductance per km may be calculated (approximately) from—

$$L(\mu H) = \frac{0.1\, a^2 N^2}{l} \times K \text{ (Ref. (i) Ch.10, Appendix K)} \qquad \ldots \text{F3}$$

where

L	=	inductance in microhenries (Maximum achievable)
a	=	'radius' of loop, taken as 500 m
N	=	number of turns (1)
l	=	length of coil (1 m)
K	=	Nagaoka's constant (chart given in Ref. (i) relating to end effects from $\frac{a}{l}$ ratios) the figure used, $K = 0.02$

This equation is imperial, using inches (1 metre ≈ 40 inches)

$$\text{Maximum } L = \frac{0.1 \times 20\,000^2 \times 1^2 \times .02}{40} \text{ mH}$$

$$= 20\,000\,\mu\text{H}$$

$$= 20\,\text{mH}$$

$$\text{Maximum Reactance } X_{\text{L}} = 2\pi \text{ f L}\,\Omega$$

$$= 6.28\,\Omega$$

The calculation above assumes that all current returns at the equivalent depth. This is, of course, not so. The return current, in three dimensions, will diverge through various resistivity layers in accordance with Kirchoff Laws, and will also respond to various lateral resistance paths. The inductive reactance will in consequence be considerably less than the figure shown. Where no great variation in ρ occurs, the divisor may be expected to be between 2 and 3. Extreme low values of *L* will occur when ρ is very small (e.g. 0.2 Ω.m). In such cases X_L will be of the order of 0.2 Ω.

More apt processes to derive X_L have been suggested in published works by several authors. However, the most effective means is by measurement.

Capacitive current and transmission effects from the pipeline coating have been ignored. This is because the effects of capacity are of an order less than the high loop current (up to 300 A in some cases) between protection electrodes, along the pipeline.

When the inductive reactance of the pipeline is obtained, by means of Items (a), (b) or (c), it may be used to carry out earth electrode design.

F2 DETERMINATION OF EARTH ELECTRODE RESISTANCE

The determination of the required value of the exposure end earth electrode resistances is illustrated in the following example, using pipeline parameters as listed in Items (a) to (d):

(a) The exposure to HV earth fault conditions is 3 km.

(b) The calculated pipeline voltage induction under earth fault is 2000 V.

(c) Assume, from measurement on a similar pipeline in 50 Ω.m earth, that the inductive reactance is 2 Ω/km.

(d) The protection fault clearance time on the high voltage system is 100 ms. The adopted maximum acceptable voltage is 350 V (See Clause 5.3).

A simple circuit is shown in Figure F1.

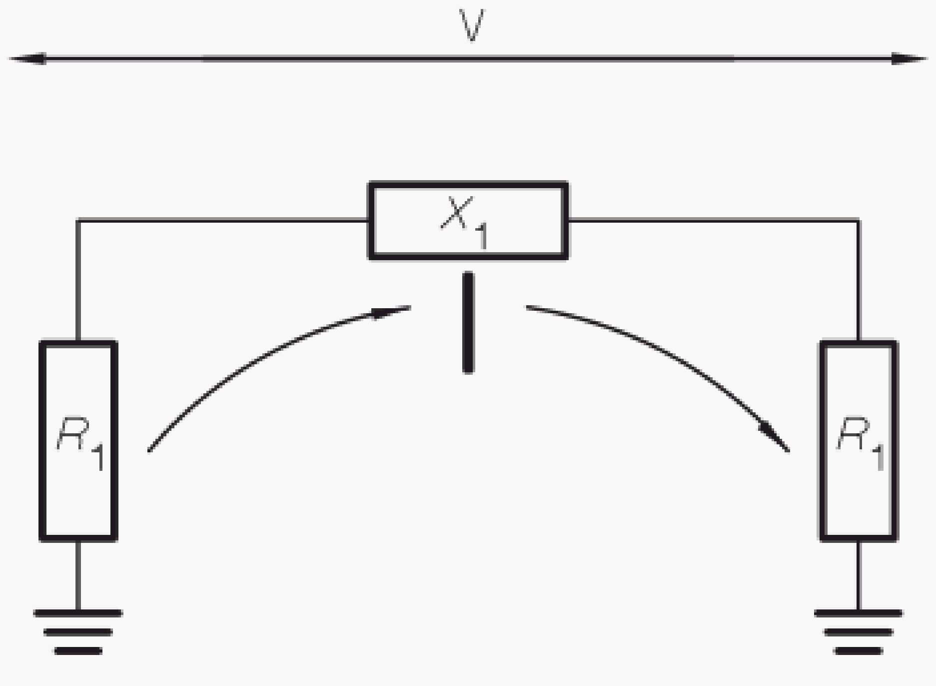


FIGURE F1 TYPICAL PIPELINE LOOP IMPEDANCE CIRCUIT

It is required that the resultant current I should not produce a voltage V_{R1} or V_{R2} (Ohm's law) in excess of 350 V (Assume $R_1 = R_2$).

$$I = \frac{V}{Z(\text{circuit impedance})} \quad \text{. .F4}$$

$$= \frac{2000}{\sqrt{(R_1 + R_2)^2 + (X_L)^2}}$$

$$= \frac{2000}{\sqrt{(2R_1)^2 + 36}}$$

This equation allows various values of earth resistances to be considered as follows:

(i) For R_1 = 0.75 Ω; I = 323 A; V_{R1} = 242 V.

(ii) For R_1 = 1.0 Ω; I = 316 A; V_{R1} = 316 V.

(iii) For R_1 = 1.25 Ω; I = 307 A; V_{R1} = 384 V.

Clearly a resistance of 1 Ω nominal is required for each electrode. The short-term current capability is 316 A for the electrode and connecting cables.

F3 OTHER OPTIONS

In a moderate proportion of cases where LFI is of serious concern, a simple current flow/voltage reduction will not offer sufficient protection based on any one of the following reasons:

(a) Resistivity of the environmental earth is too high to allow design and installation of adequately low resistance electrodes.

(b) The cost of the installation of such electrodes may be prohibitive.

(c) The very high current levels involved may be considered a security or maintenance difficulty.

In such event, several options may be applicable, though these may have specific factors that limit their adoption. These options include the following:

(i) *A Category B design to Clause 5.4* Accept a higher than optimum pipe end voltage than might be desired, but exclude access by personnel to metal work connected to the pipeline. Where access is inevitable, provide equipotential mats (Faraday cages or partial Faraday cages) around ancillary points such as valves and test points. These equipotential mats are also termed grading rings, fault current shields and other titles in different industries. In such a case, the design of the mats must ensure that they do not introduce a hazard in their own right.

In the event that some excess voltage is to be tolerated, suitable design arrangements and warning notices will usually be required at pipeline terminals to protect and/or warn operational staff of potential differences possible across isolating joints, flow monitoring equipment or other breaks in the pipeline continuity.

This option, commonly the result of high earth resistivity, would nevertheless normally include an earth electrode at each end of the exposure. These are to mitigate the severity of the LFI, at least to the level where CP converters and system telemetry systems would be not unduly stressed. Also, such partially effective electrodes could serve as effective lightning protection electrodes.

(ii) *Segmentation using isolating joints* It may be possible to segment the LFI condition by placing isolating joints at designed intervals. This allows each segment to be treated as a separate entity, though the earth electrodes for each must be placed to avoid current field overlap with the next segment. The product carried by the pipeline will have a bearing on the feasibility of this process. Hydrocarbon lines carry an insulating product, and so do not present a problem. On the other hand, a large trunk water main carries a conducting fluid, and the insertion of an isolating joint may well only add a few ohms to the pipeline continuity.

A redesign of CP systems into smaller modules will be required for this option.

(iii) *Segmentation using isolating pipe lengths* For a pipeline conveying conducting fluid, the effect of an isolating pipe length is to add a series resistance to the current flow. This series resistance greatly limits the LFI current, thus making the exposure end electrodes more effective in producing a safe level of voltage divider output. It does mean that there will be a severe voltage, momentarily, across the isolating section.

The isolating section may be either an insulating pipe, such as unplasticized PVC (UPVC) or a steel section, wholly coated, inside, outside and at joints, with a high voltage withstand, adherent polymer. Sintered polyethylene is a coating of choice for this purpose. A thickness of at least 1 mm will be required.

A redesign of CP systems will also be required for this option.

(iv) *Sequential earthing system* Allow the pipeline to remain continuous, but design an earthing system along its length to provide a mitigating sequential current loop. The design of such a system is complex, and will usually result in the installation of earth electrodes at 1 to 5 km intervals, at selected resistivity sites.

This option makes the design of fully automated CP systems, using mains powered converters, almost impossible. An alternative system is to utilize galvanic (sacrificial) metal earth electrodes for the LFI suppression.

The use of polarization cells, on long sections of pipeline, to avoid CP current loss will usually be inappropriate, as automated systems generally require more voltage ‘headroom’. This, combined with load current LFI and telluric effects, makes this arrangement unworkable.

