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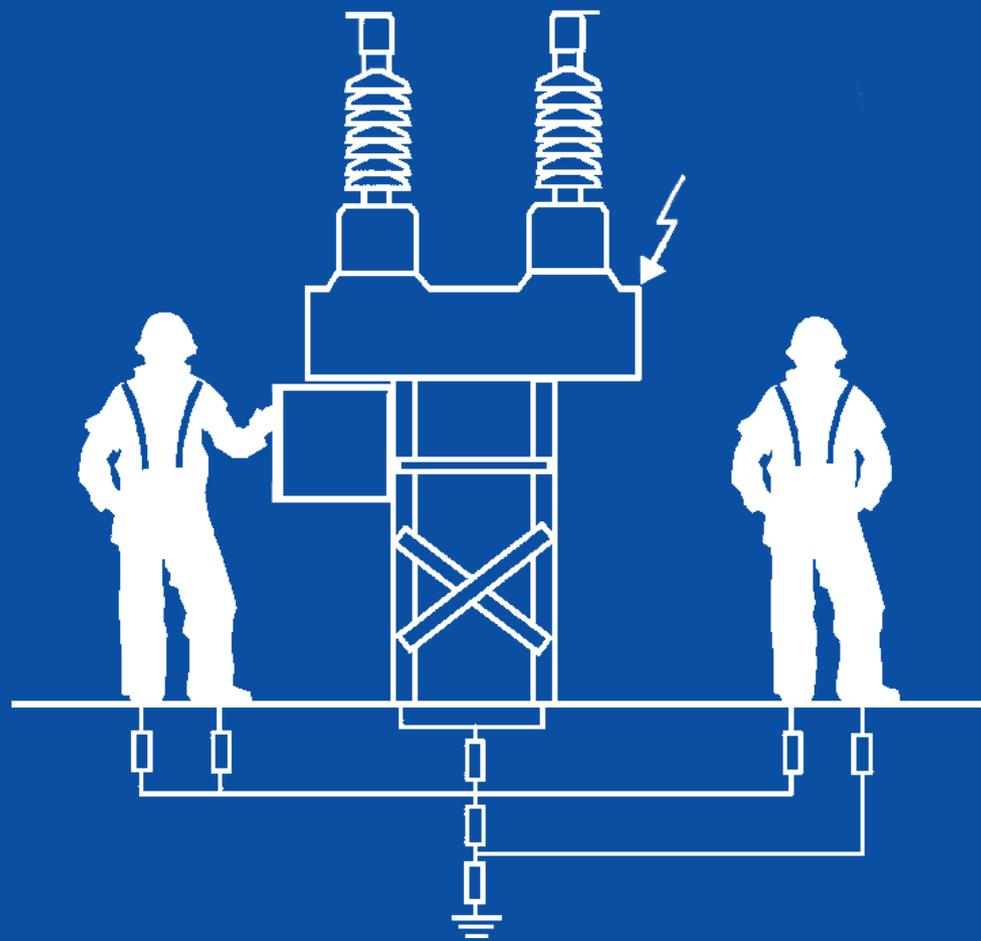
Power System Earthing Guide

Part 1: Management Principles
Version 1— May 2010

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Correspondence should be addressed to the Electricity Technical and Regulatory Committee (ETRC), c/o Energy Networks Association, Level 3, 40 Blackall Street, Barton, ACT 2600.

This Guide was prepared and published by the Energy Networks Association:

> Level 3
> 40 Blackall Street
> Barton ACT 2600.

Contents

1.   Scope

This Guide addresses the high level aspects of policy associated with power system earthing. It provides a framework for managing earthing related risk associated with electrical power systems to meet societally acceptable levels. This framework provides principles for the design, installation, testing and maintenance of the earthing systems associated with power system assets on a.c. systems with nominal voltages up to EHV. A central part of this framework is a probabilistic derivation of allowable voltage criteria and exposure under fault conditions. It is intended for use by electrical utilities and HV asset owners, operators and customers, specifically regarding:

- » major substations
- » distribution networks
- » transmission lines
- » power stations, and
- » large industrial systems.

It does not apply to the design or installation of any of the following which may be covered by other standards or codes:

- » customer premises LV earthing (refer AS3000)
- » earthing systems associated with d.c. systems
- » earthing systems associated with electric railway traction systems
- » earthing systems on ships and off-shore installations
- » test sites
- » mining equipment and installations
- » electrostatic equipment (for example, electrostatic precipitators).

2. Regulatory framework and standards

The management of earthing related risk is undertaken within the context of both legislative requirements and adherence to industry practice and standards. Where it is less than certain that an adequate level of safety will be provided throughout the lifetime of an asset, regulation is required. This is particularly true where a measure of the safety is not commonly available to stakeholders such as in earthing safety, where, for example, a person simply using their back tap could not reasonably know what voltage hazard could be present due to an HV earth fault. In these cases regulation is not only important in ensuring an adequate safety level but also in engendering stakeholder trust; in the regulator but more importantly in the industry.

2.1 Regulatory framework

Electrical utilities operate within a regulatory framework implemented via law, codes and licences, each of which confers rights and obligations on utilities and customers. There are also requirements and responsibilities incumbent on electrical utilities to not merely operate and develop their networks in a safe manner but also to promote and encourage the safety of persons and property in relation to that electrical infrastructure.

The law is not always detailed in specifying the methods to follow to achieve acceptable outcomes, often nominating required outcomes rather than processes. Such law often relies on the adoption of appropriate standards, codes of practice and industry guides to assist in the delivery of these outcomes. Some of these codes are prescriptive, maybe as a licence condition, and some rely on the utilities to adopt or employ appropriate controls.

The expected policy intent of emergent National Electricity Regulations is that electrical utilities be required to adopt and implement a cost effective program for design, construction and ongoing supervision of compliance of assets with applicable safety standards. Management of earthing and lightning related risk is clearly included in this requirement. This legislation also specifies the licensing requirements for electrical workers and electrical contractors together with the standards required for electrical work and the associated compliance obligations.

In New Zealand the *EEA Guide to Power System Earthing Practice* which complies with legislation and codes of practices is also applicable in New Zealand.

2.2 Standards and codes of practice

The following referenced documents are useful and are related to the application of this Guide. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Australian Standards

  » AS 1824.1—*Insulation co-ordination—part 1: definitions, principles and rules*

  » AS 1824.2—*Insulation co-ordination (phase-to-earth and phase-to-phase, above 1kV)—Application guide*

  » AS 2067—*Power installations exceeding 1kV a.c.*

  » AS 60038—*Standard voltages*.

Australian/New Zealand Standards

  » AS/NZS 1768—*Lightning protection*

  » AS/NZS 3000—*Electrical Installations*—known as *The Australian/New Zealand wiring rules*

  » AS/NZS 3835 (all parts)—*Earth potential rise—Protection of telecommunication network users, personnel and plant*

  » AS/NZ 3907—*Quality management—Guidelines for configuration management*—also called ISO10007

» AS/NZS 3931—*Risk analysis of technological system—application guide*

» AS/NZS 4360—*Risk management*

» AS/NZS 4383 (all parts)—*Preparation of documents used in electro technology*

» AS/NZS 4853—*Electrical hazards on metallic pipelines*

» AS/NZS 60479.1—*Effects of current on human beings and livestock—Part 1: General aspects*

» AS/NZS 7000—*Overhead electrical line design, part 1: detailed procedure.*

IEC documents

» IEC 60050—*International electrotechnical vocabulary*

» IEC 60479-1—*Effects of current on human beings and livestock—Part 1: General aspects*

» IEC 60479-5—*Effects of current on human beings and livestock—Part 5: Touch voltage threshold values for physiological effects.*

Other documents

» ENA C(b)1—*Guidelines for design and maintenance of overhead distribution and transmission lines*—superceded by AS/NZS 7000 (see reference above)

» ENA EG1—*Substation earthing guide*

» EEA New Zealand Electricity Networks *Guide to Power System Earthing Practice*—Electricity Engineers Association of New Zealand

» IEEE Std 80—*IEEE Guide for Safety in AC Substation Grounding*—The Institute of Electrical and Electronic Engineers

» IEEE Std 837—*IEEE standard for qualifying permanent connections used in substation grounding*

» CJC5—*Coordination of power and telecommunications—low frequency induction*—Standards Australia

» SAA/SNZ HB 436—*Risk management guidelines* (companion to AS/NZS 4360)

» *National Electricity Rules*—AEMC Version

» BS 7354—*Code of practice for design of high-voltage open-terminal stations*

» BS EN50341-1—*Overhead lines exceeding AC 45kV—General requirements—common specifications*

» ITU-T K.33—*Limits for people safety related to coupling into telecommunications system form A.C. electric power and A.C—electrified railway installations in fault conditions—series K: Protection against interference.*

3. Definitions

For the purpose of this Guide, the following definitions apply:

ALARA—'as low as reasonably achievable'	The underlying risk management principle whereby risk is reduced to 'as low as reasonably achievable' within a risk cost benefit framework. Sometimes referred to as ALARP (i.e. 'as low as reasonably practicable').
asset	An HV power system asset with an earth. Examples—Timber pole with downlead for earth wire, timber pole with transformer, steel or concrete pole, tower.
backyard	An area with a contactable metallic structure subject to fault induced voltage gradients. This metallic structure (for example, fence) is not an HV asset but becomes live due to earth fault current flow through the soil.
clearing time	The time taken for the protective devices and circuit breaker(s) to isolate the fault current.
coupling factor	The magnitude of the current returned on a faulted cable's screens and sheath or on an overhead powerline earth wire, expressed as a percentage of the fault current magnitude.
distribution	HV power system assets such as lines and cables with system voltages of less than 66kV, and distribution transformers with LV secondaries.
distribution substation	A small substation from which electricity is supplied direct at 33kV or less to a consumer or end user. The distribution substation may consist of one or more ring main units (RMUs) or transformers on a pole, on the ground, underground, or in a building; and includes the enclosure or building surrounding the transformer(s) and switchgear. Excludes zone substations.
duty holder	The utility that bears responsibility for managing the risk assessments and the safety of both the public and work personnel.
earth electrode	Uninsulated conductor installed vertically in contact with the earth (or an intermediate material) intended for the conduction and dissipation of current. One part of the earthing system. [IEV 195-02-01, modified]
earth fault	Fault caused by a conductor or conductors being connected to earth or by the insulation resistance to earth becoming less than a specified value. [IEV 151-03-40 (1978), modified] *NOTE: Earth faults of two or several phase conductors of the same system at different locations are designated as double or multiple earth faults.*

earth fault current	Current that flows from the main circuit to earth or earthed parts at the fault location (earth fault location). For single phase and double phase earth faults, this is in systems with:
	» isolated neutral, the capacitive earth fault current
	» high resistive earthing, the earth fault current
	» resonant earthing, the earth fault residual current
	» solid or low impedance neutral earthing, the line-to-earth and two line-to-earth short-circuit current.
earth potential rise (EPR)	Voltage between an earthing system and reference earth.
earth return current	The portion of total earth fault current which returns to source by flowing through the earth grid and into the surrounding soil.
	NOTE: This current determines the EPR of the earthing system.
earth grid	Interconnected uninsulated conductors installed in contact with the earth (or an intermediate material) intended for the conduction and dissipation of current and or for the provision of a uniform voltage reference. One part of the earthing system.
earth rod	Earth electrode consisting of a metal rod driven into the ground.
	[IEV 604-04-09]
earthing conductor	Conductor intended to provide a conductive path for the flow of earth fault current for the control of voltage rise and reliable operation of protection devices. Where a conductor is intended to also carry neutral return current (under normal load) it is not usually called an earthing conductor.
	NOTE: Where the connection between part of the installation and the earthing system is made via a disconnecting link, disconnecting switch, surge arrester counter, surge arrester control gap, then only that part of the connection permanently attached to the earthing system is an earthing conductor.
earthing system	Arrangement of earth conductors, typically including an earth grid, earth electrodes and additional earth conductors such as overhead earth wires (OHEWs), cable sheaths, earth continuity conductors (ECCs) and parallel earthing conductors (PECs or ECPs).
	[IEV 604-04-02, modified]
(effective) touch voltage	Voltage between conductive parts when touched simultaneously.
	NOTE: The value of the effective touch voltage may be appreciably influenced by the impedance of the person in electric contact with these conductive parts.
	[IEV 195-05-11, modified]
(effective) step voltage	Voltage between two points on the earth's surface that are 1m distant from each other while a person is making contact with these points.

electrical equipment	Any item used for such purposes as generation, conduction, conversion, transmission, distribution and utilisation of electrical energy, such as machines, transformers, apparatus, measuring instruments, protective devices, equipment for wiring systems, appliances.

[IEV 826-07-01] |
embedded earth	The use of steel reinforcing bar in concrete structures to interconnect with, and to augment, the earthing system. Used to both lower the earth resistance (where the concrete structure/slab/footing is in contact with the soil) and to create an equipotential plane (around HV equipment in a building or around sensitive equipment).
equipotential bond	A bonding conductor applied to maintain continuity of conductive structures with the main earth grid in order to prevent voltage hazards. The equipotential bonding conductor may not be designed to carry fault current.
equivalent probability	A probability value which has been adjusted to account for the simultaneous exposure of multiple individuals.
event	Occurrence of a particular set of circumstances.

NOTE: The event can be a single occurrence or a series of occurrences. |
hazard	Potential to cause harm.
HV	High voltage—voltage exceeding 1000V a.c..
induced voltage	The voltage on a metallic structure resulting from the electromagnetic or electrostatic effect of a nearby powerline.
LV	Low voltage—voltage not exceeding 1000V a.c..
MEN	Multiple earth neutral LV power system.
nominal voltage of a system	Suitable approximate value of voltage used to designate or identify a system.

[IEV 601-01-21] |
| non-power system plant | Metallic infrastructure that is nearby power system equipment and subject to voltage hazard via some electrostatic, electromagnetic or conductive coupling. |
| PEN (Protective Earth Neutral) conductor | Conductor combining the functions of both protective earth conductor and neutral conductor.

[IEV 826-04-06, modified]

NOTE: In a MEN system, this is the conductor connected to the star point of the transformer which combines the functions of both protective earth conductor and neutral conductor. |
| potential | Voltage between an observation point and reference earth. |
| probability | A measure of the chance of occurrence expressed as a number between 0 and 1. |

prospective touch voltage	Voltage between simultaneously accessible conductive parts when those conductive parts are not being touched.
	[IEV 195-05-09, modified]
prospective step voltage	Voltage between two points on the earth's surface that are 1 metre distant from each other, which is considered to be the stride length of a person.
	[IEV 195-05-12, modified]
reference earth (remote earth)	Part of the Earth considered as conductive, the electric potential of which is conventionally taken as zero, being outside the zone of influence of the relevant earthing arrangement.
remote	A location where the contact frequency is sufficiently low that the fault/contact coincidence probability is less than the target fatality probability. Typically, it is a location with few people around such as a rural area. For this case there is no touch voltage target required.
residual risk	Risk remaining after implementation of risk treatment.
resistance to earth, R_e	Real part of the impedance to earth (ohms).
risk	The chance of something happening that will have an impact on objectives. Potential for realisation of unwanted, adverse consequences to human life, health, property or the environment.
	NOTE : A risk is often specified in terms of the expected value of the conditional probability of the event occurring times the consequences of the event given that it has occurred.
risk assessment	The overall process of identifying, analysing and evaluating the risk.
risk event	An event that results in the occurrence of a hazard that impacts on the asset, or group of assets, which are being assessed.
risk criteria	Terms of reference by which the significance of risk is assessed.
risk management	The culture, processes and structures that are directed towards realizing potential opportunities whilst managing adverse effects.
risk management process	The systematic application of management policies, procedures and practices to the tasks of communicating, establishing the context, identifying, analysing, evaluating, treating, monitoring and reviewing risk.
risk treatment	Process of selection and implementation of measures to modify risk.
	NOTE: The term 'risk treatment' is sometimes used for the measures themselves.
soil resistivity	Specific resistivity of a material is used to define the resistance of a material to current flow, and is defined as the electric field strength (V/m) divided by the current density (A/m2). Values tabled are normalised to 1 amp flowing into a one metre cube of material yielding units of ohm-metre (Ωm).

structural earth electrode	Metal part, which is in conductive contact with the earth or with water directly or via concrete, whose original purpose is not earthing, but which fulfils all requirements of an earth electrode without impairment of the original purpose.
	NOTE: Examples of structural earth electrodes are pipelines, sheet piling, concrete reinforcement bars in foundations, the steel structure of buildings.
substation	Part of a power system, concentrated in one place, including mainly the terminations of transmission or distribution lines, switchgear and housing and which may also include transformers. It generally includes facilities necessary for system security and control (for example, the protective devices). For the purpose of this Guide, the term 'major substation' may refer to either a transmission substation or a zone substation.
	Examples: transmission substation (66kV and above), zone or distribution substation.
	[IEV 605-01-01]
transmission	HV power system assets such as lines and cables and associated infrastructure (for example, poles, earth pits) with system voltages of 66kV and above.
transmission substation	Major substation with secondary side voltage of 66kV or above.
transferred potential	Potential rise of an earthing system caused by a current to earth transferred by means of a connected conductor (for example, a metallic cable sheath, PEN conductor, pipeline, rail) into areas with low or no potential rise relative to reference earth resulting in a potential difference occurring between the conductor and its surroundings.
	NOTE: The definition also applies where a conductor, which is connected to reference earth, leads into the area of the potential rise.
urban interface	An HV power system asset outside normal public thoroughfare with a low frequency of direct contact by a given person.
value of statistical life (VoSL)	The cost of a human death used in statistical studies and insurance.
	NOTE: According to the nature of the system within which the substation is included, a prefix may qualify it.
value of saved life	A risk cost benefit calculation based around the cost of a fatality in terms of VoSL and fatality related organisational costs including investigations, subsequent actions and reputation impacts.
zone substation	A major substation with secondary voltages less than 66kV. Excludes pole mounted transformers and transformer kiosks.