(v) *Detailed analysis* More detailed analytic methods which model the power system and pipeline more closely may be justified. Such methods have the following advantages:

(A) Simplifying the process of determining the most cost effective mitigation measures to adopt.

(B) The ability to consider detailed interaction between particular pipeline and power network earthing system configurations.

(C) Modelling in areas with multilayered soil resistivity.

(D) Model power systems more closely with non-uniform cross-sections (i.e. varying tower impedances, overhead shield wire type and spacing) and non-parallel exposures.

(E) Model more complex pipeline protection systems such as continuous counter poise earths.

(F) Modelling power cable networks.

It must be remembered that in adopting any of the options in Items (i) to (v), the effect is modular. That is, a mitigating arrangement does not cover an unlimited length of pipeline. Voltage is progressively developed along the pipeline length and intermediate devices such as valves may show an excessive voltage.

F4 ALTERNATIVE METHOD TO DERIVE LFI FAULT VOLTAGE

There is an alternative method to derive the LFI fault voltage on the pipeline in some situations. Its reactance may also be derived. Some electricity distributors offer a commercial current injection service to determine the effect of faults on their transmission lines. This is an 'off-frequency' (usually 48 Hz) system whereby a current is passed along the line to allow measurement of its effect on other services. The specific result on a pipeline can be electrically separated from 50 Hz by a filter, and the resultant voltage measured. This current/voltage relationship can be extrapolated to the maximum value on the transmission line fault profile curve.

The voltage is measured on one end of the pipeline exposure, with the other end earthed to a test earth electrode of known resistance. Only completed pipelines, with no other earth electrodes or earth features, may be so measured.

Data for determination of pipeline reactance may also be derived by linking the measuring end of the pipeline to a local test earth electrode of known resistance. The fall in voltage allows calculation of X_L, as shown in Paragraph F1, and hence calculation of required earth electrode resistance values.

The foregoing process has a number of potential hazards and should only be carried out under the direction of a professional electrical engineer or another appropriately trained and experienced electrical supervisor.

APPENDIX G

SAMPLE CALCULATION OF INTERCEPTED CAPACITIVE CURRENT

(Informative)

G1 INTRODUCTION

This Appendix sets out a general approximation of the current interrupted by—

(a) an insulated pipeline; or

(b) a single pipe length stored or handled;

under high voltage power lines.

G2 GENERAL APPROXIMATION

An approximation of the current intercepted capacitively by an electrically continuous pipeline under a high voltage power line can be made as shown in this Paragraph.

For a 275 kV high voltage power line, the phase voltage is $275 \div \sqrt{3} = 159\,\text{kV}$.

NOTE: This value is used throughout this Appendix.

Line capacity depends on the conductor configuration. Many high voltage power lines are two wires per phase, either 380 mm or 520 mm, apart vertically. This is for both current carrying capacity and corona control.

With the slightly more onerous (higher capacity to ground) 520 mm spaced condition, calculation of the capacity for high voltage power line, installed 25 m high, gives about 0.007 μF/km. This equates to 440 000 Ω susceptance/km (Z). Current to earth is—

$$I = \left(\frac{E}{Z}\right) / \text{km} \qquad \text{. . .G1}$$

$$= \frac{159\,000}{440\,000}$$

$$= .36\ \text{A} / \text{km}$$

This is not of any immediate concern. However, in the unlikely event of an exposed, long, well-insulated pipeline, not earthed at any point, it would be quite relevant. The pipeline would not intercept all of this current, of course, but a likely proportion would be 5% to 10%.

G3 SINGLE PIPE LENGTH

A reasonably common condition is the manipulation of a single pipe length (say 20 m) under high voltage power lines. From Figure G1, it can be seen that the current through a person will depend on the value of the capacitance C.

For a reasonable approximation, the pipe length may be considered a capacitor 'plate' equal to its length by its diameter, suspended under, but about 30° to one side, of the lowest conductor. See Figure G2.

The phase conductor is a 'plate' of 520 mm width, at 60° to the plane of the pipe horizontal diameter.

As the distance between the 'plates' is several times the largest width dimension of the larger 'plate' (the pipe), the average 'plate' width may be calculated as the effective net area.

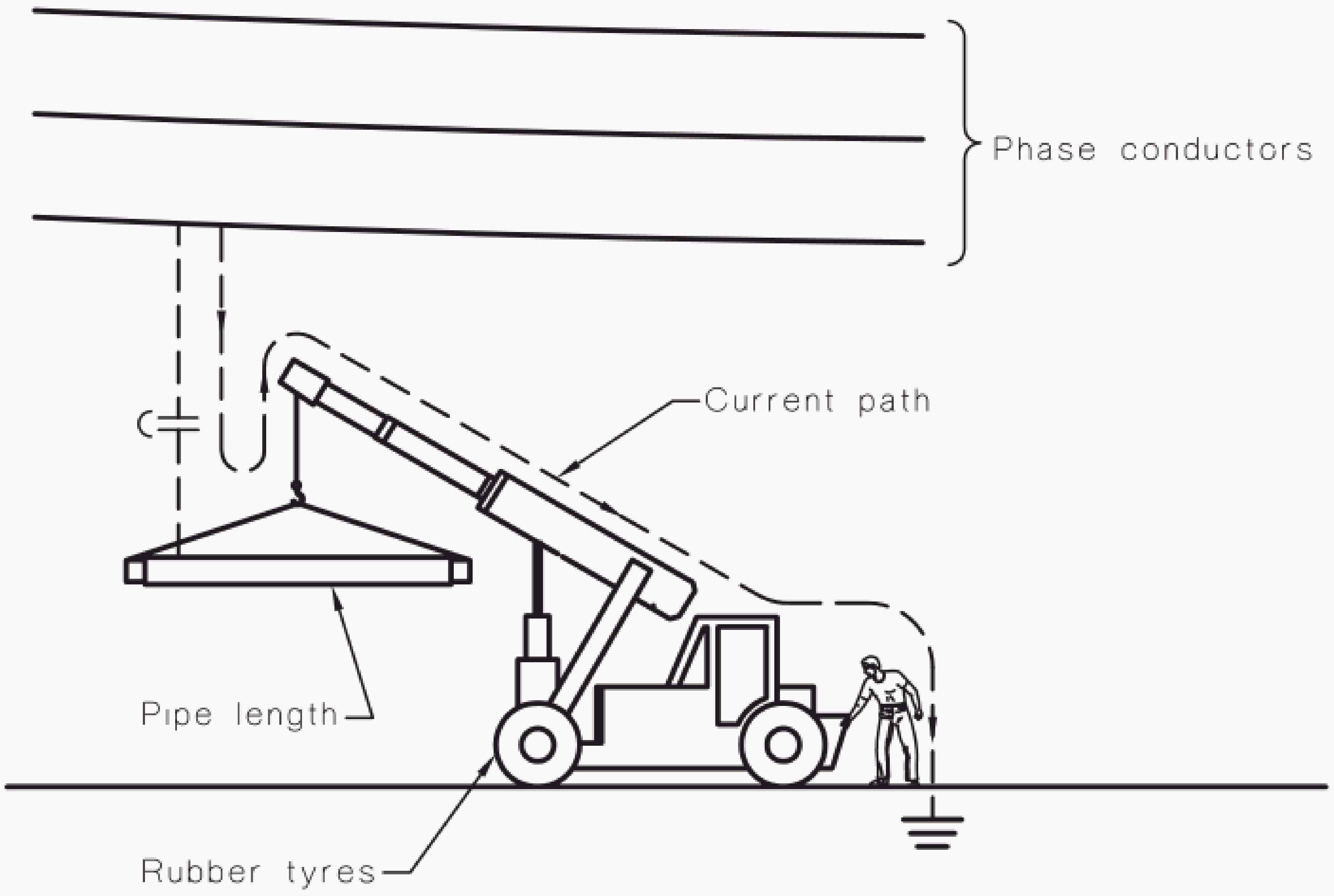


FIGURE G1 CONDITIONS RESULTING IN CAPACITIVE COUPLING FOR A VEHICLE SUPPORTING A SINGLE PIPE LENGTH

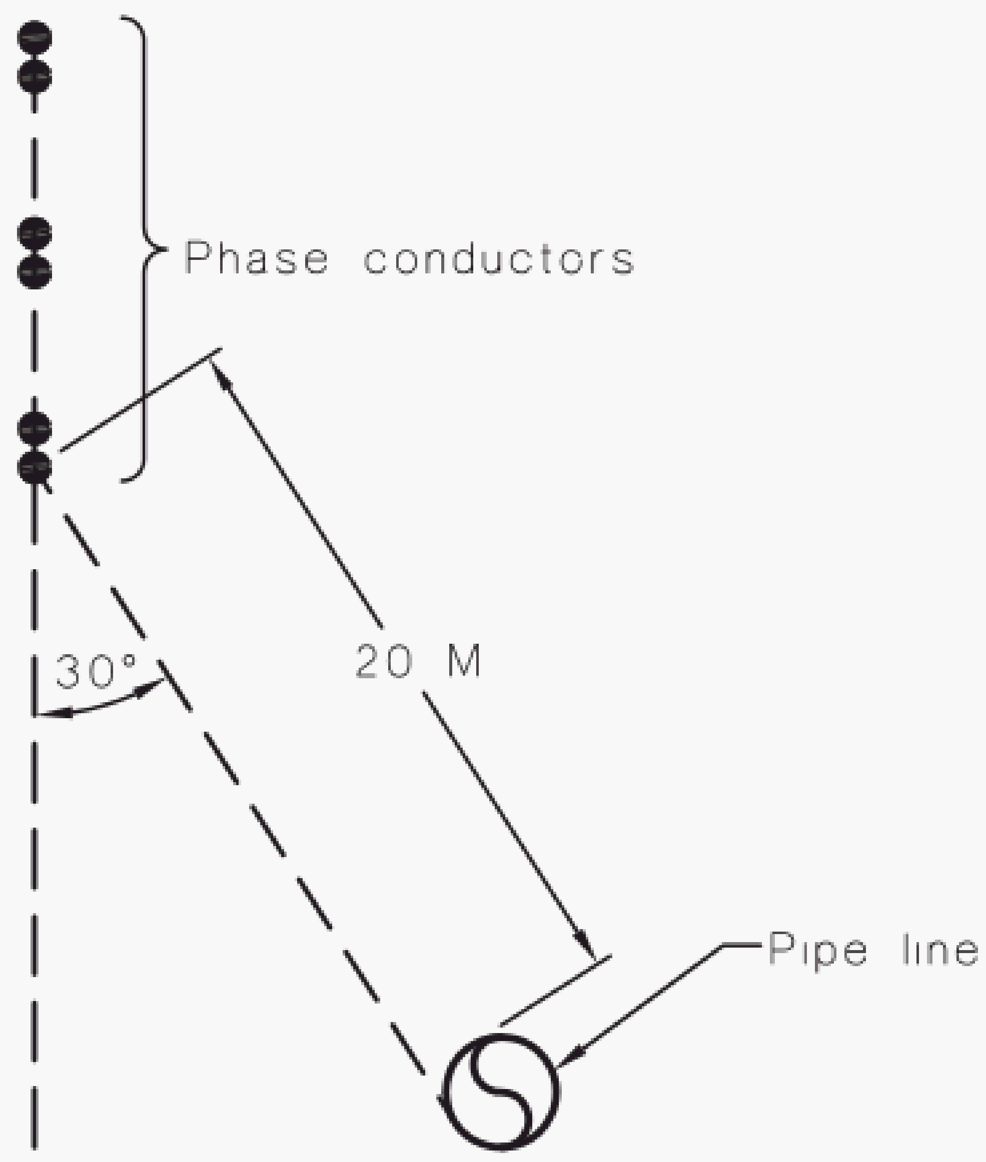


FIGURE G2 SUSPENDED PIPE LENGTH IN RELATION TO PHASE CONDUCTORS

The equation, from Langford Smith's *Radiotron Designer's Handbook* (Ref. (i)) for capacity between plates is—

$$C = \frac{KA}{11.31\,d}\ \text{pF} \qquad \ldots\text{G2}$$

where

K = 1 for air

A = length of pipeline × average width of plate (≈ diameter of pipeline)

11.31 = 4 π × 0.9; to allow for edge effect

d = distance between plates.

Using a minimum clearance distance (d) (the spacing between 'plates' pipeline and phase conductors) and 10 m, and 'plate' areas of 520 mm × length (phase conductor) and 1 m × length (pipeline). The average width is thus approximately 650 mm, allowing for the 30° orientation of the smaller 'plate' (phase conductor). Therefore for—

A (in cm) of 2000 × 65 and d of 10 m

$$C_{10)} = \frac{1 \times A}{11.31 \times 1000}$$

$$= \frac{2000 \times 65 \text{ x} 1}{11.31 \times 1000} \text{ for 10 m spacing}$$

$$= 11.5 \text{ pF}$$

$$\text{Similarly, } C_{5)} = 23 \text{ pF for 5 m spacing}$$

The dimensions of the crane should also be added to the pipe length of 20 m, but normally the crane would be at right angles to the pipe length, and hence of little consequence.

The current to earth for these two conditions would be—

$$I = \frac{E\,(=159 \text{ kV})}{X_c} \Omega$$

$$\text{at 50 Hz, } X_{c10)} = 276 \times 10^6 \ \Omega \text{ for 10 m spacing}$$

$$X_{c5)} = 138 \times 10^6 \ \Omega \text{ for 5 m spacing}$$

$$I_{10)} = 0.58 \text{ mA}$$

$$I_{5)} = 1.16 \text{ mA}$$

Neither of these currents is harmful to personnel, though it would be discernible. However, metallic contact would cause a tiny spark which could ignite fuel vapour.

G4 SUMMARY

In summary, handling of individual pipe lengths at safe distances (from the non-contact viewpoint) will not give rise to conditions electrically harmful to personnel.

Very long lengths (significant fractions of a kilometre for example) of well insulated, non-earthed pipeline could become a hazard. The electrical condition is continuous, that is, it is not subject to fault current switching or the like, and relates to the presence of phase voltage on the conductors.

If it is necessary to have a considerable length of exposed (above ground) insulated pipeline, it is advisable to keep this length to under 0.5 km. At ground level, the capacitive coupling current would be about 8 mA, which is below the 'let-go' figure of 10 mA, and certainly not in the electrical hazard area. However, it is likely that a length of 0.5 km of pipeline, above or below ground, would produce a significant fault current LFI hazard. Any protective measures (for example earth(s) for LFI control) would totally neutralize any capacitive coupling hazard. Handling techniques to mitigate possible hazards during construction should be determined in conjunction with LFI analysis and as discussed in Appendix I.

APPENDIX H
EPR NEAR A HIGH VOLTAGE INSTALLATION
(Informative)

H1 INTRODUCTION

When an earth fault occurs at a high voltage installation, the current flowing through the earthing system to earth will produce an increase in the potential of the earthing system (with respect to a remote earth). This potential rise will also affect the soil and other structures (e.g. pipelines) surrounding the earthing system.

The magnitude of the EPR of the earthing system (V_e) is given by Equation H1, as follows:

$$V_e = I_e R_e \qquad \ldots \text{H1}$$

where

I_e = the current flowing into the earthing system

R_e = the resistance to earth of the earthing system of the installation.

Therefore, to determine the maximum EPR, it is necessary to determine the magnitude of the fault current flowing to earth at the fault location, and the resistance to earth of that installation.

H2 DISTRIBUTION OF FAULT CURRENTS

Where a high voltage power line is equipped with one or more overhead earth wires (OHEW) then the current flowing into the earth at the location of the fault (I_e) is only a portion of the total fault current (I_f). This portion is given by Equation H2, as follows:

$$I_e = \frac{Z_t}{2R_e + Z_t} K_{SF} I_f \qquad \ldots \text{H2}$$

where

K_{SF} = the shielding factor of the overhead earth wire

I_f = the total fault current

Z_t = the impedance to earth via the OHEWs and surrounding towers, and is given by Equation H3.

$$\begin{aligned} Z_t &= 0.5[Z_s + \sqrt{Z_s(4R_e + Z_s)}] \\ &\approx 0.5Z_s + \sqrt{R_e Z_s} \end{aligned} \qquad \ldots \text{H3}$$

where

Z_s = the zero sequence (phase to earth) impedance of the OHEW (with earth return) per span

The determination of total fault current (I_f) is beyond the scope of this Appendix. It is normally determined by the electricity distributor using complex computer analysis and communicated via a fault current profile diagram. An example of a fault current profile is given in Figure D4, Appendix D.

The OHEW shielding factor (K_{SF}) is a measure of the inductive effect of the fault current on the current flowing in the OHEW. Fault current flowing in the faulted line will induce an opposing current in the OHEW, thus reducing the current to earth at the fault point. The more shielding provided by the OHEW, the lower the shielding factor.

H3 CALCULATION OF RESISTANCE OF EARTH SYSTEM

H3.1 General

Various forms of electrodes are used for earthing. These include electrodes installed solely for earthing purposes and other connected, buried metallic structures. The two types are primary earth electrodes, and auxiliary earth electrodes.

Earthgrids, counterpoise conductors and earth rods are typical primary electrodes.

Underground metallic structures, overhead earthwires, underground cable sheaths and reinforcing bars encased in concrete, if connected to the grounding grid, are typical auxiliary electrodes.

H3.2 Primary electrodes

Assuming homogenous resistivity, earth resistances can be calculated using simple equations, as follows (see also Figure H1):

(a) *For a simple vertical rod* As given by Equation H4, as follows:

$$R = \frac{\rho}{2\pi L}\left[\ln(4L/r) - 1\right] \qquad \text{. . . H4}$$

where—

R = resistance in ohms

ρ = earth resistivity in ohm metres (Ω.m)

L = length of rod in metres

ln = natural logarithm

r = radius of rod in metres.