4.   Earthing management issues

4.1   Purpose

Earthing systems are required to manage the transfer of fault energy in such a manner as to limit the risk to people, equipment and system operation to acceptable levels. An earthing system is required to perform this function for the life of the electrical network for which it is installed, for the range of configurations of the network and nearby infrastructure that are foreseeable. The earthing system may need to be augmented over time so as to continue to fulfil this function.

4.1.1   Safety for personnel and public

The earthing system is required to manage any hazardous potential differences to which personnel or members of the public may be exposed. These potential differences include:

» touch voltages (including transferred touch voltages)

» step voltages

» hand to hand voltages.

These voltages can be present on metallic equipment within substations, associated with substations or equipment associated with powerlines/cables, or even on non-power system plant items nearby (and not associated with) the electrical system. The soil potential relative to the metallic equipment needs to be carefully considered. For a hazardous situation to arise, a power system earth fault must be coincident with a person being at a location exposed to a consequential hazardous voltage.

The earthing system achieves an acceptable risk of shock for people by equipotential bonding or isolating the metallic equipment and infrastructure. The earthing system may also involve the use of insulating barriers to reduce the risk of hazardous potential differences. Earthing systems, while not actively operating for the majority of time, are 'safety critical' systems in that under fault conditions they must operate to ensure safety of staff and the public as well as protection of system equipment. As 'constant supervision' is not usually available (as it is for the phase conductors) deterioration or damage can remain latent. For this reason the design, installation and maintenance is all the more critical. Where an earthing system is inadequately designed, poorly installed, or not supervised through appropriate maintenance it will not reliably operate to provide safety when required to do so. This risk is not acceptable, as responsible management can generally ensure safety for a reasonable cost.

4.1.2   Protection of electrical network equipment

The earthing system is required to limit the level of transient voltage and power frequency voltage impressed on electrical equipment. It is also required to provide appropriate current paths for fault energy in such a manner that those fault energies do not impair equipment or equipment operation. System events/disturbances may otherwise cause extensive damage to equipment and associated ancillary equipment such as insulation breakdown and thermal or mechanical damage from arcing, fires or explosions.

4.1.3   Ensure correct system operation

The earthing system is required to ensure proper operation of protective devices such as protection relays and surge arresters to maintain system reliability within acceptable limits. It is intended to provide a potential reference for these devices and to limit the potential difference across these devices. The earthing system is required to achieve the desired level of system reliability through:

» facilitating the proper and reliable operation of protection systems during earth faults. This entails reliable detection of earth faults and either clearing the fault or minimising the resulting fault current

» limiting equipment damage and the consequent need for repair or replacement

» limiting or reducing substation secondary system equipment (for example, SCADA) interference.

In order to meet the foregoing operational requirements, earthing systems need to be adequately robust and able to be monitored:

» **robustness**—the earthing system, its components and earthing conductors shall be capable of conducting the expected fault current or portion of the fault current which may be applicable and without exceeding material or equipment limitations for thermal and mechanical stresses

> » **ongoing monitoring—**the earthing system shall be designed and configured to enable the system to be tested at the time of commissioning and at regular intervals as required, and to enable cost effective monitoring of the key performance parameters and/or critical items.

4.2 Earthing system operation

4.2.1 Fault energy sources

The energy which earthing systems must manage comes from a wide range of sources and system events, including:

» generating plant

» conductively coupled earth fault current

» inductively coupled earth fault current

» lightning discharges

» transient discharges (for example, switching surges)

» capacitively coupled induction.

To manage the foregoing energy sources it is necessary to identify and understand the interactions between contributory systems. **Figure 4-1** illustrates the earth fault process from an energy transfer perspective, which highlights flow of fault current 'driving' the creation of hazardous potentials. It is significant that many non-power system plant items, such as fences, pipelines and conveyors, are an active part of the return current path. The key principle is that the current balance between the installed earthing system (fixed plant), the power system 'neutral' conductors (for example, variable plant such as cable sheaths), non-system plant (for example, pipelines), and the soil, must be understood if the resultant hazard magnitudes are to be determined. The understanding of the overall system, whereby the earthing system behaves as a 'contact' by which the fault energy is transferred to the soil or to other metallic systems, is central to effectively and efficiently resolving safety hazards.
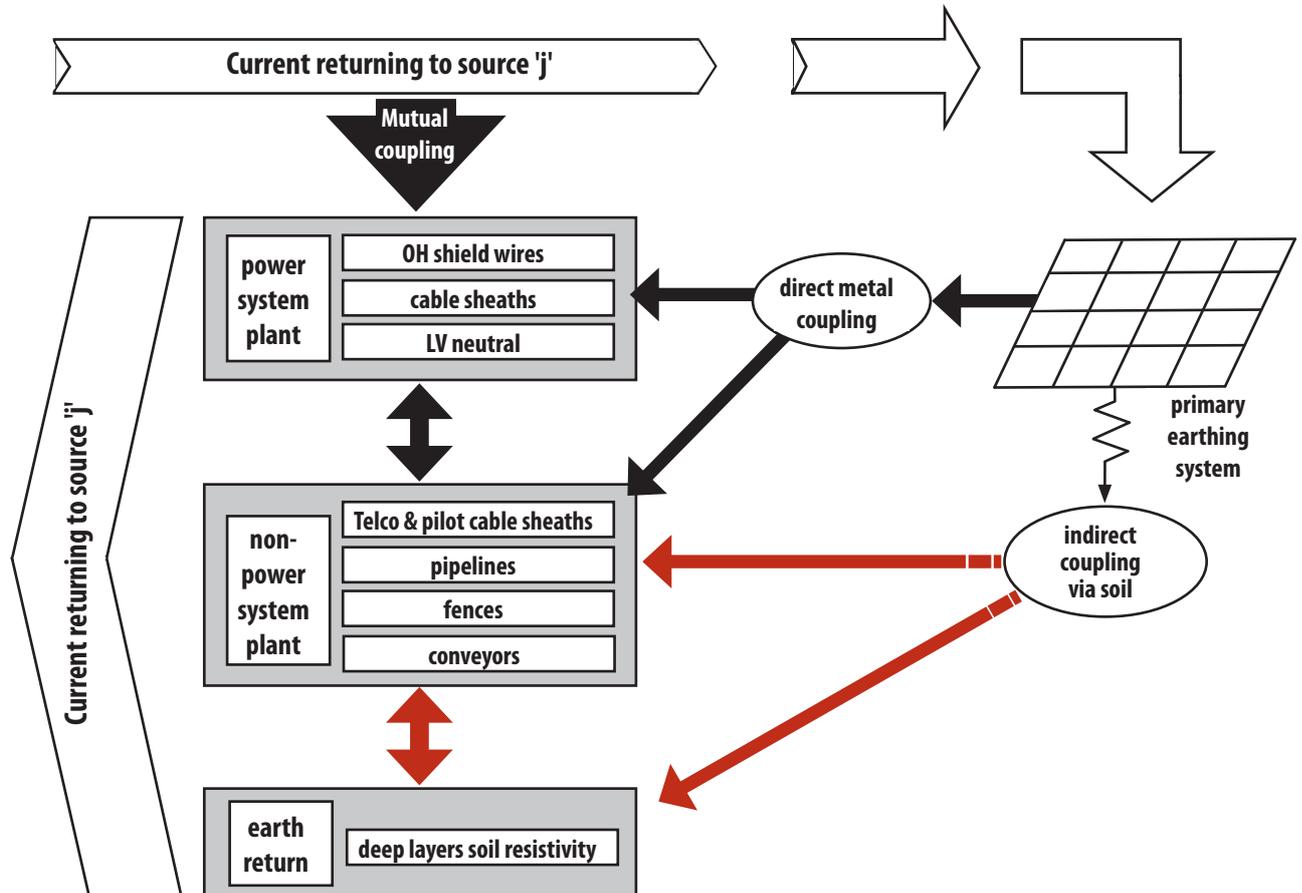
Figure 4-1: Earth fault energy transfer overview

4.2.2   Hazard scenarios

Consideration of appropriate safety criteria (usually an allowable shock voltage) is required for all electrical assets that form part of the network. Consideration should be made for substations (both inside and outside) and for the accessible portions of the powerlines and cables. As fault current can be coupled to non-power system plant, so it is required to also consider the safety requirements at those locations outside the substations and easements.

The specific locations will represent a different risk profile by virtue of the fact that there will be different coincident probabilities of system events and human contacts and different series impedance (for example, footwear and surface coverings).

Consideration should be given to factors such as:

» probability of multiple simultaneous human contacts (particularly in public places), (i.e. touch, step, hand-to-hand or transfer voltage impacts)

» susceptible locations (wet areas)

» controlled access areas (fenced easements or remote areas)

» series impedance (surface coverings and footwear)

» future possible encroachments upon the electrical network and the effect of system events on those encroachments

» conductive and inductive coupling into non-power system plant such as communications infrastructure, telecoms, pipelines and conveyors.

Not all risk is imposed by the earthing system. There are external factors that may also impact upon the earthing system resulting in a change in the risk profile of the installation. **Figure 4-2** summarises the main risk elements in each category.

Some external factors that need to be addressed (during design and installation) are theft and/or vandalism of earth system components. Consideration should be given to protecting exposed components and/or monitoring key components to ensure an acceptable risk profile.

The interaction between the substation or powerline earthing systems and secondary systems (for example, SCADA) needs also to be considered as those systems can adversely affect each other.
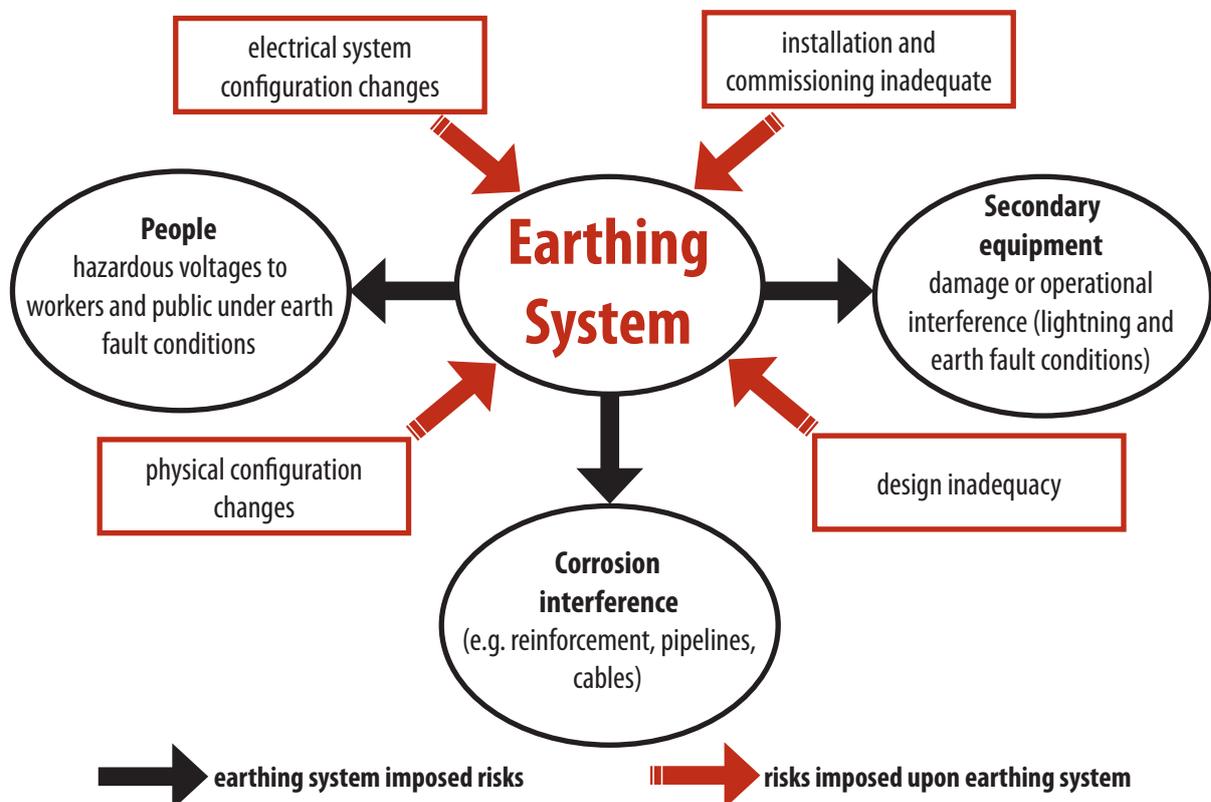
Figure 4-2: Earthing system risk profile

NOTE: Substation secondary equipment is associated with equipment such as SCADA, communications or protection systems.

4.3   Earthing system components

An electrical network has many components which require earthing. The earthing systems of substations and powerlines/cables need to be carefully coordinated and cannot be considered as independent, even where they are isolated. The major components of an earthing system are described in the following sections.

4.3.1   Primary earthing system

4.3.1.1   Local earth (buried earth grid)

Nominally, the primary earthing system at substations and associated powerlines and cables is the buried metallic earth grid. The earth grid is comprised principally of a mesh of interconnected buried conductors. Sometimes the earth grid is installed with electrodes bonded to it. The earth rods (i.e. electrodes) are typically either mechanically driven into the earth, or comprise a drilled hole with the electrode installed and the hole backfilled. The hole is backfilled to ensure contact is maintained between the electrode and the surrounding soil.

4.3.1.2   Embedded earthing system (structural earth electrode system)

Many substation sites have a significant portion of the site footprint covered in reinforced concrete structures. As substation footprints have reduced, it has become increasingly necessary to utilise this space as part of the earth grid. It is, however costly to excavate trenching beneath concrete slabs and footings to install copper conductors. On many sites the structural steel reinforcing has been welded to ensure electrical continuity and current carrying adequacy. It is typically bonded to and forms part of the earthing system.

Concrete poles also have steel reinforcement that is often used to form an embedded earth conductor to interconnect over head earth/shield wires to some buried earth grid/electrode.

4.3.2   Auxiliary earthing systems

Usually it will be impractical for the entire fault current to be dissipated via a local substation earth grid, and it will be required for auxiliary earth paths to be bonded to the primary earthing system. While nearby additional earth grids are sometimes used, they can be difficult to justify (cost and maintenance) unless associated with another electrical asset. Examples of auxiliary earthing systems are as follows:

4.3.2.1   Cable sheaths/screens

Underground cable sheaths/screens and earth continuity conductors run with underground cable systems are able to be used to interconnect earth grids associated with substations and transition points. The cable sheaths/screens in many instances are of significant benefit to earthing system performance as they are subject to close inductive coupling from the cable system especially the cable core conductors of which they are a part. The inductive and conductive interconnection coupling can assist in improving the earth system performance.

4.3.2.2   Overhead earth wires

Overhead earth wires offer lightning protection benefit as well as being able to carry inductively coupled return earth fault current. Where they are bonded to an earthing system, they augment the buried earth grid through interconnecting the transition point or substation earth grid and the earthing systems of the powerline structures. Additionally they interconnect the terminal substation earth grids. Underslung earth wires also provide benefit through interconnection with distributed earths.