(b) *For a buried horizontal wire* As given by Equation H5, as follows:

$$R = \frac{\rho}{\pi L}\left(\ln\frac{2L}{\sqrt{2DR}} - 1\right) \qquad \text{. . . H5}$$

where

L = length of buried wire in metres

R = radius of wire in metres

D = depth of burial in metres

(c) *For a buried large flat plate* As given by Equation H6, as follows:

$$R = \frac{\rho}{4}\sqrt{(\pi/A)} = 0.44\,\rho\,/\sqrt{A} \qquad \text{. . . H6}$$

where

A = area of the flat plate in square metres.

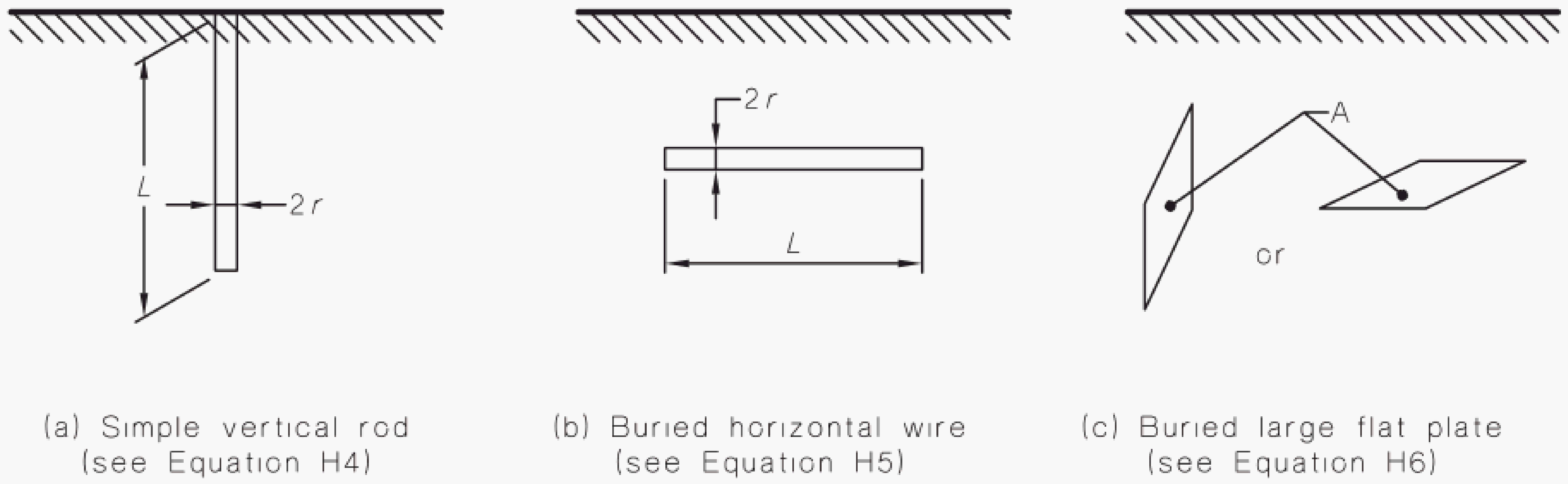


FIGURE H1 DETAILS OF PRIMARY ELECTRODES

H4 DETERMINING SURFACE VOLTAGE CONTOURS

H4.1 General

Two methods of calculating voltage contours are described in Paragraph H4.2. The first assumes a known earth resistivity, and the second a known earth system resistance.

These calculations often yield conservative results, therefore it may be economically beneficial to undertake more detailed modelling or carry out field tests if the initial calculations indicate further action is necessary.

H4.2 Surface voltage gradients

H4.2.1 *Only earth resistivity known*

The simplest earthing system to analyse is a hemispherical earth electrode. A hemispherical earth electrode in a homogenous earth will produce hemispherical contours of equipotential voltage. The resulting voltage profile for the potential (V) at a point near the earthing system with respect to remote earth is given in Equation H7 (see Figure H2), as follows:

$$V_r = \frac{\rho I}{2\pi\ r_x} \qquad \text{for } r_x > r_e \qquad \text{. . .H7}$$

where

V_r = voltage at r_x in volts

ρ = the earth resistivity in ohm metres (Ω.m)

I = earth current in amperes

r_e = radius of an equivalent hemispherical earth in metres

r_x = distance from the centre of the earth grid in metres.

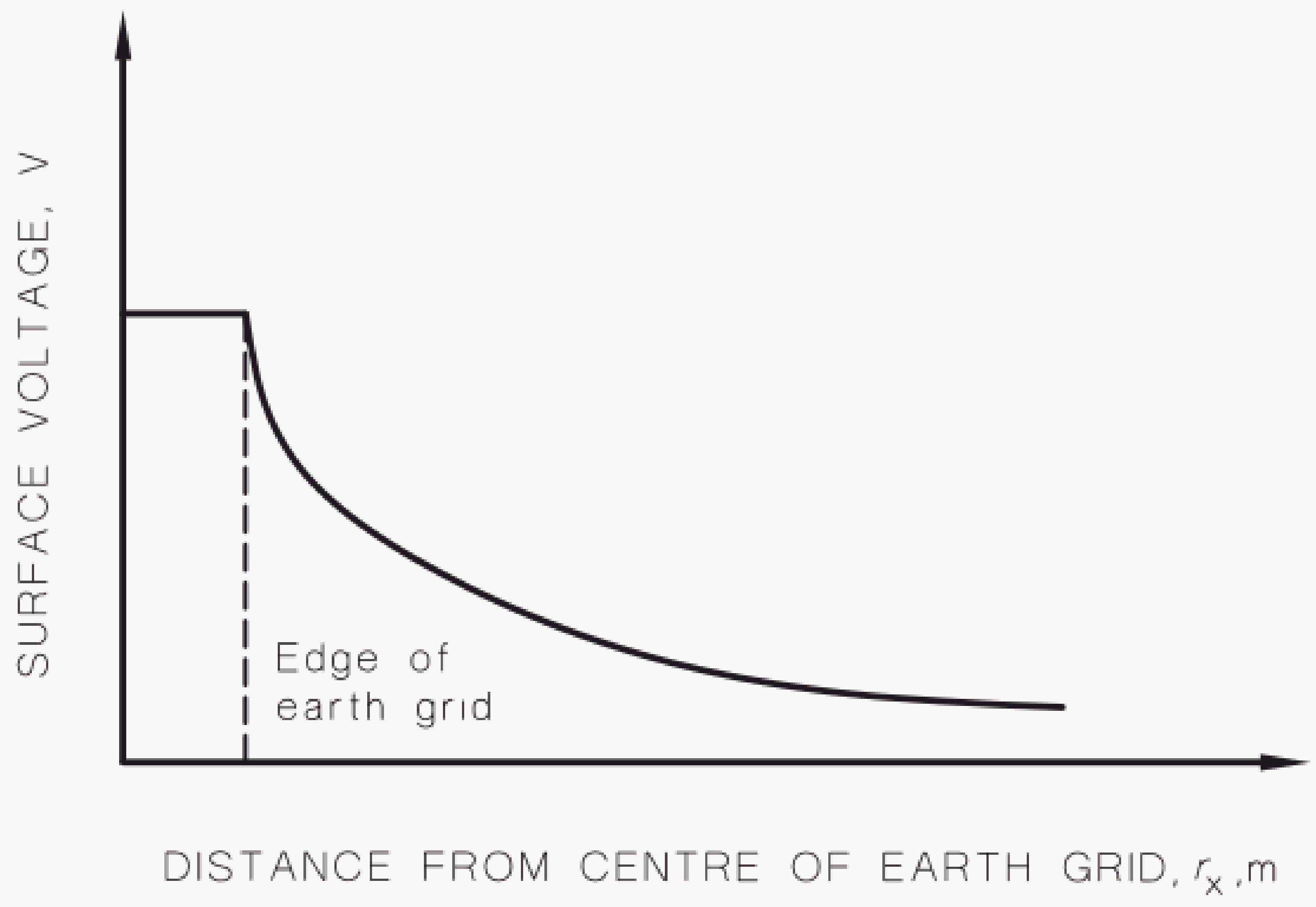


FIGURE H2 TYPICAL SURFACE VOLTAGE GRADIENTS

H4.2.2 *Grid resistance known*

For most practical situations the earth resistivity is not known with sufficient accuracy or the earth is not uniform. Often, however, the earth resistance and dimensions may be known along with the maximum earth fault current. Accordingly, the maximum EPR can be calculated. For this purpose, the following Equation H8 is more useful:

$$V_x = V_{grid} \frac{r_e}{x + r_e} \quad \text{. . . H8}$$

where

V_x = voltage at distance x in volts

V_{grid} = EPR in volts

r_e = radius of an equivalent hemispherical earth in metres

x = distance from the edge (or corner) of the earth grid in metres.

Equation H8 also shifts the profile so that the surface voltage equals the EPR at the edge of the grid. However, this affects the accuracy slightly (voltage increase) far from the grid. Inside the grid, the voltage should be close to the EPR.

In general, values of equivalent hemispherical earth electrode radius can be obtained as follows:

(a) *For a surface plate* As given by Equation H9, as follows:

$$r_e = 0.3592\sqrt{A} \quad \text{. . . H9}$$

where

A = area of earth grid in square metres.

(b) *For a driven rod* As given by Equation H10, as follows:

$$r_e = \frac{l}{\left[\ln\left(\frac{8l}{d}\right) - 1\right]} \qquad \text{. . . H10}$$

where

l = driven depth of the rod in metres

d = diameter of the rod in metres.

Equations H9 and H10 are derived from simplified considerations of the items. Accordingly, for more complicated structures, e.g. large substations, it is better to measure the resistance of the earth and the earth resistivity and to calculate the equivalent hemispherical electrode radius from Equation H11, as follows:

$$r_e = \frac{\rho}{2\pi R_e} \qquad \text{. . . H11}$$

where

R_e = resistance of the electrode in ohms.

Where the resistance of the earth grid is not known, a value of half the largest dimension of the grid may be used, but the result will probably be very conservative as r_e is in Equation H8.

H4.3 Limits for the application of simplified calculations

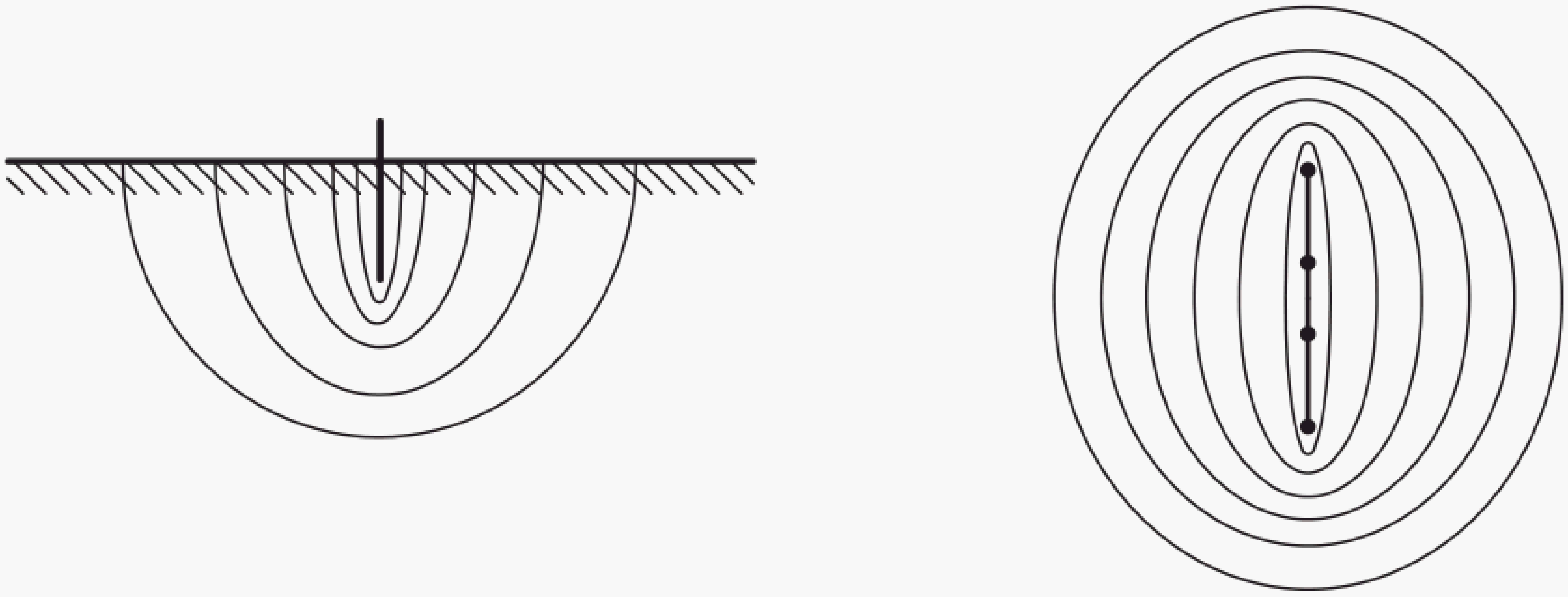
H4.3.1 *General*

The simplified calculations are based on an ideal situation in which a hemispherical earth electrode is installed in an even and continuous earth (homogenous resistivity). Limitations are described in Paragraphs H4.3.2 to H4.3.4.

H4.3.2 *Non-hemispherical earthing systems*

Real earths are not hemispherical, although from a distance there is little difference between the voltage contours of a non-hemispherical earth electrode and the equivalent hemispherical earth electrode. In close proximity, however, there can be significant differences between different earth electrode shapes. Figure H3 illustrates how the equipotential contours of a single earth electrode and a linear array vary from a hemispherical earth electrode up close and how the contours get closer to the hemispherical pattern as the distance from the earth electrode increases.

To minimize the errors from this proximity effect the simplified calculations should only be used for distances greater than five times the maximum dimension of the earth electrode. For distances less than this detailed calculations or measurements should be used to ensure that the EPR values are realistic.



(a) Single rod (profile) (b) Linear array of rods (top view)

FIGURE H3 VOLTAGE GRADIENTS OF NON-HEMISPHERICAL EARTHING SYSTEMS

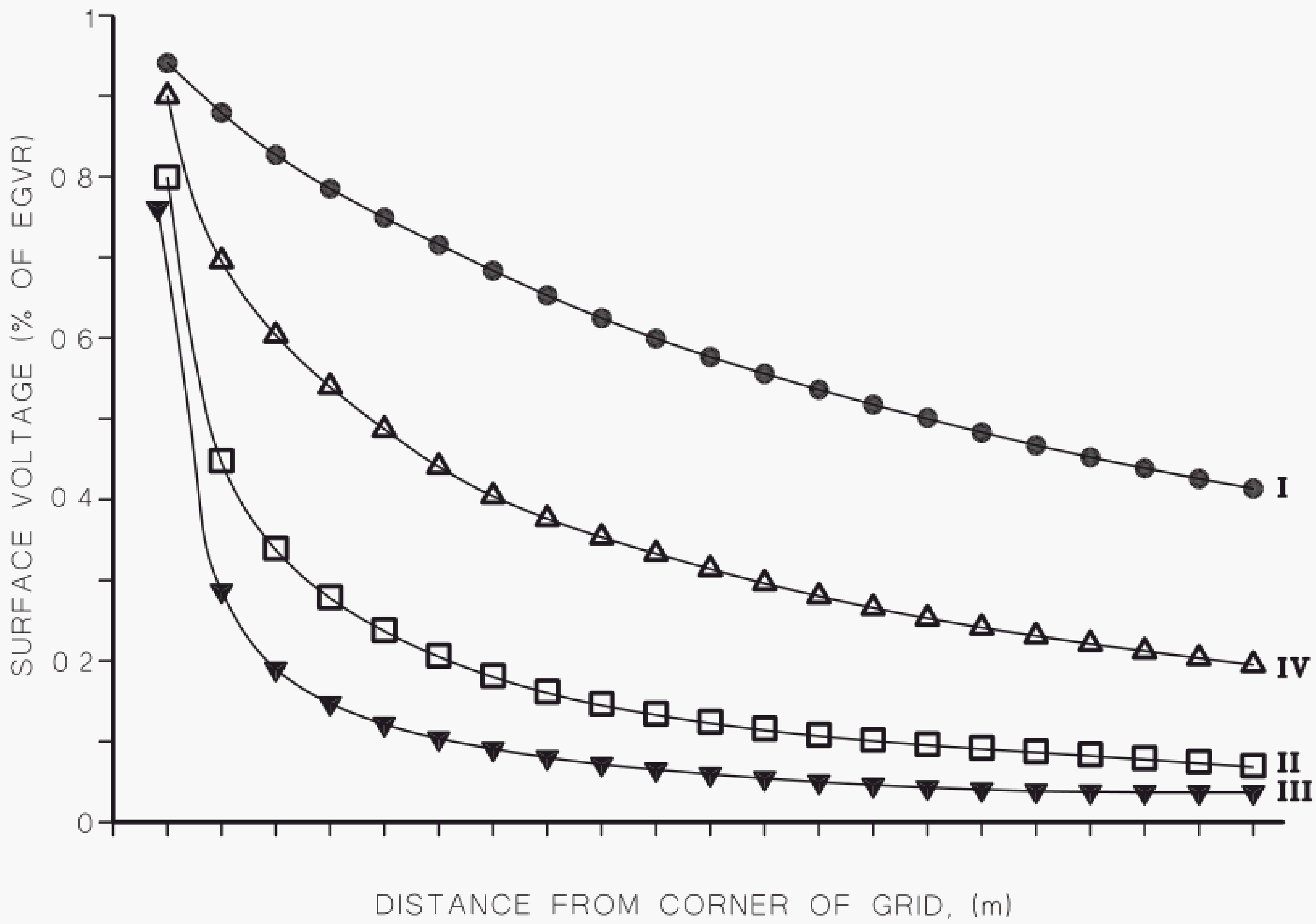
H4.3.3 *Multilayer earth resistivity effects*

The simple calculations described assume that the earth is uniform, with a constant resistivity. Most soils are layered, with each layer having a different resistivity. If the value of the resistivity in different layers is of the same order of magnitude then the highest value can be used to generate conservatively approximate values from the simple calculations. Where the earth system is deep enough to penetrate an area of relatively constant resistivity, that value of resistivity can be used in conjunction with the penetration depth of the earthing system into the lower layer for the purposes of simple calculations. Where the variations of resistivity are complex or of very large values, detailed calculations or measurements should be used to ensure the EPR values are realistic. Supplementary information from geological data is also helpful in assessing resistivity at depth. Figure H4 provides an indication of the variation in voltage profile with soil resistivity changes.