4.3.2.3   Counterpoise

A bare buried earth conductor run radially from an earth grid will effectively increase the area of the earth grid and thereby lower the earth resistance of the system. Counterpoise earth conductors are often installed in the trenches that are excavated for the installation of HV cables.
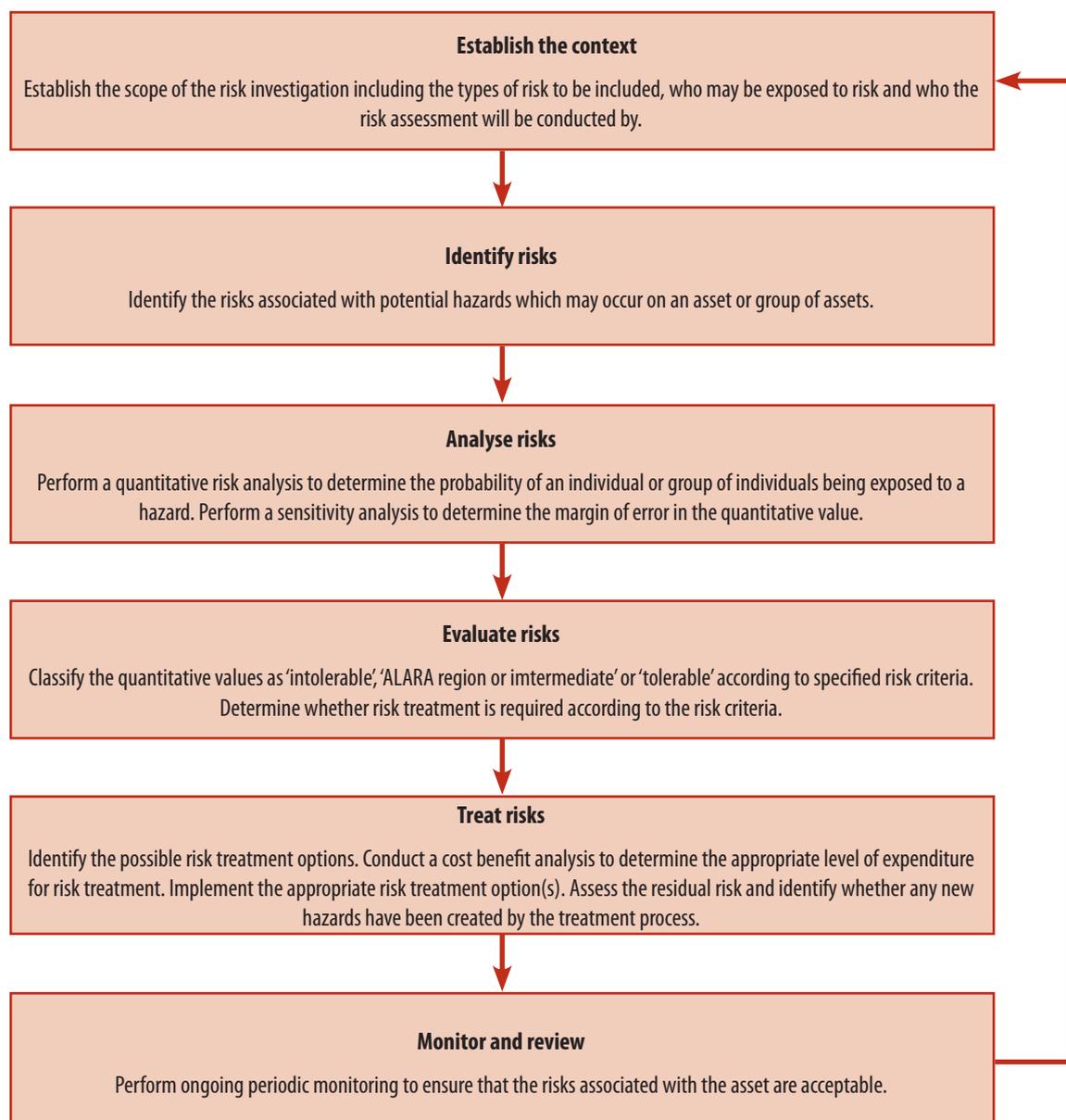
4.4 Risk management

All life activities involve some form of inherent risk. The tolerability of injury or death to a member of the public is therefore dependent upon several factors including the types of hazards, the control measures implemented, frequency of occurrence, the likelihood of actions of the individual(s) exposed and the associated consequences.

Risk in this context is defined as 'the chance of something happening that will have an impact on objectives' (i.e. a combination of the consequences of an event and their likelihood, frequency or probability). The risk associated with a hazard is determined using a risk assessment process in which hazards are identified, analysed using quantitative methods and qualitatively assessed against specific criteria. Once the risks are evaluated, the appropriate risk treatment process shall be implemented where appropriate to effectively and efficiently manage the risks.

4.4.1 Risk management process overview

The process of identifying, analysing, controlling, and mitigating hazards according to the associated level of risk is part of the risk management process. The risk management process presented in this Guide is based on the framework of AS/NZS 4360. Every major hazard created by an asset or activity must be identified, assessed and controlled according to the risk management process shown in *Figure 4-3*.

Establish the context

Establish the scope of the risk investigation including the types of risk to be included, who may be exposed to risk and who the risk assessment will be conducted by.

Identify risks

Identify the risks associated with potential hazards which may occur on an asset or group of assets.

Analyse risks

Perform a quantitative risk analysis to determine the probability of an individual or group of individuals being exposed to a hazard. Perform a sensitivity analysis to determine the margin of error in the quantitative value.

Evaluate risks

Classify the quantitative values as 'intolerable', 'ALARA region or imtermediate' or 'tolerable' according to specified risk criteria. Determine whether risk treatment is required according to the risk criteria.

Treat risks

Identify the possible risk treatment options. Conduct a cost benefit analysis to determine the appropriate level of expenditure for risk treatment. Implement the appropriate risk treatment option(s). Assess the residual risk and identify whether any new hazards have been created by the treatment process.

Monitor and review

Perform ongoing periodic monitoring to ensure that the risks associated with the asset are acceptable.

Figure 4-3: The risk management process (based on AS/NZS 4360)

A risk management process is a logical and systematic method to ensure that the risks are effectively and efficiently managed. The framework for managing earthing related risks, incorporated in the design process flowchart (*Figure 5-1*) and outlined in *Sections 5, 6* and *7*, has been structured to facilitate a systematic risk management approach. The risk associated with an activity or asset can vary considerably according to the type of the risk.

4.4.2　Types of risk

The tolerance of the public to risk of a human fatality depends on specific factors which allow the risk to be classified accordingly.

4.4.2.1　Voluntary and involuntary risk

Certain activities in life are considered hazardous, however, in spite of a high probability of injury or fatality, society continues to tolerate the consequences of such risks because the exposed individuals usually consider that the 'benefits' gained outweigh the risks. These are called 'voluntary' risks and include activities such as smoking, cave diving and riding a motorcycle.

Activities that do not allow an individual choice in participation are tolerated to a much lesser extent and must be analysed carefully and controlled to a much higher level. Such risks are called 'involuntary' and include terrorist attack, gas explosion or exposure to carcinogens in consumable products. As there is no choice available to the individual concerned, there is often no escape or warning associated with involuntary risks. Risks associated with earthing-system-related electrical hazards are usually categorised as involuntary and the primary responsibility for risk management lies with the owners of the hazard source.

4.4.2.2　Risks and non-random hazards

The acceptability of injury or fatality to individuals varies significantly according to whether the risk event was caused by a human error or occurred as an unforeseen event. Injuries or fatalities caused by gross negligence are not covered within the scope of this Guide and are therefore not included in the risk management process. Asset owners have a responsibility to provide a duty of care for members of the public and employees however individuals must also act responsibly so as to provide a basic level of personal safety. A central tenet of risk management is that equity and fairness must be maintained wherever possible. Therefore, it follows that no person should be exposed to a level of risk above that accepted by society as reasonable. Thus acceptable safety levels should be maintained independent of location and power system asset class (i.e. distribution or transmission). The need to more objectively and intentionally achieve this aim is one of the key drivers behind the criteria derivation process.

4.4.2.3　Individual and societal risk

The tolerance of society to risk is also dependent upon the number and ages of the individuals exposed to the risk. The occurrence of a hazard (risk event) which results in exposure of vulnerable members of society or results in simultaneous exposure for multiple people is considered less tolerable. The assessment of the impact of the release of a hazardous substance may be undertaken both in terms of risk to the segment of the society exposed to the risk and risk to an individual. Any given fault event will present a risk profile via conductive components at a range of locations, and one or more people may be in a position to sustain an electric shock at one or more of these locations. The difference between individual risk and societal risk is explained in the following definitions:

Individual risk: The annual risk of fatality for an exposed individual.

The risk associated with an individual is usually calculated for a single hypothetical person who is a member of the exposed population. Individual risk assessments do not account for the danger to an exposed population as a whole.

Societal risk: The risk associated with multiple, simultaneous fatalities within an exposed population. When considering the impact on society it is usual to consider the annual impact upon a 'typical segment' of society. Societal risk may be a determining factor in the acceptability of the risk associated with a hazard for areas where many people congregate.

Risk limit targets for both individual and societal exposure cases are discussed in *Section 4.4.6*.

4.4.2.4   Risk of injury, damage or livestock fatality

Hazardous activities may result in damage to equipment and injury or fatality to animals or humans. A common practice is to determine the appropriate levels of risk according to the possible harm to humans.

The notion that risk is only calculated for fatality in humans does not, however, imply that responsibility is absolved for damage to equipment or fatality of livestock. The cost of replacing equipment or livestock, therefore, should be accounted for when undertaking a cost benefit analysis to determine the justifiable cost of risk treatment.

4.4.3   Risk assessment

Risk assessment is a process which can be applied to any potential hazard (or risk event) that could cause injury or fatality to a worker or member of the public. Risk assessments must be conducted with a responsible and even-handed approach and in complex cases a peer review by experts in risk analysis may be required. Typically, a defined risk may be assessed based on one common scenario that is representative of many field installations.

Risk assessments should be conducted prior to construction and reassessments should be made on a periodic basis according to the changing level of public exposure and asset performance. Risk assessments should not be based on the premise that, because no accidents have been reported in the past, no accidents will occur in the future.

The risk assessment process provides direct guidance concerning the relative risks associated with the range of hazards generated. It supports the decision making process, and provides a firm basis on which to make presentations to management to demonstrate due diligence in risk mitigation.

The process of risk assessment and monitoring, incorporating both qualitative and quantitative elements, is undertaken considering the full life of the installation/asset. Particular attention is to be paid at times of system augmentation, to ensure all systems complement each other. It is also critical to maintain staff that are cognisant of the critical issues and trained to identify preliminary hazard indicators and respond in an appropriate manner.

4.4.4   Conducting a risk analysis

Risk assessment, as highlighted in *AS/NZS 4360*, is the overall process of risk identification, risk analysis and risk evaluation. Risk analysis is a systematic process to understand the nature of and to deduce the level of risk. Risk analysis also provides the basis for risk evaluation and decisions about risk treatment.

Risk may be analysed using quantitative, qualitative or a combination of the two methodologies. There are various risk methods that can be used to analyse risk. Some of these methods are:

- » Probabilistic Risk Analysis
- » Event Tree Analysis
- » Fault Modes and Effects Analysis
- » Fault Tree Analysis
- » Hazard and Operability Study

- » Human Reliability Analysis
- » Preliminary Hazard Analysis
- » Reliability Block Diagram
- » Monte Carlo Analysis.

In this Guide, the probabilistic risk analysis is used to determine the probability of causing fatality to one or multiple individuals. The probabilistic model which is a commonly adopted method of risk assessment is:

$$\text{Risk} = \mathbf{f}\,(\text{hazard, coincidence})$$

Where 'coincidence' represents the frequency of public exposure to a risk event and 'hazard' represents the consequences of failure. Risk in this context is a function of hazard and exposure. Risk analysis may be carried out for individual assets or for groups of assets with similar characteristics (for example, earth fault frequency, exposure).

4.4.5   Who should conduct a risk assessment

Risk assessments must be conducted by those who create and control the extent of the risk—the asset owners or those acting on their behalf. The personnel who bear responsibility for managing the risk assessments and the safety of both the public and work personnel will be hereafter referred to as 'duty holders'.

The duty holders must be able to access site specific data which may be used to form the basis of the assessment and are in an appropriate position to determine the risk treatment methods. The duty holders are also in the best position to conduct regular risk reassessments and ensure that risk treatment methods are implemented satisfactorily.

4.4.6   Risk limit targets

Any injury to or fatality of a worker or member of the public is unacceptable, however the inherent danger of electricity and disproportionate cost of protecting every individual from every conceivable hazard requires that some level of risk be tolerated. Risk targets set for environmental health and safety cases, while having an appearance of uniformity, are in fact greatly variable. The main variation concerns how uncertainty and variability in contributing parameters is managed. As for most decisions of this nature the outcome is contingent upon a wide range of issues, including: size of exposed populations, duty of care and legal precedence, physical implementation limitations, economic criteria, equity and fairness, stakeholder values and perceptions, physiological criteria, comparable risks existing.

It is important that staff analysing a particular risk scenario are consistent in assigning values to parameters and interpreting the results of the risk quantification. To meet that goal this Guide aims to articulate assumptions and tools, and to provide both 'by hand' and software-based analysis tools. In setting risk criteria, the underlying principle is that people should not involuntarily be subject to a risk which is significant in relation to the background risk associated with what could be realistically expected to be 'normal movements'.

Individual and societal risk should be considered separately and the more stringent outcome used as the risk scenario to be managed. While an individual's concern about their life or safety is largely independent of whether the risk is from an isolated incident or a major disaster, society's risk perception is strongly influenced by events with potential for multiple injuries or fatalities [9].

4.4.6.1   Tolerable individual fatality risk limits

The risk increase to which an individual may be inadvertently exposed may be calculated on an annual basis and assessed against the target fatality probability limits in common use **Table 4-1** following (for example, *NSW Risk Guidelines* [8], [9], or *WA EPA Guidelines* [27]). The assessment is made considering the risk to a person who represents the maximum exposure that could be expected of a person acting reasonably. For a distribution of population behaviours from least to most risk attracting, maximum reasonable exposure is considered to be an estimate of the behaviour of 90 to 95 percent of the population.

Table 4-1: Target individual fatality probability limits

Probability of single fatality	Risk classification for public death	Resulting implication for risk treatment
$\geq 10^{-4}$	High or Intolerable risk	Must prevent occurrence regardless of costs.
10^{-4}-10^{-6}	Intermediate or ALARA Region	Must minimise occurrence unless risk reduction is impractical and costs are grossly disproportionate to safety gained.
$\leq 10^{-6}$	Low or Tolerable risk	Risk generally acceptable, however, risk treatment may be applied if the cost is low and/or a normally expected practice.

4.4.6.2   Tolerable societal fatality risk limits

The tolerable societal limits imposed on different industries for multiple fatalities are usually based on the occurrence of accidents which have resulted in multiple fatalities. The tolerable limits for societal risk in this Guide are defined according to the number of people 'N' simultaneously exposed to hazard.

Societal risk relates to any person(s) being affected, based on a typical or average expected exposure. For a distribution of population behaviours from least to most risk attracting, average expected exposure is considered to be an estimate of the 50 percent behaviour.

The most common measure of societal risk is the Frequency-Number (F-N) curve representing the total frequency (per year) of events resulting in N or more fatalities. The F-N curve is usually constructed in a two-step process:

(i)   Calculate the number of fatalities resulting from each incident case.

(ii)   Construct the F-N curve showing the results in cumulative frequency form,

where

F_N = Sum (F_i) for all incident outcome cases i for which $N_i >= N$,

where

F_N = frequency of all incident outcome cases affecting N or more people/year

F_i = frequency of incident outcome case i.

The tolerable societal limits vary between countries depending upon the nature of the hazards and exposed population. A conservative set of limits which have an $N^{-1.5}$ dependence on the number of fatalities has been adopted in line with common Australian usage when assessing potentially harmful effect of hazardous industries [8, 9]. The societal F-N risk limits are presented in *Figure 4-4* following. These risk limits are independent of population size.

For the case of electric shock during earth fault conditions the F-N curve may be built based upon the likelihood of one or more people (out of the exposed population) being in an exposed position (refer to *Appendix A.1.2*).

Three cases have been identified as warranting separate analysis:

 (i)   **Uniform exposure (time independent)**: An individual's movements are largely independent of one another (for example, people in separate households). Calculation of the societal risk is based upon extension of the expected individual exposure to include more than one person (acting independently) being in an exposed position at the same time.

(ii)   **Gathered exposure (time dependent)**: Individual movements are governed by an external organising event or location, which may result in one or more people being exposed to a higher degree than for the totally random cases. Gathered exposures could include events or situations such as large sporting complexes, municipal swimming pools or cattle sale yards. People's exposure may be characterised as being of higher contact frequency, but over a limited time span. Therefore, the coincidence must be calculated based upon non-uniform arrival rates, as outlined in *Appendix A.3*. For the purposes of this Guide it is understood that while people are 'gathered' in a location for a fixed duration they still exhibit essentially random movements whilst in that location (uniform behaviour). Therefore, the same analysis techniques may be used to calculate exposure during a given event. In this case of the fault, frequency is considered constant.

(iii)   **Generalised (time dependent)**: In this scenario the rate at which people make contact and fault events occur are both non-uniformly distributed. The approach outlined in *Appendix A.3* allows for seasonal fault conditions as well as time of day/week exposure profile.

The points on the F-N curve relate to the Frequency of events occurring with 'N or more' fatalities.

Therefore it is understandable that the greater the number of people possibly exposed the higher the values. The value of 'F' on the 'Y' axis is therefore the highest value as it related to 'one or more' fatalities.

The boundary conditions on the ALARA Region have been aligned with those in common use within Australia relating to hazardous industries [11]. The position on the Y axis crossing and slope of the lines defining the upper and lower limits have been developed based upon the relative utility of the product (i.e. value of electricity to society), and experience in assessing risk profiles. A steeper gradient is sometimes used to assess incidents which might be considered to have an exceptional negative impact upon a large percentage of the population (for example, nuclear power plants, large dams). Nevertheless, the graph is interpreted in a similar manner to the individual risk assessment, where if part of the curve lies within each of the Regions the following steps should be taken.

- » **Intolerable Region**—The risk profile must be reduced.

- » **ALARA Region**—Reduce the risk profile whenever possible, and only accept the residual risk on the basis of a risk cost benefit analysis (RCBA) (see ***Appendix F***). The use of the ALARA principle (or ALARP) is clearly intended to form a key part of the Due Diligence process embodied in this Guide. The ALARM principle that requires a designer and asset owner to reduce the risk profile whenever possible provides a consistent yet practical means for managing earthing system related risk.

- » **Low or tolerable Region**—Risk generally acceptable, however, risk treatment may be applied if the cost is low and/or a normally expected practice.

Both the individual and societal hazard scenarios should be assessed and the risk profile of both managed depending upon the region in which the risk is placed (i.e. intolerable, ALARA, or neglibible).