H4.3.4 *Conductors extending the EPR*

For locations where other underground services exist there is a risk that the EPR zone will be distorted by conductive services running through or near the site. See Figure H5 for the effect.

In addition, where underground services (cable sheaths, buried conductors) and overhead earth wire conductors connect adjoining earths, the EPR may be transferred to the adjoining structures. Where other services are concerned, details of the coupling to these services or the earthing effect of them might be unknown. In these cases the resulting EPR effect may be established by more detailed analysis or measurement.



NOTES:

1 The voltage profiles are intended to be indicative only, and relate to the following cases:

Case I: Equation H8

Case II: ρ = 100 Ω.m, R = 2.04 Ω

Case III: ρ_1= 10 Ω.m (5 m depth), ρ_2 = 100 Ω.m, R = 0.41 Ω

Case IV: ρ_1= 100 Ω.m (5 m depth), ρ_2 = 10 Ω.m, R = 0.64 Ω

2 The grid comprises four 10 m meshes with a 10 m stake at each of the four outside corners, where ρ_1 = top layer resistivity of depth 5 m, and ρ_2 = lower layer resistivity.

FIGURE H4 EFFECT OF SOIL RESISTIVITY ON SURFACE POTENTIAL GRADIENTS

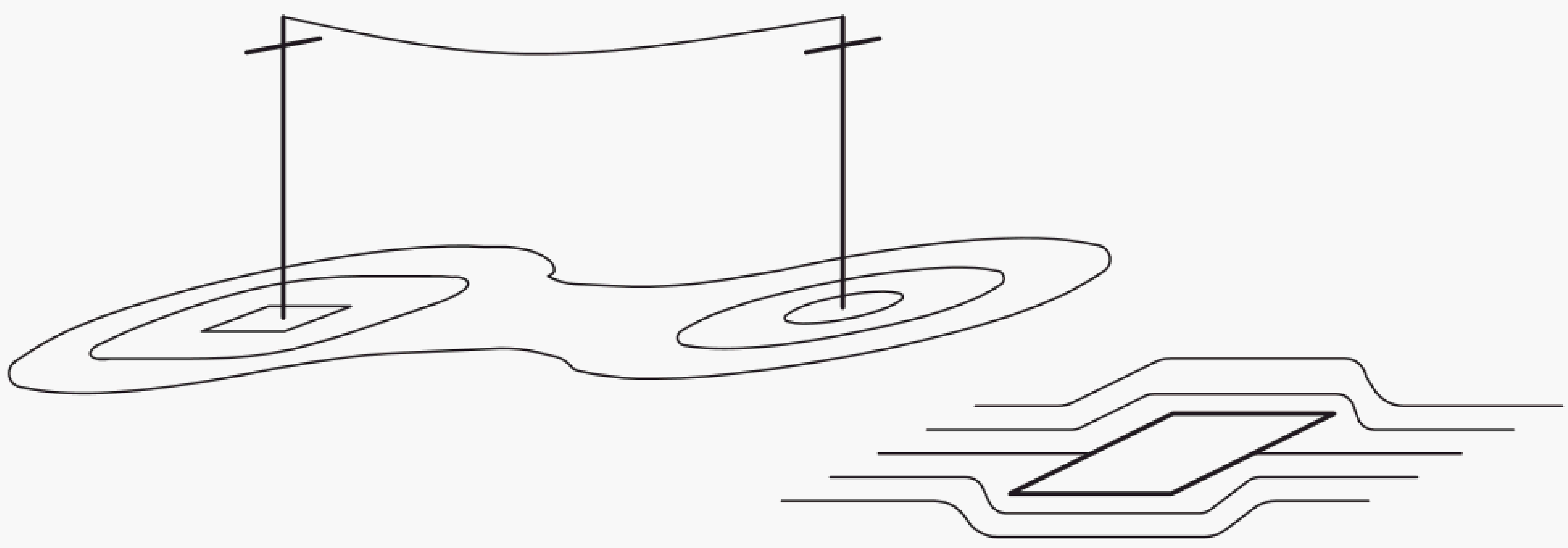


FIGURE H5 DISTORTION OF EPR CONTOURS

H5 EXAMPLE—EARTH POTENTIAL RISE SURROUNDING A 275 KV TRANSMISSION TOWER

H5.1 Parameters

Earthing for each tower consists of four, 5 m deep footings of 300 mm radius approximately 8 m apart.

Total fault current (from fault current profile) .... I_f = 9000 A.

Soil resistivity (from 4 pin test)... ρ = 200 Ω.m.

Shielding factor of dual overhead earthwire .... k = 0.8.

Impedance of dual overhead earthwire per span... Z_s = 0.33 Ω.

H5.2 Resistance of tower footing

The resistance of each tower leg can be determined from Equation H4, as follows:

$$R_{\text{each leg}} = \frac{\rho}{2\pi L}\left[\ln\left(\frac{4\times L}{r}\right) - 1\right]$$

$$R_{\text{each leg}} = \frac{200}{2\pi 5}\left[\ln\left(\frac{4\times 5}{0.3}\right) - 1\right]$$

$$= 5.25\,\Omega$$

The combined resistance of the four tower legs (assuming that they are sufficiently separated so that their mutual resistance is not significant) is—

$$R_e = \frac{R_{\text{each leg}}}{4}$$

$$= \frac{5.25}{4}$$

$$= 1.31\,\Omega$$

NOTE: A more accurate value of the combined resistance, including mutual impedance between the electrodes, may be obtained using the nomogram given in Figure 7.2 of ESAA-EGI(97). From this nomogram R_e = 1.8 Ω, which is used in the calculations in Paragraphs H5.3, H5.4 and H5.5.

H5.3 Earth fault current

The current flowing into the ground can be determined from Equations H2 and H3, as follows:

$$Z_t = 0.5[Z_s + \sqrt{Z_s(4R_e + Z_s)}]$$

$$Z_t = 0.5[0.33 + \sqrt{0.33(4\times 1.8 + 0.33)}]$$

$$= 0.95\,\Omega$$

$$I_e = \left[\frac{Z_t}{2R_e + Z_t}\right] K_{SF} I_f$$

$$I_e = \left[\frac{0.95}{2\times 1.8 + 0.95}\right] 0.8\times 9000$$

$$= 1503\text{ A}$$

H5.4 Earth potential rise

The EPR of the earthing system can then be calculated from Equation H1, as follows:

$$V_e = I_e R_e$$

$$= 1503\times 1.8$$

$$= 2705\text{ V}$$

H5.5 Surface voltage contours

Using the value of R_e calculated in Paragraph H5.2, the radius of the equivalent hemisphere (r_e) can be determined from Equation H11, as follows:

$$r_e = \frac{\rho}{2\pi R_e} = \frac{200}{2\pi 1.8} = 17.7 \text{ m}$$

The surface voltage contours surrounding the tower can be calculated from Equation H8, as follows:

$$V_x = V_{grid} \frac{r_e}{x + r_e}$$

where

x = the distance from the tower leg.

Consider a case of an insulated pipe which passes within 10 m of the tower. The voltage of the surface of the soil 10 m from the tower is given as follows.

$$V_{10} = 2705\left[\frac{17.7}{10+17.7}\right] = 1728 \text{ V}$$

Therefore, if the coating of the pipe will not withstand 1728 V, in the event of a fault, a breakdown may occur and current would be conducted away via the pipe. This could cause a hazardous situation at a remote location. This may also damage insulating flanges or CP equipment, as well as providing a leakage point for CP current in the future. The effect would be moderated by the impedance of the pipeline to earth.

If there was a point where the pipe could be accessed at that location (e.g. manually operated valve), then personnel would be exposed to this voltage. The distance required to be below the safe limit of 350 V can be calculated from Equation H8, as follows:

$$350 = 2705\left[\frac{17.7}{x+17.7}\right]$$

$$x = 119 \text{ m}$$

That is, the EPR would be reduced to the safe limit of 350 V at a point 119 m from the tower.

H6 MITIGATION

Pipelines which run parallel to high voltage power lines should be routed as far as possible from the high voltage earthing systems. Pipeline facilities (valves, CP test points, etc.) should, whenever possible, be positioned about midspan of the high voltage power line towers.

For pipelines which are not parallel, but which cross high voltage power lines, the pipeline facilities should be positioned as far as possible from the high voltage earthing systems.