It should be noted that when calculating societal risk, account should be taken of possible future increases in population density, particularly in cases where assets are in areas where there is surrounding residential land that has not yet been fully developed.
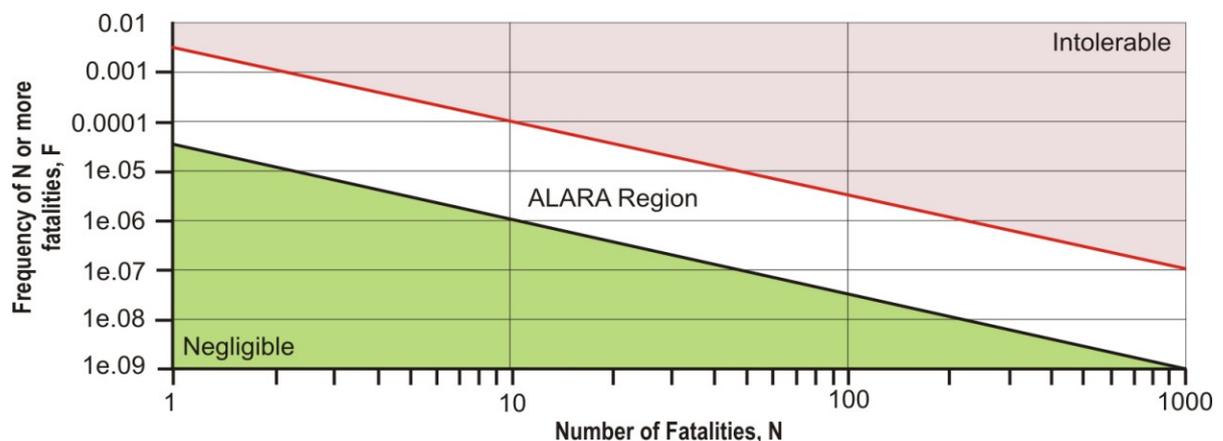
Figure 4-4: Societal F-N risk limits

4.4.7   New Zealand risk management approach

A similar approach to risk assessment for earthing systems has been adopted in New Zealand and is outlined in the *EEA Guide to Power System Earthing Practice*. The New Zealand approach utilises a similar method for calculation of the coincidence probability and applies similar individual risk limits, but does not include probabilistic analysis in the calculation of design voltage limits.

5. Design

5.1 Introduction

Traditionally, an earthing system with a low overall earth resistance was considered to be safe. However, there is no simple relationship between the resistance of the earthing system (for example, 1Ω or 10Ω) and the chance that a fatality could arise in any particular situation. Appropriate analysis that takes into account all the necessary factors and includes a realistic assessment of the risks is therefore required.

The goal of earthing system design decisions is to ensure adequate robustness in the design at the same time as finding a balance between cost, practicality and management of risk. Multiple risk scenarios (for example, with both touch and step voltage hazards) often need to be analyzed with regard to interactions between individual scenarios (for example, trade offs), and the impact of the various design configurations on the overall risk profile for the site and system. The design process goals which need to be met include:

» compliance with safety criteria

» operational requirements

» equipment interference constraints

» corrosion interference constraints

» be cost effective

» practical to implement

» testable at time of commissioning

» able to cost effectively monitor the key performance parameters or critical items, and be

» reliable and robust over the whole of life (i.e. resistant to critical failure modes and easily testable for longer acting deterioration mechanisms).

The performance criteria identified above may be used within a risk-cost-benefit analysis when resolving competing design configurations. The risk-based design process is outlined in the next section, and the individual design steps are discussed more fully in the ensuing sections.
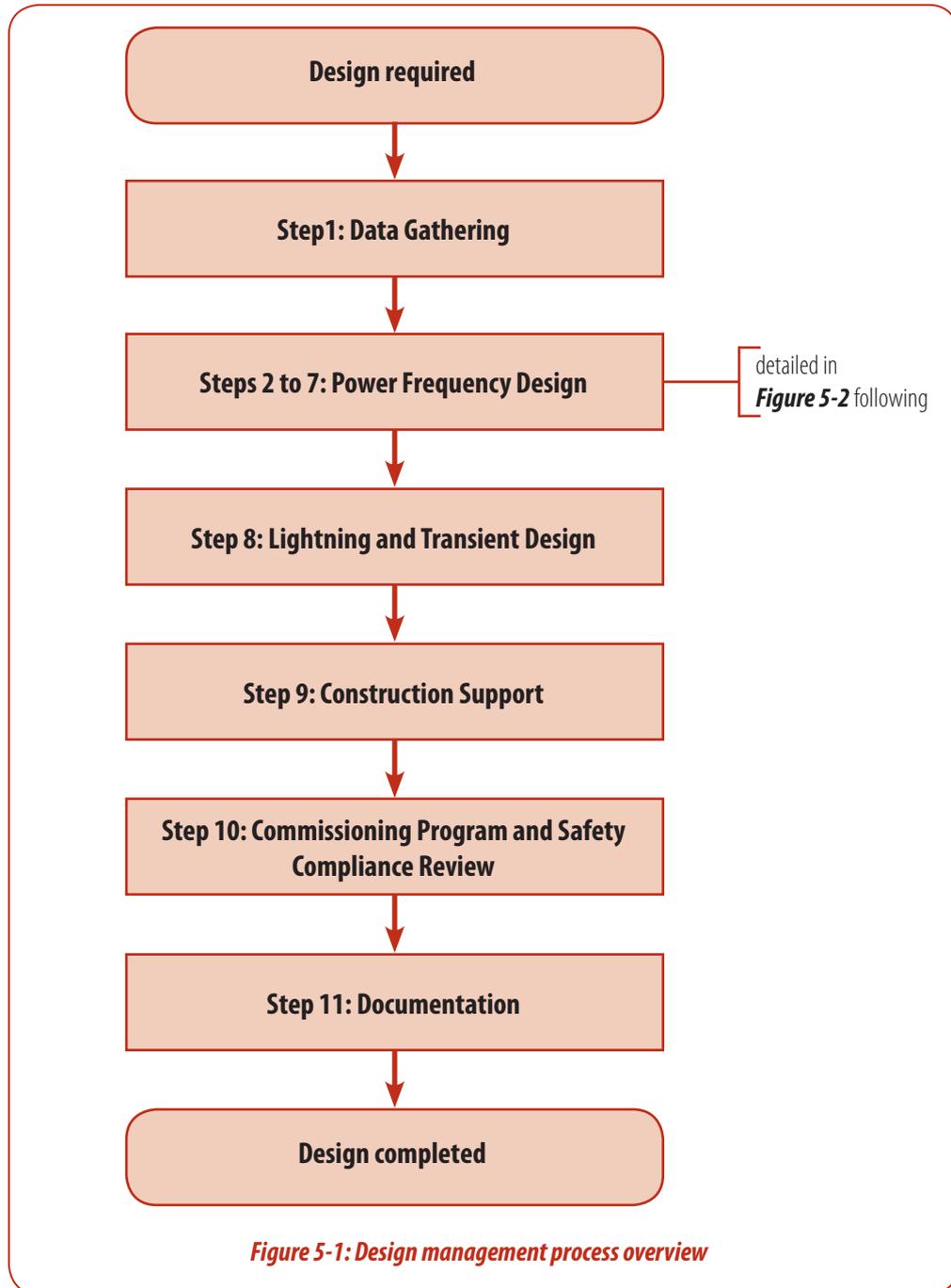
5.1.1 Design management process overview

The following design management procedure (presented in **Figure 5-1**) is a high level view of the recommended process for earthing system designs. It has been structured with the aim of providing flexibility, and leading designers to make conscious (and articulated) decisions, to identify hazards, meet appropriate risk targets and facilitate ongoing compliance. In this way it is intended that the risks associated with earthing system operation are managed in a cost effective, practical, supportable manner that is clearly documented and implemented.

The design steps outlined above are presented and discussed in the remainder of this chapter.

5.1.2 Safety criteria selection

The selection and assessment of safety criteria is part of the Power Frequency Design (Steps 2-7) which is presented diagrammatically in **Figure 5-2** following. This Guide provides two methods of safety criteria selection:

1. Standard curves (case .matching): Aligning the design to be undertaken with a published case and using the specified voltage/time curve (which was probabilistically derived) as the design safety criteria (see **Section 5.6**).

2. Direct probabilistic: Directly calculating contact and fault incidence coincidence and fibrillation probability to derive a 'design specific' safety criteria (see **Section 5.7**).

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┌─────────────────────────────────┐
│         Design required         │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│      Step1: Data Gathering      │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐      detailed in
│ Steps 2 to 7: Power Frequency   │───── Figure 5-2 following
│             Design              │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│ Step 8: Lightning and Transient │
│             Design              │
└─────────────────────────────────┘
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│   Step 9: Construction Support  │
└─────────────────────────────────┘
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│ Step 10: Commissioning Program  │
│  and Safety Compliance Review   │
└─────────────────────────────────┘
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│     Step 11: Documentation      │
└─────────────────────────────────┘
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│        Design completed         │
└─────────────────────────────────┘
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Figure 5-1: Design management process overview

Figure 5-2: Power Frequency Design for Standard V/t Criteria

5.1.3   Power frequency design process summary

The following points (see **Table 5-1**) summarise the intent of each step within the preceding design procedure flowchart.

Table 5-1: Design and management process

Step	Process Description
1	**Data gathering and project integration** The validity of any design is contingent on the accuracy of the data used. The data is collected in a staged manner, as required by the designer.
2	**Initial design concept** Determine the earthing system that will likely meet the functional requirements. Detailed design is necessary to ensure that all exposed conductive parts, are earthed. Extraneous conductive parts shall be earthed, if appropriate. Any structural earth electrodes associated with the installation should be bonded and form part of the earthing system. If not bonded, verification is necessary to ensure that all safety requirements are met.
3	**Determine design EPR** Based on soil characteristics and the likely proportion of total earth fault currents flowing into the local earthing system (see *Section 5.3.1*), determine the expected earth potential rise (EPR). Include the full extent of the system under consideration by including the effect of interconnected primary and secondary supply systems for each applicable fault scenario.
4	**Detailed earthing layout** **Conductor configuration (4a)** Generate an earthing conductor layout to meet earthing system functional requirements (see *Section 5.5*). **Shock hazards-location identification and Magnitude (4b)** Identify locations where staff or the public may be exposed to shock hazards. Such hazards include, touch, step, transfer and hand-to-hand contacts. For each location calculate the expected shock voltages for each applicable fault scenario identified in Step 3.
5	**Standard V/t criteria applicable at hazard locations** Based on the specifics of the design concept and the broader context attempt to match the design to a standard voltage/time (V/t) curve or curves from the case studies. Conservative assumptions and comparisons are advisable.
6	**Undertake direct probabilistic design** For each shock risk location determine fault/presence coincidence and shock circuit impedances (for example, footwear and asphalt) and then the fibrillation probability. For each shock risk location determine if the magnitude of the shock voltage (Step 4) is less than the applicable safety criteria (Step 5). The voltage will fall in one of the three categories (see *Sections 4.4.6* and *5.6*). **Intolerable**—Unacceptable risk. Mitigate the risk. **ALARA region**—Reduce the risk to as low as reasonably achievable (ALARA). A risk cost benefit analysis may be required to assess the cost of the risk treatment against a range of criteria. For risks classified to be in the ALARA region or intermediate the cost and practicality of any mitigation measure is assessed against a range of criteria (see *Section 5.6*). **Negligible**—(for example, operator equipotential mats within switchyards). If the EPR is sufficiently low it is a simple matter to classify the whole system as presenting an acceptably low risk.
7	**Design improvement** Improve the design and identify and implement appropriate risk treatment measures. Typical treatment measures might include global and/or local risk reduction techniques (see *Section 5.6*).
8	**Lightning and transient design** Consider the need to implement any particular design precautions to manage the impact of lightning and other transients (see *Section 5.9*).
9	**Construction support** Provide installation support as necessary to ensure design requirements fulfilled and construction staff safety risk effectively managed (see *Section 6*).
10	**Commissioning program and safety compliance review** Review the installation for physical and safety compliance following the construction phase of the project. Ensure that the earthing system performs adequately to meet the requirements identified during the design (see *Section 7*).
11	**Documentation** Documentation is to include the physical installation description (for example, drawings) as well as electrical assumptions, design decisions, commissioning data, and monitoring and maintenance requirements (see *Section 7.4*).

5.2　　Data gathering and project integration (step 1)

5.2.1　　Data gathering

The initial data gathered is intended to enable the designer to prepare a preliminary design from which a maximum projected EPR may be deduced. While the available information will differ, depending upon the system under design (for example, transmission, distribution or major substations), the following data would be generally required:

- » fault levels and protection clearing times (for relevant fault scenarios)
- » soil resistivity and geological data
- » site layout (for example, structure placement)
- » primary and secondary power system conductor details (for example, cable sheaths, overhead shield wires/earth wires OHEW's)
- » data concerning existing earthing systems (for example, location, test results)
- » points of exposure (services search and neighboring infrastructure).

The benefits of investing investigative time up front include:

- » Ability to undertake a soil resistivity test program during conservative climatic conditions. This will allow the designer to provide input to the site selection process.
- » Locating previously unknown/unexpected hazards (for example, fences, pipelines).
- » Gathering better location specific information resulting in significant cost savings (for example, special constraints, lower resistivity locations, additional availability of secondary earthing systems for interconnections).
- » Enable the designer to identify and quantify the vital hazards. The issues can be addressed earlier rather than once the system is installed (for example, retrofitting can be hazardous and costs are significantly higher than at the initial stage).
- » More accurate understanding of bonded earthing systems.

Once the information is gathered, the design procedure may be structured to minimise complicated analysis. For example, detailed analytical modelling is only recommended in order to:

- » find appropriate designs if simple empirical formulae cannot be acceptably applied to the particular installation
- » investigate a range of remedial measures, and
- » minimise manpower and material costs by more accurate modelling when appropriate.

Some detailed data may be gathered gradually during the design process, as each of the identified hazards and minimum installation requirements are addressed. Testing can sometimes be used to determine key parameters which are difficult to model (for example, earth fault current distribution) and often not available in power system databases. Also, some data may only be reliably determined by testing in the field (for example, low voltage (LV) MEN input impedances).

Collecting the full set of data required in the design will facilitate mitigation of the hazards using realistic values for parameters rather than conservative estimates. Having the full data set reduces the risk of 'unexpected issues' arising at a later stage in the design process. The main data streams may be delineated based upon the various hazard categories and risk analysis requirements as follows:

- » current flow—electrical power system configuration and performance
- » main installation area—electrical equipment and structural layout, metallic services, geological data and soil resistivity
- » external interference
- » access/exposure estimates—movement of people
- » transients and EMI
- » corrosion
- » electrostatic coupling.

5.2.2   Project management integration

From the inception of a project the earthing and lightning protection system design should be closely integrated within the overall project management and other design processes (for example, civil and structural design). The design engineer should take responsibility to ensure that the final operational system complies with all requirements. A number of areas for integration are discussed in the following points:

5.2.2.1   Project management plan

Points of integration with the project management program need to be identified and communicated to the project team. Points of integration include:

» siting, feasibility assessment

» area requirements

» supply cable or transmission line design

» civil construction

» interaction with assets 'external' to the main contract (for example, cables, communication lines, pipelines)

» installation timing and project staging

» construction staff safety (for example, working within or adjacent to areas with energised power systems)

» inspection hold points

» staged commissioning requirements, and

» training or briefing session timing for project and construction staff.

5.2.2.2   Overall electrical system design process integration

It is necessary to identify and communicate with the design team any issues requiring coordination with other parts of the design process (for example, protection, cable specifications, line design (for earthed structures), architectural and civil designs). Input requirements to structural and civil specifications, and tender documents, must be identified at an early stage to ensure adequate coordination.

5.2.2.3   Design and installation decision documentation and communication

What decisions are made (with reasoning) should be documented within the design system. As built drawings and key earth system parameters need to be available to the duty holder (refer *Section 4.4.5*) at the conclusion of any project. The system that retains this data must also be auditable.

5.3   Initial design concept (step 2)

The initial design is to include adequate conductor placement and sizing to withstand fault currents and manage voltage gradients. Inductive and conductive current flows in the earthing components of the primary and auxiliary power networks (for example, cable sheaths/screens and overhead earth wires) may be allowed for in the analysis, as these reduce the current dissipation locally and therefore the EPR, more realistically depicting the system performance. Most earthing networks depend on these interconnections.

The process and complexity of an earthing system design varies according to the requirements of the application, however, a number of design considerations are largely universal when designing an earthing system. These include:

» the area available for installation of the earthing system

» soil resistivity, structure, water table and seasonal variation

» fault currents and durations

» regulation requirements applicable to the locations and the type of site

» site safety of personnel and the general public

» transferred hazards

» earthing conductor ratings (minimum earthing conductor size requirements), and redundancy targets (number of conductors).

The design of an earthing system should take into account all the relevant parameters. Further discussion regarding the installation practicalities to be considered in the design (for example, sizing and corrosion) is included in the Detailed Earthing Layout section (**Section 5.5**).

The design parameters critical to the initial design concept include the fault current magnitude and auxiliary systems coupling factors, fault current duration, soil resistivity and earth grid area. These are briefly discussed as follows:

5.3.1   Design earth fault current

The worst case fault scenario for every relevant aspect of the functional requirements shall be determined. The following points provide some advice regarding factors to be considered, and shall be examined at each voltage level present in the installation:

» Single phase to earth fault or double phase to earth fault conditions (when close to generation sources or reactive plant; although even then probability may be taken into account given the infrequency of double phase to earth faults).