It is accepted in the pipeline industry that the minimum separation from the high voltage earthing system is 3 m. (Also see calculation in Paragraph H5.5) This may not prevent minor coating damage but should, in conjunction with an appropriate pipeline earthing system, minimize risk to personnel and damage to pipeline metal.

Consequently options available for protection of personnel include the following:

(a) Insulate and isolate all accessible pipe facilities.

(b) Provide a Faraday cage to house or surround accessible facilities.

The insulation of valve spindles is feasible enough, but where valves, metering equipment and isolating joints have to be worked on, or tested, this is not an option. It is restricted, therefore, to items like air valves, where there is no below-ground access.

The provision of a Faraday cage is more of an industry standard, though the format varies greatly in different countries. Faraday cages, or more often partial Faraday cages, are also termed 'fault current shields', 'grading rings' or 'equipotential zones'. A typical arrangement, for an access hole siting of a pipe stop valve, is depicted in Figure H6.

NOTE: An alternative system can be produced external to the pit by fitting metallic rings around the pit and bonding them to the pipeline.

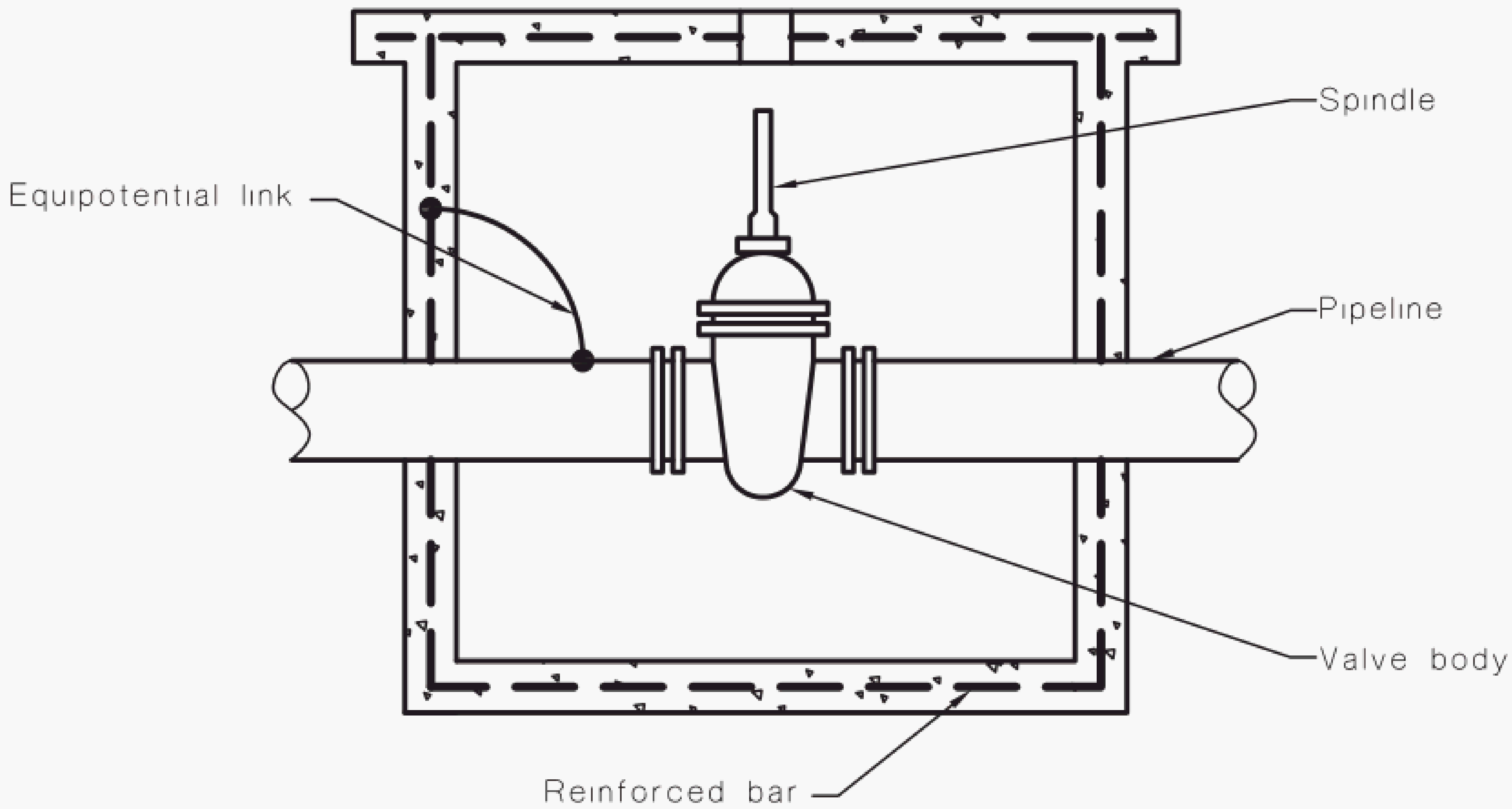


FIGURE H6 FARADAY CAGE CONCEPT FOR EPR AT VALVE

Essentially, a metal mesh is arranged to surround the pipe facility. This mesh is, by convention, also the reinforcing mesh for the access hole, and must be bonded at all gaps in the mesh to the next section. The whole assembly is then bonded to the pipeline, or to the valve assembly if this is more convenient.

If then, the EPR condition rises around the access hole, an operator inside experiences no effect, as the mesh potential, and therefore the surface of the concrete, is at pipe potential. The pipe, of course, will discharge any current picked up by the mesh to some distant point, probably the LFI suppression earth electrodes at the ends of the exposure section.

This form of Faraday cage may be reduced to merely the slab cover if no below-ground access is required. A slab platform, with a valve spindle hole in the centre, bonded to the slab mesh provides a safe working platform. A further abbreviated form of cage is the 'gradient ring', a surface conductor ring at ground level, bonded to the pipeline. This gives some protection but is not totally effective, as the electric field will normally penetrate under the ring conductor, and possibly expose an operator to EPR between the vertical component and the pipe, at distant earth potential.

Faraday cages also provide protection at exposed access points, where the effect of LFI can be experienced. In this case the pipeline is 'live', but access to local earth is blocked by the presence of the cage mesh.

Some installations around the world make the Faraday cage of solid zinc bars. These are placed on either side of the pipeline, to pick up EPR current on one side and discharge it on the other side (a slightly simplistic concept). Also, if the pipe coating is damaged the zinc provides CP accordingly (again, a rather simplistic approach).

The above system requires attention from specially knowledgeable staff. The condition of a progressively corroding zinc cage system is very difficult to monitor by testing. It may well be that the segment of the electrode system required to equalize fault current (EPR conditions) has been sacrificed by CP current generation. Yet the electrode would test 100% at an overall surface connection.

There is good reason to provide separate protection electrodes, Faraday cages and CP electrodes to provide optimum performance for each function. Galvanized steel electrodes, which share CP current with the pipeline, will have a long life and will always be effective.

APPENDIX I

MECHANICAL HANDLING OF PIPE LENGTHS

(Informative)

I1 MECHANICAL HANDLING EQUIPMENT

If mechanical equipment used to handle the pipe lengths is rubber tyred, it is possible the equipment will not be earthed. Where this equipment can extend parts of its machinery above the driver's seat, both the machinery or the pipe lengths being transported may be in a dangerous proximity to overhead power lines.

NOTE: Rubber tyres usually contain carbon particles and while tyres are able to provide a degree of insulation at low voltage, they may conduct and catch fire when exposed to high voltages.

Local electrical authorities can provide confirmation of heights of overhead power lines and the operating voltage of all overhead conductors. They can normally also advise on the recommended clearance plant such as cranes, side booms and unloading machines should maintain from the overhead conductors.

Plant operators should also take precautions to provide a trailing earth to pneumatic-tyred machinery that is poorly earthed. Such an earth would provide protection only against sparking from capacitive coupling but no protection for personnel against contact with the overhead conductors.

I2 HANDLING WELL-COATED PIPE IN THE VICINITY OF HIGH VOLTAGE POWER LINES

Handling short lengths of pipe or long welded strings of pipeline can pose a hazard when in close proximity to high voltage power lines. This problem is increased where lifting slings or gear are made from non-conductive materials such as webbing.

In such circumstances, it is recommended that the pipe in question be provided with a temporary earth.

I3 HANDLING LONG LENGTHS OF PIPE STRINGS

It is normal construction practice for pipelines to complete long lengths of pipe above ground prior to lowering the pipe strings into the trench. This usually also includes reinstatement of the pipeline's coating system over the entire length of the pipe string. This operation usually includes the pipe being supported in the above-ground position on high resistance skids such as timbers, sand bags or similar.

It is therefore only practicable to earth the pipe strings at each end of the string. However, at locations where the pipe strings are dangerously close to the overhead high voltage power lines or towers and this may cause hazardous voltages on the pipe strings, it is recommended that the pipe strings be fitted with a temporary earth on both ends. A similar requirement is necessary for holiday testing of the pipe strings in the above-ground position.

NOTE: Due to the high coating resistance of new pipelines, the use of timber skids to support the pipe will accentuate the above problem.