» Faults both within and outside the installation site, shall be examined to determine the worst case earth potential rise.

» Due consideration shall be taken of the combined effect of the magnitude (including DC offset) and duration of the fault in establishing the levels of stress imposed on a person, equipment or earthing component.

» While the fault level selected should be the highest which is likely to occur with allowance for future increases (for example, future maximum that could be reasonably expected), some allowance may also be made for line and fault impedance if appropriate. It is not usually appropriate to use the switchgear fault short circuit rating when selecting future fault levels.

» Future fault level increases may be due to:

  » installation of additional transformers or larger transformers

  » installation of generation equipment

  » removal of fault limitation devices such as neutral earthing resistors or reactors (NER's), earthing transformers or line reactors.

» System reconfiguration (for example, new powerlines which interconnect power systems)

» Often only a small proportion of the prospective earth fault current will return via the general mass of the earth (through the local earth grid and the soil). In some cases, fault current is diverted from the mass of the earth via cable screens, overhead earth wires, LV neutrals (MEN conductors) or other bonded conductors such as pipelines. Some of the earth fault current may also circulate within an earth grid and not contribute to the earth potential rise. Therefore, before calculating the earthing system potential rise, step voltages and touch voltages, it is important to first calculate the realistic earth return current which will be a portion of the total earth fault current.

» For calculating the size required for the earthing conductors, the expected portion of the maximum earth fault current shall be used. Where parallel earthing conductors exist such as for an earth grid, the rating of the parallel conductors may be based on a design current which is a portion of the maximum expected earth fault current. The portion depends on the number of parallel conductors.

5.3.2   Earth fault duration

Realistic earth fault current clearing time must be considered for the calculation of the earthing conductor sizes and when assessing step and touch voltage hazards.

5.3.2.1   Personal safety

The fault clearing time of primary protection relays (or first upstream protection device) and circuit breakers shall be used for personal safety. Refer to **Appendix A.3** for typical primary protection clearing times. The initial fault and auto reclose events should not be aggregated.

The assessment of step and touch voltage hazards often requires the consideration of a number of earth fault scenarios with different fault clearing times. It is then necessary to evaluate which combination of fault current and clearing time represents the worst case for step and touch voltage hazards assessment. Quite often, it may be necessary to assess more than one set of fault current and fault duration scenarios.

5.3.2.2　Conductor sizing

Back-up relay protection operating time, plus circuit breaker operating time shall be used as a minimum when designing for conductor and connecting joint thermal requirements. Refer to **Appendix A.3**, **Table A4** for typical backup protection clearing times. These times may be used if more accurate data is not available.

The total accumulated fault time needs to be considered where auto-reclose is applied as there is very little cooling during the auto-reclose dead time. Further details on the selection of earth fault duration are included in Section 10 of the *ENA EG-1—Substation earthing guide* for use when specifying conductor sizes.

5.3.3　Soil resistivity

The soil resistivity and the structure of the soil have significant effects on the earth potential rise of the earthing system. Care must be taken to ensure that reliable soil resistivity data is obtained from field testing. It is preferable that a sufficiently wide resistivity traverse be employed to enable the correct resistivity lower layer value and layer depths to be identified. An alternative nearby test site, or a driven rod test, may sometimes be used when space is at a premium at the site under investigation.

Testing after recent rainfall should be avoided and rainfall history data can be checked to gain an appreciation of soil moisture conditions. Data should be evaluated and cross checked whilst in the field. Incorrect readings and inaccurate or erroneous values should be identified and eliminated. Because many sites have been developed and redeveloped over many years, interference may be caused by in-ground metallic services and objects such as underground cables, water supply pipes, drainage pipes, sewerage pipes, and building and machinery foundation piles. Buried services may also provide an unintended conductive path for transfer potentials. Geotechnical data identifying soil/rock types and depths also provides a useful cross check when interpreting test results.

Computer software or other methods should be used to convert the test data to a model which represents the soil structure 'seen by the test'. Measured soil resistivity data may need to be adjusted for seasonal variation or test limitations, based upon additional data gathered and engineering experience, when deciding upon a resistivity model to use in each part of the earthing system design analysis.

5.3.4　Standard design templates

Standard design components or templates may be used to good effect provided the 'limits of applicability' or boundary conditions are well understood, and assessed prior to application. However, undue reliance upon standard designs can result in a range of unwanted outcomes such as:

» Overlooking site specific issues which require additional or specific risk treatment.

» Over-designing! Unfortunately it is not easy to be certain when a designer is being too conservative.

» Failing to achieve compliance over 'all of life' due to site specific threats.

» Reliance of the designer on the standard design can facilitate a lack of due diligence.

» Design as a drawing—limiting the output of the design process to a layout drawing ignores the significance of documenting the basis for decisions, parameter assumptions and earth system performance.

The use of standard designs is seen as a valuable component in the design methodology provided it is coupled with rigorous checking of compliance with boundary conditions. Whilst a standard design may save time, its development must incorporate the rigour of the full design methodology detailed in this Guide.

Standard designs may be adequate to resolve all the identified hazards, however, their indiscriminate use cannot be condoned. The 'standard design' must be accompanied with clearly defined assumptions and boundary conditions which define the limits of its applicability. The standard design package must also incorporate commissioning and supervision guidelines. A standard design may be technically correct, but without having the boundary conditions specified it is unacceptable. Designers and management should enforce such rigour, as relying on unsubstantiated design standards may produce an unacceptable liability to utility organisations.

Installations with very low earth fault levels are those which are most likely to benefit from the use of standard design. While it may appear overly repetitive, having to consider if a standard design can be used to mitigate the risk associated with each hazard location introduces worthwhile rigour to the design process (with little added time).

5.4 Expected design earth potential rise (step 3)

Based upon the soil characteristics and the likely proportion of total earth fault currents flowing into the local earthing system the expected EPR is calculated for each of the key fault cases identified. This is the major outcome of the initial design concept phase as it enables assessment of which areas require further assessment. Fault scenarios that are not significant may be acknowledged and discounted from further analysis.

This initial first pass sets a conservative upper limit for the EPR. It enables assessment of which fault scenarios should be the focus of the detailed design effort. Some fault scenarios may later be shown to exhibit a maximum EPR that is less than the applicable compliance criteria (for example, allowable touch voltage) and so achieve compliance without specific mitigation.

These values are critical in that all other hazard voltages (for example, step, touch, transfer) are calculated by scaling based on the relative EPR's for each key fault case.

5.5 Detailed earthing layout (step 4)

The technical analysis which follows (refer **Section 5.5.2**) looks at the system performance, however, it is only effective if the physical practicalities of the design (refer **Section 5.5.1**) meet certain robustness and earthing system interconnection requirements. These detailed requirements are specified either on site/project specific drawings, or in standard constructions drawings or practices that installation staff use.

5.5.1 Earthing conductor layout (step 4a)

An earthing system bonds the required equipment and structures to earth via some form of local earth grid (for example, series of electrodes or embedded earth system). The physical practicalities of the design need to achieve a level of robustness for the life of the installation. The earthing equipment and material selection is therefore critical. Further the method of installation and manner in which conductors are protected, the level of redundancy employed and the corrosion consideration employed will need to ensure the correct outcomes are achieved. The design should specify conductor sizing, terminations, acceptable jointing methods, material types, conductor protection, labeling and inspection and testing requirements as a minimum. Many of the requirements are addressed in some detail in other guides such as the ENA EG-1 *Substation earthing guide*. The following sections provide some detail regarding these requirements.

5.5.1.1 Current rating of earthing conductors

The cross-sectional area of earthing conductors shall be capable of carrying the maximum earth fault current to which the conductor is expected to be subjected. The value of earth fault current used should allow for the possibility of future growth or reconfiguration of the system and any resultant fault current increases (refer also to **Section 5.3.1**).

The current rating of any conductors forming part of the earthing system may be determined using appropriate formulae or charts. Appropriate formulae may be obtained from *IEEE Std 80* or the *EG-1 ENA Substation earthing guide*. For the rating of earthing conductors, the fault clearing time achieved by the backup protection (see **Table A5** in **Appendix A.3**) shall be used. However, when rating all buried

earthing conductors, additional factors such as the long term service life of the conductors, future growth and the corrosive nature of the soil in which they are installed should also be considered. This may justify the selection of a larger sized conductor considering the cost involved in future reinforcement or replacement of the conductors.

Earthing conductors also need to be sufficiently physically robust to match the intended duty, taking into consideration factors such as exposure to traffic, corrosion, physical protection and support.

The range of ambient temperatures of a specific Region should be considered when rating earth conductors. Different values are usually applicable for buried conductors and for above ground conductors.

The design should take precautions to ensure that the maximum temperature that any earthing conductor is allowed to reach does not pose a danger to the safe operation of the electrical asset and does not cause deterioration of the conductor. The maximum conductor temperatures are usually limited by jointing/connection methods. Historically, where bolted or compression joints are used, IEEE *Standard 80* and ENA *EG-1* have recommended a maximum temperature of 250°C for bare copper earthing conductors. IEEE Std 80 also recommends a maximum temperature of 250°C to prevent annealing of hard drawn copper conductors. Maximum temperatures of 450°C have been used for bare copper earthing conductors that are welded or brazed. PVC covered conductors should not exceed a maximum temperature of 160°C to avoid damaging the insulation. Both IEEE *Standard 80* and ENA *EG-1* provide some further guidance regarding allowable temperature rise.

5.5.1.2　　　Material and corrosion considerations

The design, selection of materials and construction of the earthing system should take into consideration the possibility of theft and deterioration due to corrosion over the expected period of use of the installation. Typical materials used as earth conductors include:

(a) **Copper** is the most common material used for earth electrodes. It has a high conductivity and has the advantage of being corrosion resistant in most soil conditions. Copper clad high tensile steel is often used for electrodes. The thickness of the copper coating or sleeve used on the rods shall be substantial enough to avoid rapid corrosion of the steel rod. A minimum thickness of 250 μm is suggested.

(b) **Stainless steel** may be considered in some soil conditions where copper may suffer from excessive corrosion.

(c) **Mild steel** is not preferred due to excessive corrosion rates. Galvanized steel may be used in cases where there is an extensive buried steel pipe network in close proximity such as a power station as copper earthing would corrode the steel pipe network. Galvanized steel will give a very short service life in corrosive soils. The use of mild steel or galvanized steel earth electrodes in conjunction with or in close proximity to copper earth grids is not recommended. The steel will act as a sacrificial anode and could corrode away relatively quickly. In areas where a considerable quantity of buried galvanized steel or structural steel is present near a copper earth electrode, stainless steel may be an attractive alternative to copper (depending upon presence of certain salts in the soil).

(d) **Aluminum** or **solid zinc** should not be used as a buried electrode.

(e) **Corrosion control**

Earthing system components may be subject to corrosion, or be the cause of corrosion in other systems. While standard installation guidelines are sufficient in many instances to handle corrosion risks, it is considered prudent to include at least a basic corrosion risk assessment in the design process to determine if special conditions exist. Earthing systems in or near industrial plant often require special consideration of corrosion risks either due to the presence of aggressive chemicals or the need to coordinate with cathodic protection (CP) systems. Proximity to d.c. traction systems may lead to electrolysis due to stray traction current flow, requiring the designer to consider mitigation (for example, separation or 'drainage' bonds).

To enable a secure or robust design to be realised, a review of the parameters affecting corrosion performance is recommended. The following points are useful to assess:

» the nature of the surrounding soil environment
» abnormal environmental factors
» alternating and direct current sources (for example, traction or CP systems)
» climatic and tidal factors
» operating conditions of the system
» system security assessment
» system configuration
» other factors (for example, abrasion, erosion).

While it is difficult to obtain an exact quantitative value of the risk of corrosion under the conditions discovered in the initial phase of the investigation, it is often possible to draw broad qualitative conclusions. This approach may be used as the basis for a construction strategy considering a wide range of corrosion causes or types as follows:

(i)   Uneven distribution of moisture or soil types in the vicinity of the electrode.

(ii)   The acidity and chemical content of the soil, as well as the presence of foreign materials including cinders, scrap metal or organic material. For instance the presence of certain salts has been shown to lead to corrosion of copper conductors.

(iii)   The presence of stray electric current—particularly, d.c. from traction system return currents or cathodic protection systems.

(iv)   The interconnection of dissimilar metals in the soil or above ground where moisture is present. This is among the most common causes of corrosion of earth electrodes. For example, the connection of copper mounted on galvanised steel structures can lead to corrosion. Special care is also required in selecting the fixing of conductors to structures.

(v)   Pitting corrosion is an issue to consider with stainless steels or clad conductors.

(vi)   The resistivity of the soil, as an electrolyte, is an important factor associated with corrosion. Soils having resistivity lower than approximately 15 Ω-m are highly conductive and therefore considered to provide a highly corrosive environment. Corrosion of conductors at the soil/air interface should be also carefully considered.

The mitigation of corrosion is complex and it is not possible to lay down rigid rules. If corrosion problems are encountered or are anticipated, these should be investigated on a case by case basis.

5.5.1.3   Joints and terminations

During fault conditions the joints within an earth system are required to maintain electrical integrity while carrying large currents at increased temperatures. The most common acceptable joints between earth conductors include: welded (exothermic), brazed, compression and wedge type. Compression fittings or exothermic products used for jointing conductors shall comply with the requirements of an acceptable standard such as IEEE Std 837.

The use of bolted joints in below ground applications should be carefully considered. It is not considered acceptable for bolted joints to be directly buried, and care should be taken when used in earth pits to ensure the pit doesn't fill with soil or water. Corrosion of the conductors and connectors may result in the joint becoming loose or high impedance if steel connections are used with copper conductors.

Corrosion issues associated with joints should be considered, especially where dissimilar metals are involved. The use of joint sealing compounds may also be considered where appropriate to ensure water does not penetrate the joint.

5.5.1.4   Layout practicalities

Earthing conductors perform three main functions:
» dissipating current directly into the soil
» collecting and/or carrying current between dissipation points, and
» providing surface voltage gradient control.

The design layout should always be prepared with a view to:

» simplifying the installation process

» simplifying ongoing supervision needs, and

» minimising exposure to 'external risks' (i.e. damage through vandalism or theft).

The interconnection of equipment to the buried earth system should be undertaken with consideration of loss damage and failure of either the bonding/or earth conductor or the terminations. In the event of some singular failure, it is desirable that the earth system remains functional and especially that both personnel and equipment are protected.

Providing clear details on drawings is important as any ambiguities may be misinterpreted and buried before they can be identified, and many incorrect configurations cannot be identified by continuity testing during the commissioning program. Therefore visual checks are recommended to check installed connections and conduction configurations.

5.5.2 Shock hazard-location identification and magnitude (step 4b)

The risk profile associated with earthing systems varies greatly for different locations and circumstances. During the first phase of an earthing system design or redesign it is necessary to identify the hazard scenarios applicable to the particular site and power system configuration that could be presented during the period of the project and life of the installation/asset.

The nature of the power system operation is such that earth fault investigations need to look at the overall power system involved, as any current flow must return to its source(s). The 'system wide' nature of the flow of possibly hazardous fault energy means that a localised view or assessment perspective is insufficient.

Once the risks associated with the site/asset are identified, catalogued and key parameters identified and possibly quantified, more directed and thorough coverage of the issues can be undertaken in the design and assessment stages. By formally cataloguing these risks they can also be taken into account when making decisionsregarding the future augmentation of the plant.

Hazardous step and touch voltages can appear on the metal structures or equipment associated with high voltage power systems, or may be transferred via metal structures or equipment located near high voltage power systems due to one or a combination of the following factors:

» direct connections (fences, conveyors)

» indirect coupling (close proximity via soil)

» electric field (capacitive) coupling

» electromagnetic induction.

The following sections briefly discuss the range of safety related hazard mechanisms associated with the management of earthing systems.

5.5.2.1 Earth potential rise (EPR)

An earth fault current flowing through an earthing system causes an EPR on the earthing system and on metal structures and equipment connected to the earthing system. The EPR can result in significant voltage differences appearing between the local earth and the equipment connected to the earthing system. The voltage rise (EPR) can be considered as the driving voltage for many of the following electrical shock descriptions.

Aside from driving voltage consideration should be given to independent voltage obligations such as the telecoms code, the pipeline standard or other rules that may be in place to limit maximum voltage rise.

5.5.2.2 Touch voltage

Touch voltage is the voltage generated during an EPR event which may appear between conductive simultaneously accessible conductive parts. When those conductive parts are not being touched the touch voltage is termed the prospective touch voltage and is the open circuit voltage. The touch voltage becomes the effective (loaded) touch voltage when the conductive parts are being touched simultaneously. In this case, the touch voltage circuit becomes loaded by the body impedance along the current path.

When comparing calculated or measured touch voltages with touch voltage limits, the touch voltage is taken as the potential difference between the conductive part and any point on the surface of the earth within a horizontal distance of one metre from the vertical projection of the point of contact with the conductive part.