I4 STORAGE OF PIPE BELOW HIGH VOLTAGE POWER LINES

If, due to restricted space in narrow construction easements, it is necessary to store or stockpile pipe below a high voltage power system, it is possible that the pipe lengths may intercept the electric field from the high voltage power line and present a hazard. (See Appendix G.) This should therefore be avoided where possible. Otherwise, appropriate precautions should be taken to ensure that the pipe is adequately earthed during storage and/or handling.

I5 PERSONNEL PROTECTION

I5.1 Protective clothing

As workers may be exposed to hazardous induced voltages they should wear insulated footwear when working on pipelines that are installed parallel to high voltage power lines. The footwear should have rubber or elastomer soles and be maintained in good condition. Also as workers would be required to connect and disconnect any earthing or bonding conductors required, they should wear insulated gloves providing covering of the hands and forearms.

I5.2 Protective equipment

Equipotential mats should be used when welding or jointing pipelines and when restoring coating on pipelines that are installed parallel to high voltage power lines. Suitable mats consist of a metallic mesh with a bonding conductor connected to the pipeline.

The mats are intended to ensure no hazardous voltages can appear between the pipeline being worked on and the adjacent earth.

I5.3 Measuring tapes

All measuring tapes used when working on pipelines that are installed parallel to high voltage power lines should be of non-metallic construction. Nylon or other plastic tapes with a metal strengthening core are not acceptable.

APPENDIX J

INTERACTION OF CATHODIC PROTECTION SYSTEMS WITH PIPELINE PROTECTIVE EARTHING SYSTEMS

(Informative)

J1 GENERAL

This Appendix provides guidance on the interaction of the various earthing systems fitted to pipelines. The main reasons for fitting earthing systems to pipelines are as follows:

(a) Low frequency induction (LFI) protection for personnel protection in situations where pipelines are installed along electricity transmission corridors. LFI may have ramifications on the pipeline hardware and ancillary equipment survival.

(b) Lightning protection (LP) primarily for personnel protection, also for ancillary equipment survival.

(c) Cathodic protection (CP) anodes for corrosion control.

J2 LFI PROTECTION

LFI protection should normally be designed first. This is not only because it protects personnel from likely and repeated electrical hazard, but also because it imposes significant problems on the subsequent CP concept. Unfortunately, CP design is often produced first and even installed before LFI protection is considered. When this happens, it often follows that the CP system is completely disabled by the former.

LFI mitigation is often achieved by fitting a substantial earth electrode at each end of the pipeline exposed to induction. The pipeline may be divided into modular lengths with some precautions in siting the earth electrodes. However, a single segment is usually more economic if it can be achieved. With the two electrodes fitted, current will flow along the pipeline to the electrode at one end, then via the earth path back to the other end electrode. Appendix F indicates the process for the determination of the electrode resistances required. These will normally be low values, between 1 and 10 Ω.

J3 LIGHTNING PROTECTION

A pipeline is very different from other structures in its behaviour on receiving lightning flash current. The pipeline is essentially a very long large capacitor with a voltage withstand, in the case of most modern pipeline coatings, in excess of 50 000 V. It may, on rare occasions, contain a direct flash episode which passes a high charge to the structure. Such an occurrence is described in Clause 8. Alternatively, and much more frequently, induction or lightning electromagnetic pulse (LEMP) will place a longitudinal (end to end) voltage on the pipeline.

In either occurrence, an electrode at each end of the pipeline section, which may be up to 100 km or longer in length, will serve to discharge direct flash energy or earth the longitudinal condition at each end, thus providing personnel protection. Typically, electrodes of 5 Ω (preferred), 10 Ω (maximum) will be required. Intermediate electrodes along the section may be provided for specific protection of associated electronic equipment (telemetry or CP converters).

It is common practice to insert surge protection devices (SPDs) in the lightning earth conductor electrode. This is to isolate pipelines CP systems from direct connection to earth at operating voltage. This avoids unnecessary CP current loss and also minimizes excess fall of potential between the CP converter and the lightning protection system site.

J4 CATHODIC PROTECTION

The CP converter or power source is commonly a power rectifier, though an increasing number of other devices are appearing. It is required to produce pipe potential to earth at a controlled level, within a small tolerance. Thus the siting of a converter at some distance along the pipelines from LFI protection earthing will usually prejudice the CP condition, as the current drain through these earthing electrodes is considerable (at CP levels). The LFI electrodes may be isolated for low d.c. potentials by fitting polarization cells. These are steel or nickel (or alloys) electrodes in strong alkali solution. They have a limited voltage withstand for low d.c. conditions, and so are preferably sited at the extremities of the converter fed section. There are some proprietary alternatives to metal/alkali cells available. These are based on semi-conductors. Designers should be fully aware of their performance properties before specifying them. Such cells, both metal/alkali and semi-conductor units, must be capable of carrying full LFI current at 50 Hz. This may be around 500 A, and typically for around 0.25 s.

Figure J1 shows the various components described above, and the siting of these in a typical pipeline section. Other arrangements are, of course, possible.

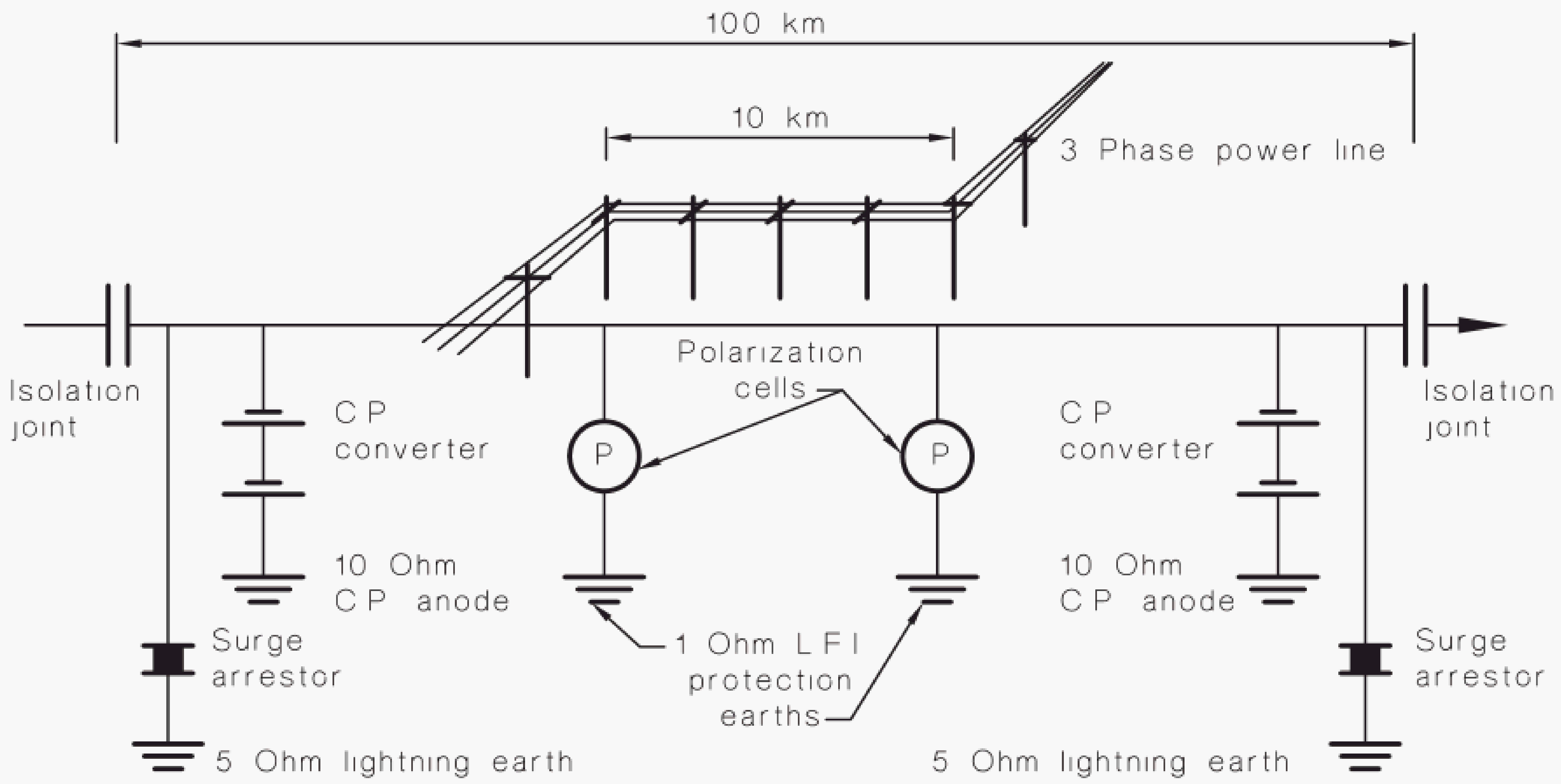


FIGURE J1 OUTLINE OF A TYPICAL PIPELINE SECTION WITH CP AND PROTECTION EARTHING

APPENDIX K

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ISBN 0 7337 3683 1

Printed in Australia

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