Touch voltages typically appear between a hand and one or both feet of a person touching a temporarily livened conductive part while standing on the earth surface one metre away from the structure (see *Figure 5-3*). Touch voltages may also occur between two conductive parts that may be simultaneously touched.
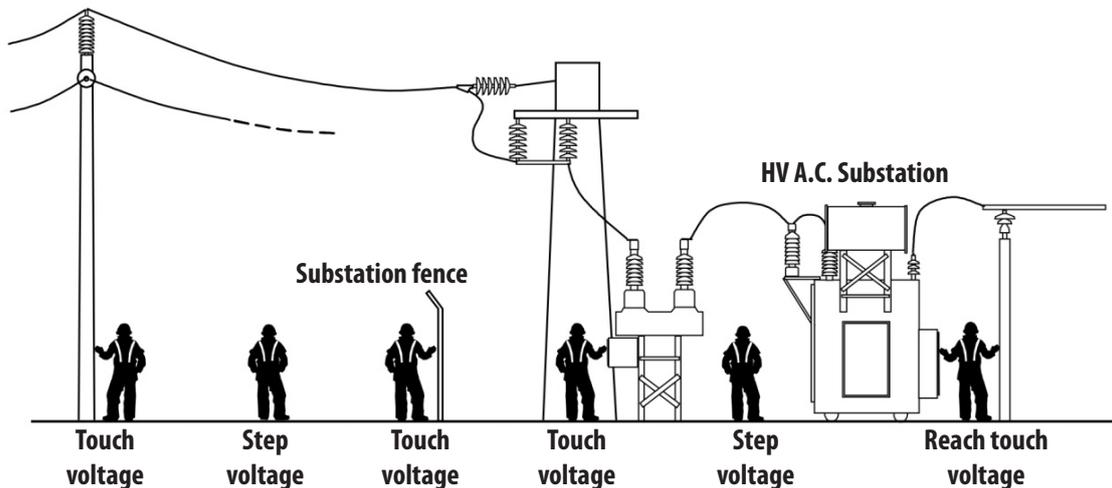

Figure 5-3: Touch and step voltages around a substation

5.5.2.3   Step voltage

Step voltage is the voltage between two points on the earth's surface that are 1 m distant from each other, which is considered to be the stride length of a person. Examples of a step voltage are shown in *Figure 5-3*.

5.5.2.4   Transferred voltage

The transferred potential is the potential rise of an earthing system caused by a current to earth transferred by means of a connected conductor (for example, a metallic cable sheath, MEN conductor, pipeline, or rail) into areas with low or no potential rise relative to reference earth resulting in a potential difference occurring between the conductor and its surroundings.
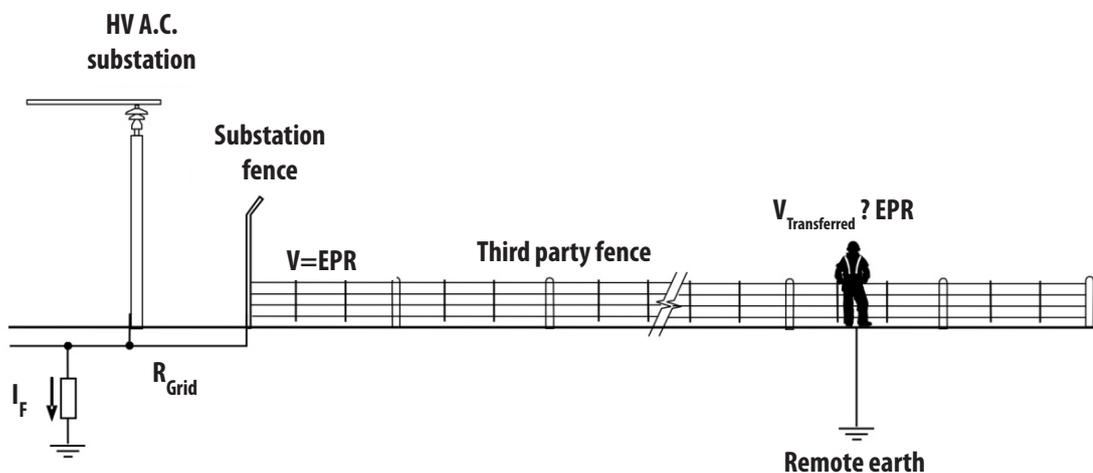
Figure 5-4: Examples of transfer voltage hazards

A transferred potential may also appear between a conductor and the surrounding area of potential rise when the conductor connected to reference earth brings reference earth into the area of potential rise. The transferred potential is a special case of touch voltage. The transferred potential may approach the full potential rise of the earthing system in some cases. Transferred potentials may affect third party plant, equipment and people.

Where potential rises on the earthing system are transferred by metalwork such as neutral conductors of a MEN system or water pipes to locations remote from the installation, allowance may be made for voltage drop in these conductors. Otherwise, the transferred potential should be regarded as being equal to the full potential rise on the earthing system.

Where transferred potential involves a long conductive part such as a fence earthed at regular intervals along its length, the conductive part will rise to a potential somewhere between the maximum and minimum potential rise affecting it. The transferred potential on the conductive part relative to the surrounding earth will vary along its length.

5.5.2.5 Magnetic field induction

Currents (steady state or earth fault currents) flowing through a powerline in parallel with metallic conductors (such as telecommunication conductors, metallic fences) can cause hazardous voltages to be magnetically induced into these parallel conductors.

Induced voltages may be a hazard to telecommunications equipment and personnel and should be limited to electrically safe values in accordance with applicable standards and guidelines (refer to list of standards in *Section 3*).

Induced voltages may also be a hazard in gas, oil or other pipelines, where they run parallel to high voltage transmission or distribution lines. Hazards arise to personnel inspecting and maintaining such pipelines.

Induced voltages may also be hazardous to the public on fences, conveyors underground mining cables or other metallic conductors which run parallel to powerlines.

5.5.2.6 Electric field (capacitive) coupling

Although not directly related to voltage rises upon earthing systems, capacitive voltages can be coupled onto an insulated metallic object in an electric field from an energised circuit. An example of electric field coupling is the voltage that appears on a de-energised overhead circuit running alongside an energised circuit.

When contact is first made with the isolated object, the stored charge in the capacitance will discharge and the final voltage on the object is likely to be low. As long as the stored energy is not very large the discharge current will be low. However, if the stored energy is large, such as on a relatively long de-energised circuit in parallel with an energised circuit, the discharge current may be high and dangerous.

Protection for this hazard is not within the scope of this Guide and would be covered by low-frequency induction codes and standards and O&M procedures for a given line (in particular for transmission lines operating above 100kV).

5.5.2.7 Lightning and other transients

Lightning is a significant source of hazards to electric utility employees and plant. Lightning over-voltages and currents can travel a long way over overhead lines and affect personnel working on earthing systems.

It is impractical to provide adequate protection to personnel in the form of earthing and equipotential bonding during lightning conditions because lightning surges typically have high current magnitude and rate of rise. All personnel should stop handling all conductors including those associated with any earthing system until the lightning hazard has passed. Guidelines existregarding managing staff risk to lightning for such circumstances (for example, flash to bang time limits, personal/group early warning systems).

5.6   Safety criteria selection (step 5)

The probabilistic method described within this Guide has been used to generate a number of safety criteria curves. The scenarios have been selected to cover a number of cases that are commonly met by design engineers within power utilities.

A particular value of the probabilistic method lies in being able to:

» Identify hazard scenarios where more traditional approaches are non- conservative and more stringent criteria may be justified on account of the risk profile to which the public or utility staff may be exposed.

» Alternatively the risk based approach is also able to identify hazard scenarios where the risk profile is very low and less stringent design targets than previously adopted may be justified.

The cases selected are summarised in *Table 5-2* following, and the additional details of the assumptions and the voltage/time (V/t) curves are included within *Appendix E*.

Remote assets: Assets may be considered as 'remote' if they do not require a certain touch voltage in order to comply with the fatality risk targets. This occurs when the coincidence probability is below the risk target.

Table 5-2: Safety criteria case study summary

Case		Description	Acronym
E-1	Transmission (≥66kV) and distribution assets (< 66kV)	Contact with transmission *asset* in urban interface location.	TU
		Contact with distribution *asset* in urban interface location.	DU
		Contact with metalwork in a backyard effected by either transmission or distribution asset.	TDB
		Contact with MEN connected metalwork (around house) where MEN or soil is effected by either transmission or distribution assets.	TDMEN
		Contact with metalwork associated with an aquatic centre that operates five months of the year.	AQ5
		Contact with metalwork associated with an aquatic centre that operates twelve 12 months of the year.	AQ12
E-2	Transmission substations (≥66kV secondary)	Backyard near major substation with primary side fault.	MSPB
		Backyard near transmission substation with secondary side fault.	TSSB
		MEN contact near transmission substation with secondary side fault.	TSSMEN
E-3	Zone substations (<66kV secondary)	Backyard near major substation with primary side fault.	MSPB
		Backyard near zone substation with secondary side fault.	ZSSBl
		MEN contact near zone substation with secondary side fault.	ZSSMEN
E-4	Inside major substations	Inside transmission substation.	TSI
		Inside zone substation.	ZSI

Note: The above case studies are examples chosen to demonstrate the application of safety voltage/time curves based on touch voltage hazards. Where applicable the allowable step voltage or hand to hand voltage/time curves (typically much less stringent than the allowable touch voltages) should also be checked and the lower voltage curve used.

The parameters have been selected with a view to conservatism, nevertheless the design practitioner should check to ensure that the assumptions do match the particular circumstances being analysed.

When the design being undertaken cannot be appropriately fitted to the published V/t criteria from the case studies producing direct probabilistic criteria may be the best option. The following section details the process for direct derivation with reference to both computer based derivation using **Argon** [28] (as has been used for the case studies) and a manual or 'by hand' method.

5.7 Probabilistic safety criteria derivation (step 6)

The allocation of allowable prospective touch voltages to specific hazard scenarios has been a common practise for many years. Various standards have included a range of allowable voltages derived by different means. The result has been that a designer has been faced with the difficult task of making sense of often conflicting, sometimes ambiguous safety target requirements from the competing standards. Although not overtly probabilistic in nature the various curves defined do embody a range of probabilistic factors including: percentiles of population current withstand and body resistance, footwear resistance and voltage withstand, and likelihood of presence at the time of a fault. This Guide provides a quantified risk based technique whereby safety criteria may be derived to reflect the various configurations found in practice. The basis applied for a safe earthing design is a low probability of electrocution.

The quantified risk analysis methodology utilises as its' basis the fact that a fatality due to an earth fault can only occur if both of the following situations exist:

» a person is present when a fault occurs, and the

» touch (or step) voltage generated is sufficient to allow a large enough current to pass through the body for sufficient time to cause fibrillation of the heart muscle.

The probability that a person will be present and in contact with an item at the same time that the item is affected by a fault is defined as the probability of coincidence $P_{(coinc)}$. The probability that the heart will enter ventricular fibrillation due to contact with an external voltage is the probability of fibrillation $P_{(fib)}$. A key purpose of earthing system design is to maintain the likelihood of a fatality occurring $P_{(fatality)}$, which can be described by the following simple equation, to within societally acceptable limits.

$$P_{fatality} = P_{coinc} \times P_{fib}$$
1

The societally acceptable limits supported by this Guide are based upon meeting both individual limits, and societal (or multiple) risk limits as covered in **Sections 4.4.2** and **4.4.6**. The process of assessing a given design for both risk categories (i.e. individual risk and societal risk), is covered in this design step.

The calculation of the probability of coincidence may be simplified significantly if the following conditions are met:

» the occurrence of an earth fault is random

» the occurrence of an earth fault is independent of the presence of a person

» the occurrence of an earth fault will be independent of the occurrence of past earth faults

» earth faults occur one at a time and have an approximately equal probability of occurring at any given time.

The development of a probabilistic risk approach on the basis of these assumptions restricts the application of the calculation to persons who will not contribute to or cause risk events to occur, and situations for which a fault which causes the risk event will not cause the generation of additional faults. For scenarios where occurrence of an earth fault is not independent of the presence of an individual (for example, operational switching) it may be prudent to consider special precautions.

The calculation of the probability of fatality is limited by the accuracy of the available data and the conditions under which the hazard may occur. The following sections provide an overview of the Safety Criteria Derivation methodology, with supporting detail and case studies being provided in the appendices:

1. methodology overview

2. coincidence calculation (step 6A)

3. fatality probability compliance assessment (step 6B)

4. calculable fatality probability and assess risk profile (step 6C)

5. hazard mitigation assessment (step 6D).

5.7.1 Methodology overview

The probabilistic safety criteria derivation methodology enables a designer to build (or select) touch voltage criteria that reflect the following requirements:

» series resistances present (for example, footwear, soil, crushed rock, asphalt)

» frequency and duration of both earth faults and contact by people

» acceptable individual risk and societal risk targets.

The methodology itself must be practical to implement (i.e. not require inordinate data gathering, or analysis time), be transparent (i.e. all embedded assumptions accessible), be consistent in application not be susceptible to misinterpretation or misuse, and be able to clearly document applicable boundary conditions.

Two methods are presented with this Guide:

» **Manual technique**—A manual technique that provides solutions for individual risk, covering a range of series resistance and contact scenarios, has been described in *Appendix C*.

» **ARGON technique**—A software based approach (**Argon** [28]) has been implemented that provides utility staff with the capability to develop safety criteria to match actual risk profiles. The remainder of this section outlines this approach.

The various stages of the criteria derivation process are incorporated throughout the overall design process (see *Section 5.1.2*, *Figure 5-2* and *Table 5-1*). To more clearly identify the shock safety management aspects a flowchart has been formulated (see *Figure 5-5* following).

Each of the steps is described in more detail in the following sections with supporting information provided in the appendices.

5.7.2 Coincidence calculations (step 6A)

The first stage in the derivation process is to determine the likelihood of a person being present at the time of a fault occurrence (i.e. P_{coinc}). While not a customary assessment this is the logical first step based upon the major significance the coincidence probability plays in the risk profile formulation.

From Equation 1, if the maximum acceptable risk of fatality is set to a predetermined value (for example, 10^{-6} or 10^{-4} $P_{fatality}$ target), then for a known value of fibrillation probability there is a value of coincidence probability that determines whether the acceptable risk of fatality has been met.
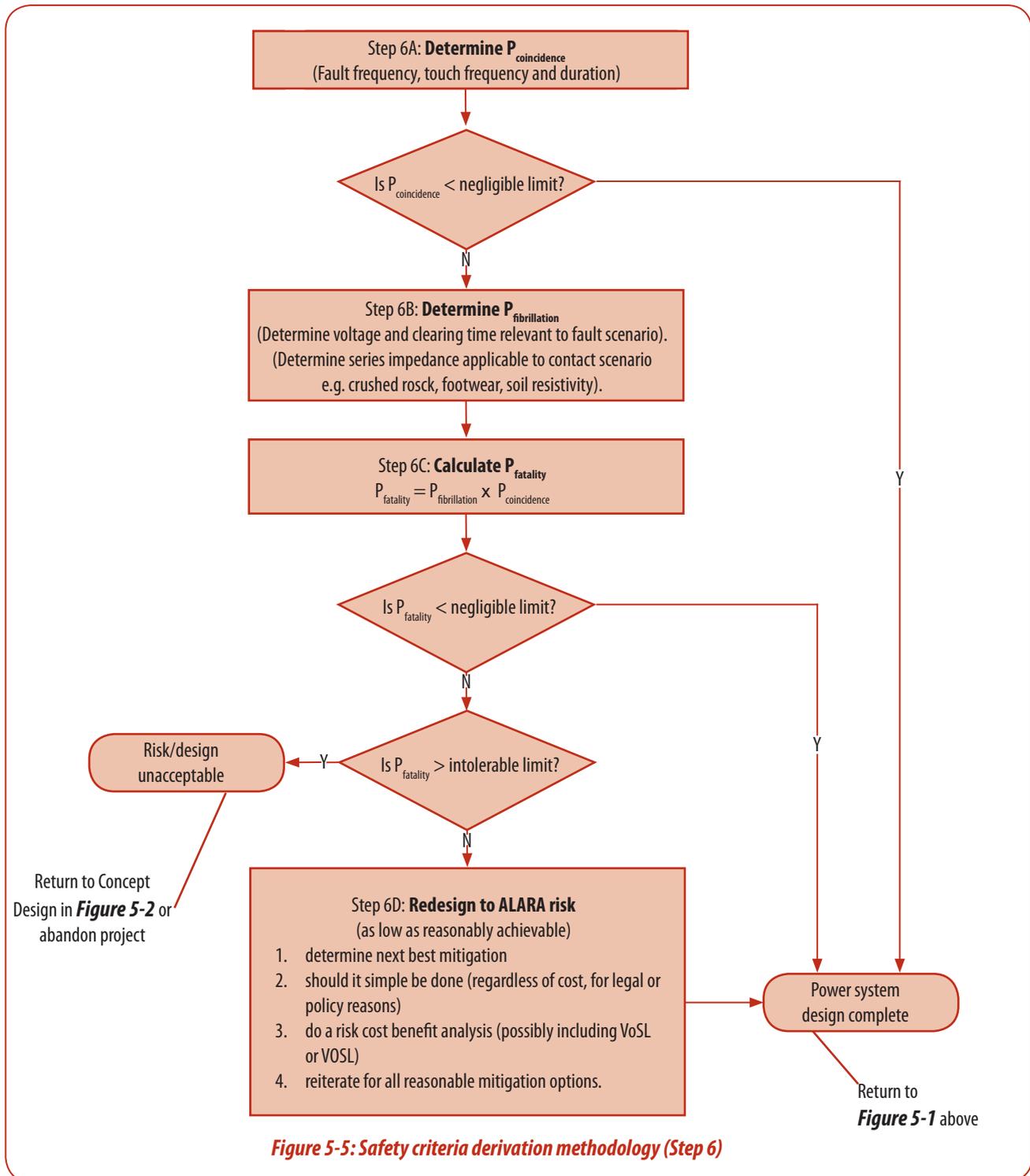
5.7.2.1 Neglibible or low risk and remote locations

If the coincidence probability is less than the allowable societal risk limits the hazard is of an acceptable level independent of the fibrillation probability. This condition is met for some low fault frequency cases (for example, some transmission structures without shield wires) or for 'remote locations' where people rarely make contact. In such instances the earthing system specifications are dictated by system reliability requirements (for example, insulation coordination and protection operation) or equipment damage requirements (for example, telecommunications plant, pipeline insulations, railways signalling equipment). In some cases a standard design procedure may still be followed if the cost is low and the action expected.

5.7.2.2 Coincidence calculation (step 6A)

The fault/contact coincidence probability, for both individual and societal (multiple) risk exposures, may be calculated using the formulae given in *Appendix A.1*. The selection of contact frequency and duration is a process that is new to most designers, and one for which very little published literature is available. Nevertheless it is implicit within all previous design methodologies and targets. It is usual that a conservative value be assumed in the first instance, and only revised downward as required within the risk cost benefit analysis (RCBA) framework.

Location classifications should be as inclusive as may be reasonably applied (i.e. encompass broad range of cases) in order to simplify the selection process and increase tolerance to local perturbations or changes in access profile. As for all engineering design methodologies it is

Step 6A: **Determine P$_{coincidence}$**
(Fault frequency, touch frequency and duration)

Is P$_{coincidence}$ < negligible limit?

N

Step 6B: **Determine P$_{fibrillation}$**
(Determine voltage and clearing time relevant to fault scenario).
(Determine series impedance applicable to contact scenario
e.g. crushed rosck, footwear, soil resistivity).

Step 6C: **Calculate P$_{fatality}$**
P$_{fatality}$ = P$_{fibrillation}$ x P$_{coincidence}$

Is P$_{fatality}$ < negligible limit?

N

Risk/design
unacceptable

Y   Is P$_{fatality}$ > intolerable limit?

N

Return to Concept
Design in **Figure 5-2** or
abandon project

Y

Y

Step 6D: **Redesign to ALARA risk**
(as low as reasonably achievable)
1. determine next best mitigation
2. should it simple be done (regardless of cost, for legal or
   policy reasons)
3. do a risk cost benefit analysis (possibly including VoSL
   or VOSL)
4. reiterate for all reasonable mitigation options.

Power system
design complete

Return to
Figure 5-1 above

Figure 5-5: Safety criteria derivation methodology (Step 6)

critical that appropriate attention be given to sensitivity and criticality analysis. In this regard the process may be checked by selecting an applied voltage/time characteristic and fault scenario and calculating the contact frequency and duration that meets the risk target.

Appendix A provides additional information regarding the calculation of fault/contact coincidence including:

» derivation of individual and societal risk coincidence probability formulae

» coincidence multiplier table for sample exposures

» fault duration and rate tables and guidance

» non uniform arrival situations.

If the fault/contact coincidence probability is less than the lower limit for individual and societal risk, then the risk associated with the hazard scenario is acceptable independent of the fibrillation

probability. Nevertheless there may be an additional reason for undertaking additional earthing or mitigation measures at the site (see **Section 5.7.5**).

5.7.3 Fibrillation probability calculations (step 6B)

If the coincidence value calculated does not meet the individual or societal 'Neglibible risk' targets then, according to Equation 1, the fibrillation probability may be calculated and used to reduce the fatality probability. A series of voltage time curves have been derived that have constant fibrillation probability independent of fault duration based upon IEC 60479. Such constant probability (P_{fib}) curves are needed to make resolution of Equation 1 possible without additional detailed calculations, as P_{coinc} is also dependant upon fault duration. The methodology used to derive constant fibrillation curves is outlined in **Appendix B**.

Tables of voltage time characteristics with constant $P_{fibrillation}$ included in **Appendix B** have been derived to cover appropriate combinations of the following cases:

» contact configuration—touch, step and hand to hand voltages
» upper layer soil resistivity—50, 100, 500, 1000, 2000, 5000 ohm.m
» surface layer materials—crushed rock, asphalt
» additional series impedances—footwear, electrical footwear
» moisture—wet or dry hands.

For situations where the voltage and clearing time give a point between two constant probability curves, the higher of the curves is used as a conservative value for the design. Alternatively the **Argon** software may be used to analyse a wider range of constant probability curves.

5.7.4 Calculate fatality probability and assess risk profile (step 6C)

Using Equation 1 it is a simple matter to calculate the expected probability of fatality associated with the specified fault/contact and applied voltage scenario selected. Both individual and societal risk scenarios (defined in **Section 4.4.2.3**) should be assessed against targets outlined in **Section 4.4.6**. Should the outcome lie in the intolerable Region the risk must be mitigated (see **Section 5.8**) and re-assessed. If it is assessed to lie in the ALARA Region then the process as outlined in **Section 5.7.5** and **Appendix F** should be followed.
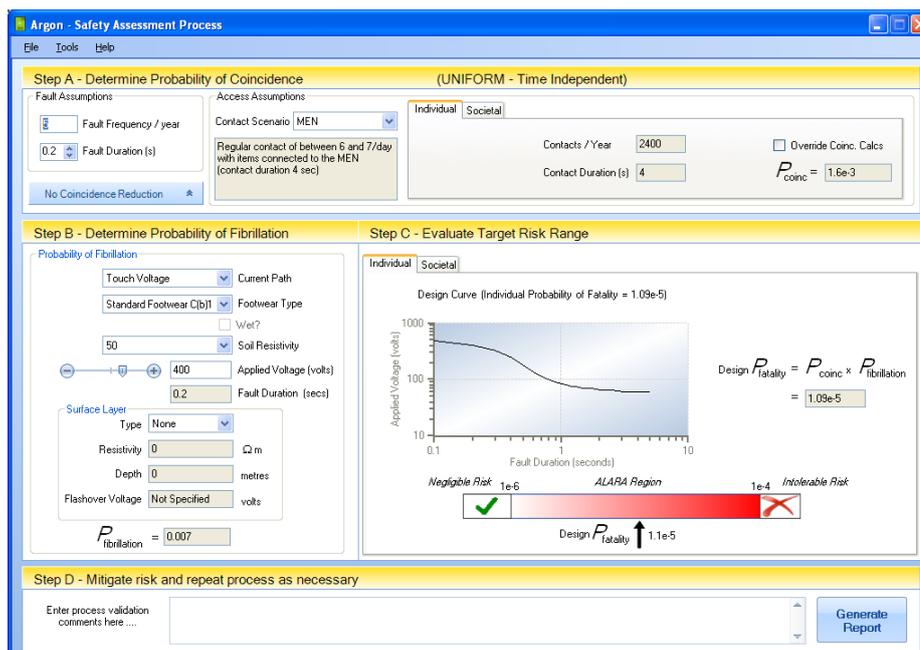

Figure 5-6: Individual safety assessment

5.7.4.1   Individual fatality risk assessment

For assessing individual risk scenarios, the **Argon** software may be used as an alternative to the manual calculation method to determine design compliance as shown in **Figure 5-6** following.

The output from the process is a design curve that corresponds to the specific probability of fatality relevant to this design case. If the design is considered compliant (i.e. either has a probability of fatality $<10^{-6}$, or is in the ALARA Region and deemed to be acceptable), then the design curve is valid for designs which have the same fault/presence profile. This requires that the number and duration of contacts be non-varying, as well as the fault frequency. The acceptable voltage/time curve has been calculated for the range of fault durations shown, allowing for the variation in fault/contact coincidence with variations in fault duration.

A similar process shall be applied for any contact configuration (i.e. touch, transfer, step or hand to hand) and the lower (i.e. more stringent) voltage curve used for the design of the earthing system.

5.7.4.2   Societal (multiple) fatality risk assessment

To determine the compliance of a situation involving a societal presence profile, it is necessary to calculate the societal probability of coincidence associated with multiple fatalities (see **Appendix A.1**) associated with average exposure characteristics. This is combined with the probability of fibrillation for the design scenario to determine the societal probability of fatality and the results can be laid over the target F-N curve.

As a demonstration, for a particular situation involving an exposed population of 100 people (i.e. number of people that could be reasonably expected to come in contact at one time), the following results for societal coincidence were obtained:

Table 5-3: Societal (multiple fatality) F-N risk curve construction example

Number of people (N)	Probability that N will be coincident with a fault	Probability that >N will be coincident with a fault
1	6.378×10^{-3}	2.36×10^{-3}
2	9.93×10^{-5}	3.67×10^{-5}
3	1.04×10^{-6}	3.83×10^{-7}
4	8.02×10^{-9}	2.97×10^{-9}

For a calculated probability of fibrillation of 0.37 (based upon an applied voltage, fault duration, and series resistance), the following curve is obtained:
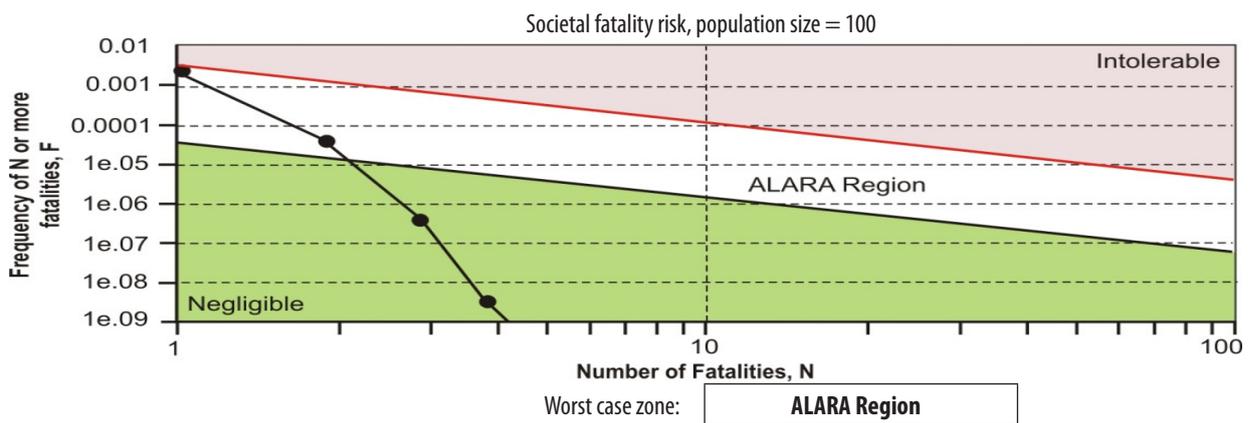
Figure 5-7: F-N societal risk curve example

Because some of the curve shown in **Figure 5-7** example exists in the ALARA Region, ALARA principles are to be used to reduce the risk profile. If the calculated fatality probability lies within the ALARA Region, it is necessary to consider mitigation in the design. Therefore move on to Step 6D of the procedure (see **Section 5.7.5**) and consider what options are appropriate.

If using the 'by-hand' methodology provided in **Appendix C** or the software based approach (see **Argon** [28] software), the results should be the same for individual risk. The 'by-hand' approach does not allow for

calculation of multiple fatalities (i.e. societal risk assessment). However, this is not a major limitation as the societal fatality scenario is usually only the critical case for locations where many people congregate regularly. In these cases the standard curves given in **Section 5.6** should be used or an analysis of the specific scenario should be undertaken using the **Argon** software 'gathering' functionality.

5.7.5 Redesign to ALARA risk principles (step 6D)

If compliance is not achieved following Step 6C then a review of available mitigation and improvement strategies is required. It is likely that substantial consideration and some reiteration will be required to determine the right improvements to make. **Section 5-8** following details a range of design improvements that may be considered. For each available improvement some ALARA consideration is prudent as is documenting options dismissed as well as those implemented.

Mitigation options often fall into two categories: either reduce the hazard (the presented voltage or clearing time), or reduce the probability of coincidence.

5.7.5.1   Option 1: Reduce presented voltage or clearing time

Table 5-4 summarises the primary mitigation options that are typically considered.

Table 5-4: Primary mitigation options

Option category	Examples
voltage reduction	» reduce return impedance (e.g. augment grid, cable screen bonding) » reassess drive current (e.g. fault impedance)
clearing time reduction	» protection setting or type changed.

Additional guidanceregarding primary mitigation options is provided in **Section 5.8**.

5.7.5.2   Option 2: Reduce the probability of coincidence

Table 5-5 gives indicative values of coincidence reduction factors that may be applied in step 6D.

Table 5-5: coincidence reduction methods

Coincidence reduction method	Coincidence reduction factor (CRF)*
» install barrier fence	0.1
» install insulation covering	0.4
» restricted access, PPE and SWMS	0.5
» install sign	0.8

NOTE (*): Indicative values only. Provided to illustrate process, yet expected to be conservative if implemented properly.

In some cases, even if the absolute level of risk associated with a given exposure scenario is very low, it may still be prudent to undertake remedial action. Conversely the cost and/or practicability may make any mitigation measure difficult to justify. The following questions provide a means for examining the issues from a range of perspectives:

» Is the level of risk above an acceptable value?

» Has the variable nature of the input parameters been assessed? For example, the actual fault current may be lower than the 'planning value' on account of additional fault resistance.

» Does a risk cost-benefit analysis (RCBA) yield a positive result considering 'all-of-life' costs? A positive result is achieved if many people are affected or it is a high exposure location, and the hazard may be mitigated with reasonable cost. The use of risk cost benefit analysis may provide a mechanism for gauging the relative value of the risk reduction options, however, it should not be used as the only arbiter in decision making [11-14].

» Does the remedial action lower the fear level of the public or raise their confidence in the utility (for example, Use of brick boundary fences)?

» Is there another reason to justify the expense? Examples might include:
  » need to maintain corporate image
  » more than one person may die at a time

» contravention of a legally binding statute
» operational imperatives at risk (for example, continuity of supply).

For detailed discussion regarding application of the RCBA process in managing earthing related risks refer to **Appendix F**.

5.8   Design improvements (step 7)

When designing earthing systems, the following primary and secondary risk treatment methods may be considered when assessing how best to manage the risk associated with step, touch and transferred voltage hazards:

» reduction of the impedance of the earthing system
» reduction of earth fault current
» reduction of the fault clearing times
» surface insulating layer
» installation of gradient control conductors
» separation of HV and LV earth electrodes
» isolation
» coincidence reduction (for example, Barriers, signs)
» relocation of non compliance infrastructure (for example, Telco pits).

Often a combination of risk treatments will be required to control EPR hazards. Each of these methods is briefly discussed in the following points.

5.8.1   Reducing earth system impedance

Reduction in the impedance of an earthing system can be effective in reducing the EPR hazards. However, since the fault current usually increases as the earth grid impedance decreases, the effectiveness of the reduction depends on the impedance of the earth grid relative to the total earth fault circuit impedance. For the reduction to be effective, the reduced impedance needs to be low compared to the other impedances in the faulted circuit. Typically, the earth grid impedance must approach the power system source impedance before the EPR starts decreasing significantly.

If the earthing system earth impedance is reduced by enlarging the earthing system, then even though the EPR on the earthing system will reduce, the resultant EPR contours may be pushed out further. In some circumstances, the increase in the size of the EPR contours may be significant for a small reduction in the EPR of the system. As a result, the size of any transferred EPR hazard zones will increase which represents an increase in risk exposure presented to the surrounding area. Whether this represents overall, a desirable outcome will depend on the particular situation.

If the earthing system earth impedance is reduced by bonding remote earths to it, then the resultant reduced EPR is also spread to the remote earths. This also introduces new transferred EPRs onto the earthing system when there are earth faults at any of these remote earths. Examples of this include bonding the earthing system to extensive LV network systems. This risk treatment measure can be very effective in significant urban areas where an extensive earthing system can be obtained by bonding together MEN conductors from adjacent LV networks.

5.8.1.1   Earth electrode enhancement

If the soil resistivity is high and the available area for the grounding system is restricted, methods of enhancing the earth electrode may be required. Such methods include the encasement of the electrode in conducting compounds, chemical treatment of the soil surrounding the electrode and the use of buried metal strips, wires or cables.

These methods may be considered as a possible solution to the problem of high electrode resistance to earth. They may also be applied in areas where considerable variation of electrode resistance is experienced due to seasonal climatic changes.

Chemical treatment of the soil surrounding an electrode should only be considered in exceptional circumstances where no other practical solution exists, as the treatment requires regular

maintenance. Since there is a tendency for the applied salts to be washed away by rain, it is necessary to reapply the treatment at regular intervals. The salts can also accelerate corrosion on systems that are subject to the treatment.

5.8.2 Reduction of earth fault current

5.8.2.1 Neutral earthing impedances and resonant earthing

Earth fault currents flowing through earthing systems may be reduced by the installations of neutral earthing impedances such as neutral earthing resistors (NER). Alternatively, resonant earthing such as Petersen Coils, arc suppression coils, earth fault neutraliser earthing, may be very effective.

NERs are typically employed in distribution networks to limit the current that would flow through the neutral star point of a transformer or generator in the event of an earth fault. The effect on protection clearing must be investigated when considering NERs at zone substations, especially where there are long rural feeders. The earth fault level is very low towards the end of these feeders. In the event of an earth fault the NERs could further reduce earth fault current preventing the fault from being cleared by the protection device. Care should also be exercised when retrofitting NERs if equipment is not sufficiently rated to withstand the additional phase voltage offset on the healthy phases during earth fault conditions. Insulation levels of transformer neutral end and arrestors, if not fully rated, will be stressed during earth fault conditions.

NERs may be an effective way of reducing the EPR at faulted sites and thereby controlling step, touch and transferred voltages especially in urban areas where distribution system earth electrodes are bonded to a significant MEN system. However, the reduction in EPR may not always be significant if the impedance of the earthing system is relatively high. The use of NERs for the control of EPR hazards should be investigated on a case by case basis. NERs can be very effective in reducing induction into parallel services such as telecommunication circuits or pipelines.

Resonant earthing (Petersen Coils) are also very effective in controlling step, touch and transferred voltages. A Petersen Coil is an inductance that is connected between the neutral point of the system and earth. The inductance of the coil is adjusted so that on the occurrence of a single phase to earth fault, the capacitive current in the unfaulted phases is compensated by the inductive current passed by the Petersen coil. Resonant earthing can reduce MEN EPR to a safe level even in systems with high MEN resistance.

Studies show that fault restriction may be useful in limiting risk at the point of fault (i.e. pole top substation), but may not be necessary if the first number of kilometres of feeder are underground cables. When examining major substation EPR magnitude it has been found that the actual fault levels can be expected to be much less than the conservative 'bus fault impedance plus one ohm', calculated value in common use.

5.8.2.2 Overhead shield wires

Shield wires are typically used on transmission lines at or above 66kV, and sometimes for only a short section of line out from the substation. Shield wires are also sometimes used on distribution lines (11 kV and above) for the first kilometre out from the substation but this is not common.

While the primary purpose of the shield wires is to provide lightning shielding for the substation or line, bonding of the shield wires to the substation earth grid can significantly reduce earth fault currents flowing through the local earth grid into the soil for faults at the station, or at conductive poles, or towers bonded to the shield wires.

Inductive coupling between the shield wire(s) and the faulted phase conductor can significantly reduce the earth return current flowing into the ground at conductive poles or towers bonded to the shield wire(s) during fault conditions. This, in turn, reduces the EPR levels at both the substation and at the conductive pole or tower. However, the incidence of (transferred) EPR events at the conductive poles or towers will become more frequent since each station or line fault EPR will be transferred to the nearby towers/poles. For a busbar earth fault at a substation, the shield wires can divert significant current away from the substation earth grid. The net effect of the shield wires is to reduce the earth return current, thereby reducing the EPR.

Consideration must be given to the shield wire size (fault rating), particularly for the first few spans from the substation.

Adjacent lines in a common easement or running nearby (but not into) a substation can benefit from interconnection of the powerline shield wires and to the substation earth system.

5.8.2.3 Cable screen

Bonded cable screens provide conductive and inductive return fault current paths for both faults on the cable faults downstream at destination substations. Bonding of cable screens to the earthing systems at both ends is advantageous to earthing systems in most situations. However, the transfer of EPR hazards through the cable screens to remote sites should be considered as part of the earthing safety design.

The bonding of single core cables at both ends may affect the rating of the cables, depending on the cable configuration (due to induced load currents in the screens and sheaths). Care should be taken to ensure the rating of the cable is adequate for the application. Alternative screen bonding methods may be required if there are heat dissipation limitations (especially for voltages greater than 33kV). The rating of the cable screens should be adequate for the expected earth fault current and fault current duration and for the current induced in the screen during normal operation.

Insulation coordination needs to be considered, especially on long cable sections to ensure the induced voltages do not cause damage to cable insulation or serving.

Sometimes an earth continuity conductor is run as a surrogate cable screen, to provide the benefit to the circuit earthing system performance without de-rating or stressing the insulation of the cables associated with the circuit.

5.8.3 Reduction of fault clearing times

EPR hazards can be mitigated by the reduction of the fault clearing time. This may be easy to implement and may be very effective.

However, reduction of the fault clearing time may require significant protection review and upgrade, and may prove impracticable. The need for adequate protection grading may also limit the effectiveness of this measure. Where sectionalisers and reclosers are used, the sections of feeder with slow clearing times (for grading purposes) often correlate with much lower fault levels due to line impedance.

5.8.4 Surface insulating layer

To limit the current flowing through a person contacting a temporary livened earthed structure, a thin layer of high resistivity material, such as crushed rock or asphalt, is often used on top of the ground surface. This thin layer of surface material helps in limiting the body current by adding resistance to touch and step voltage circuits (see also *Appendix B*).

5.8.4.1 Crushed rock

Crushed rock is used mainly, but not exclusively, in zone substations and transmission substations to increase tolerable levels of touch and step voltages during a power system earth fault, and to provide a weed-free, self draining surface.

For design purposes the following characteristics are typical for crushed rock specification.

  » a resistivity of 3000 Ω-m, and
  » a minimum thickness of 100 mm.

The insulating property of crushed rock can be easily compromised by pollution (for example, with soil). Therefore, regular inspection and maintenance of a crushed rock layer is required to ensure that the layer stays clean and maintains its minimum required thickness.

Close attention is required to the preparation of the ground prior to the application of crushed rock or asphalt. Suitable base course shall be prepared before laying the crushed rock or asphalt.

Chip seal or scoria (i.e. light, porous, volcanic rock) should not be used since the resistivity of the chip seal surface is not typically very high and its breakdown voltage is usually low.

5.8.4.2 Asphalt

Asphalt may also be used in zone substations and transmission substations but is likely to be more expensive than crushed rock. Asphalt has the advantage of providing easier vehicle access. Vehicle access over crushed rock may sometimes be problematic especially if the base course is not prepared correctly.

Asphalt can also be used to control touch and step voltages around towers and poles and is often justifiable in areas with pedestrian traffic.

Limited data is available on the flashover withstand of asphalt, which may be as low as 2kV for a 50 mm thick sample in relatively poor condition. Therefore, where asphalt is used for mitigation, touch voltage should typically not exceed 3kV and step voltage should not exceed 5kV. For some cold mix asphalt formulations even these levels may not be met. For applications where these limits are exceeded, the withstand voltage should be determined based on the type of asphalt that is being considered.

The insulating property of asphalt can be compromised by cracks and excessive water penetration. The integrity of the asphalt layer used for surface treatment must be maintained.

5.8.4.3   Concrete

Concrete should not be used to control touch and step potentials due to its low resistivity. The reinforcing in the concrete can be used to provide an equipotential zone where it is prepared and bonded appropriately. A layer of asphalt may be used within 1m of the edge of the slab if a step voltage requires hazard mitigation.

A reasonably sized house slab with PVC underlay will remain reasonably dry and tests have shown an impedance of at least 1500 ohms, between a 'foot' electrode on the moistened slab and the MEN conductor. This may be considered as a part of a design solution for a particular case (if appropriate).

Many new installations will have 'wet area' reinforcing metalwork bonded to the MEN conductor to provide equipotential bonding, and thereby reducing the shock risk. The use of non-conductive water pipes within houses will almost eliminate the shock risk associated with impressed voltages from the MEN network or soil due to neighbouring earthing installations (see *Section 5.8.7*).

5.8.5   Gradient control conductors

Touch voltages on a structure can be mitigated to some extent by using gradient control conductors buried at various distances from the structure. Typically gradient control conductors are buried at a distance of one metre from the structure. Additional gradient control conductors are also buried further out from structures as required.

In zone and transmission substations, gradient control conductors are typically used for the control of touch voltages outside the station security fence. These conductors are more effective when used in conjunction with a metre wide strip of crushed rock or asphalt installed around the outside of the fence. When designing zone and transmission substations, provision should be made to allow such a strip to be installed, if required.

Gradient control conductors can also be used to control touch voltages on distribution substations and equipment.

Step voltages can also be controlled with the use of gradient control conductors. One or more gradient control conductors may be positioned in a concentric configuration at increasing distances from the structure (i.e. 1m, 2m), and the buried depth of each gradient control conductor is increased as the distance increases. However, this measure will push the EPR contours further out from the structure and the resulting effects on third party equipment should be considered.

Bonding of reinforcement in slabs/pathways/driveways can also prove useful in reducing step voltages (see *Section 5.8.4*).

5.8.6   Separation of HV and LV earth electrodes

When an earth fault takes place at the HV side of a distribution centre, the EPR on the HV earth electrode is transferred to the LV system via the PEN conductor. By electrically (and physically) separating the HV and LV electrodes, the transfer of EPR from the HV system to the LV system can be controlled.

The minimum separation distance required between the HV and LV earthing systems is dependant on:

- »   the size of the HV earthing system
- »   soil resistivity
- »   the maximum EPR on the HV earthing system, and
- »   the distances to the earths bonded to the LV system.

A minimum separation distance of 4 m is suggested between the HV and LV earthing systems. In some instances the required separation may be much larger (i.e. low/high soil resistivity layering and a LV network with limited number of customers).

The integrity of the separated HV and LV earthing systems may be difficult to maintain into the future since other earthed or conductive structures may be installed at later stages within the area between the earth systems. These new structures may compromise the electrical separation.

Separated HV and LV earthing systems may not be effective in controlling hazardous step and touch voltages in the event of an HV line to LV line contact at the distribution transformer, or on a conjoint HV/LV line section. The following options may be considered for protecting against HV to LV contacts:

» Ensuring the configuration of LV lines at the distribution transformer poles is such that an HV line to LV line contact is unlikely.
» Replacing the LV lines over conjoint HV/LV spans with:
   » LV buried cable
   » LV lines on separate poles, or
   » LV aerial bundled conductor cable that is insulated to withstand the full HV conductor voltage.

The transformer shall be rated to withstand the maximum EPR on the HV earthing system, without breaking down to the LV side of the transformer (for example, vian HV/LV winding breakdown, or transformer tank to LV winding breakdown).

When the LV earthing system is segregated from the HV earthing system at a distribution substation, the total earth impedance of the LV earthing system plus associated MEN earths, must be sufficiently low to ensure the HV feeder protection will operate in the event of an HV winding to LV winding fault. A safety factor should be considered when calculating this maximum earth impedance value.

For the earthing of the HV and LV systems, two acceptable methods are to either combine the two earthing systems together or to separate them.

In either case, the risk associated with step, touch, transferred and stress voltages within both the HV and the LV installation shall be managed.

5.8.6.1   Combined HV/LV earth systems

For major substations such as zone and transmission substations a single combined (common) earthing system is typically used. Under special circumstances such as those involving underground mining installations or where the LV supply for the substation is fed from an external street LV supply a design departing from this principal may be necessary.

Furthermore, the HV and LV earthing systems shall be interconnected if the LV system is totally confined within the area covered by the HV earthing system.

For distribution substations (for example, 11kV/400V or 22kV/400V) a combined earthing system is the preferred configuration. However, a segregated earthing system, as detailed below in *Section 5.8.6.2*, may be necessary in certain circumstances where adequate control of the risks associated with step, touch and transferred voltages cannot be achieved with a combined earthing system.

Adequate control of the risks associated with step, touch and transferred voltage may be achieved where there is a significant density of HV and LV earth electrodes through the interconnection of local earthing systems. Large earth electrode densities are typically achieved in large urban distribution networks which are interconnected via cable screens or overhead shield wires and/or via interconnected neutral conductors. Overhead shield wires, interconnected LV neutral that are part of a common multiple earthed neutral system and HV cable sheaths may also provide a path back to source substations for HV earth fault currents. A significant portion of the earth fault currents may return to source via these paths thereby resulting in low risks from step, touch and transferred voltages.

5.8.6.2   Separated HV/LV earth systems

Separation (segregation) of HV and LV earthing systems ensures that only a small portion of the EPR on the HV earthing system is transferred onto the LV earthing system. Touch and step voltages, and voltages which are transferred to third party equipment such as telecommunication equipment are controlled in this way. Refer to *Section 5.8.6* for design considerations.

Separation is often preferred in rural areas where low values of combined HV and LV resistance are difficult to achieve as there are few LV customers.

If high voltage and low voltage earthing systems are separated, the method of separating earth electrodes shall be chosen such that the risk to persons or equipment in the low voltage installation is minimised. This means that the potential rise of the neutral of the LV installation caused by an HV fault shall carry a low risk.

5.8.7 Isolation

Access to structures where hazardous touch voltages may be present can be restricted by the installation of safety barriers or fences. These barriers or fences would typically be non-conductive such as wood, plastic or rubber. For example, a tower could be surrounded by a wooden fence to restrict access to the tower base, or a sheet of rubber could be wrapped around the base of a steel or concrete pole. The installation of isolation barriers usually requires ongoing maintenance but can be very effective in reducing the risk.

Third party fences should be isolated from the substation security fence using non-conductive section of fences. Non-conductive sections may also be required at additional locations along third party fences.

Mitigation of step and touch voltages of metallic pipelines (for example, water pipes connected to an HV or LV network earthing system) can be effectively achieved by the installation of non conductive pipes.

5.9 Lightning and transient design (step 8)

Lightning directly or indirectly (i.e. via phase conductors) incident upon a substation may cause damage to both primary and secondary plant. Collection and dissipation of the incident energy always involves components within the earthing system. Configuring the earthing system to effectively manage this energy is one task of the design engineers (See AS1768).

One aspect to be considered (particularly in transmission substations) is electromagnetic interference (EMI) associated with a range of transient current sources, including:

» lightning surges
» switching surges
» earth fault 'd.c. offset'
» gas insulated switchgear operation
» portable radio transmitter operation
» electrostatic discharge.

The voltage phenomena created by these 'noise' sources affect equipment in a number of ways which are often dependent upon the earthing system configuration:

» direct or conductive interference—voltage differences in the earthing system causing current flow in cable screens
» guided Interference—Inductive and capacitive coupling from currents and voltages in phase conductors and earth conductors
» radiated interference—caused by switch arcing, arc gap operation or insulation breakdown, are picked up by secondary circuit operating as antennae.

While earthing of secondary systems may not be the direct responsibility of the HV earthing system design engineer, incorrect coordination with the earthing and grounding of the secondary systems (i.e. protection, d.c. and a.c. auxiliary power and control wiring) may result in:

» equipment damage (for example, relays damaged)
» operational reliability reduction (for example, false or no CB tripping)
» human safety risk (for example, fires due to sparking in hazardous areas).

Assessing electromagnetic interference (EMI) sources, coupling mechanisms, interference levels, and resultant physical damage or operational impactregarding the impact of the earthing system configuration, should be part of the earthing system design scope, as it is always far harder to mitigate EMI risks following installation.

6.   Construction support (step 9)

During the site construction phase of the project there are several aspects that need to be addressed in managing the earthing system risks.

» ensuring physical implementation of the design is compliant and installed/built to an appropriate standard/quality

» addressing the electrical shock safety of construction staff

» approving design changes (or managing construction changes/variations) that may impact the earthing system and answering requests for information/clarification.

6.1   Physical implementation compliance

Many elements of an installed earthing system are only able to be inspected during construction. It is also cost prohibitive to inspect many components once buried. Designs may specify detailed requirements (such as termination) on a project basis (for example, site specific drawings) or via standard constructions (using staff training or standard drawings).

During construction, therefore, suitable hold points and witness points are required to be specified to allow accurate 'as built' drawings to be produced and to ensure an acceptable quality of workmanship is maintained.

This also provides several additional benefits:

(a)   defects and site specific issues arising during installation can be cost effectively managed through various means, including:

» quality of workmanship

» adherence to specification/approved practice

» equipment risks—corrosion risks (for example, soil contaminant near grid conductors)

(b)   methods of simplifying or easing the installation process can be incorporated and the system improvements captured/incorporated for future stages of the project or future designs

(c)   design improvements can be identified, such as

» simplifying ongoing supervision needs

» theft prevention

» Reducing material/labour needs.

6.2   Construction safety

At brown field sites or sites adjacent powerlines/distribution substations the risk profile presented by the site will be affected by the increased presence of construction staff. Consideration of this increased risk needs to be addressed. That consideration should result in site direction to construction staff. As a minimum the following items should be considered and site direction made/offered:

» Power Supply to construction areas and site sheds/offices:

» where substation power supply can be used

» where LV street supply can be used

» where appropriate use of portable generators and inverters

» use of isolation transformers if required.

» Specify locations for site sheds (either completely inside the earth grid or some minimum distance from the buried earth system).

» Specify laydown material storage areas (especially for conductive/metallic construction material), either completely inside the earth grid or some minimum distance from the buried earth system.

» Specify vehicle earthing requirements for plant such as:

» cranes near exposed HV

» concrete pumping vehicles

» trucks and motor lorry in live yards.

» Specify earthing requirements of temporary fencing.

» Specify staged earthing requirements for large projects.

» Personnel Protective Equipment—for example:

» insulating or riggers gloves

» footwear (use of rubber boots, Wellingtons)

» equipotential bonding loads

» isolating/insulation mats, etcetera.

» Required remedial works on existing assets, if required for example, earth break in third party fences.

» Defining of work areas and specific controls required in each area.

» Two examples are sectionalising bus systems to reduce the prospective fault current and disabling any reclose functions

Construction safety requirements are to be identified and the controls listed in the appropriate safe work method statement (SWMS) documentation.

7.   Commissioning and ongoing monitoring

7.1   Testing, inspection and monitoring principles

Owners or users of electrical installations must take all practicable steps to maintain their earthing systems in a configuration and condition to meet the requirements for safety and functional operation. They should also establish and operate administrative systems (including records of checks undertaken) that provide periodic safety checks at reasonable intervals appropriate to the operating environment and operational risks.

7.1.1   Documentation and records

All measurements and tests required should be properly recorded and the documentation kept. To enable the integrity of the earthing installation over a long period of time and its suitability for present fault levels to be assessed the following records should be maintained:

» initial design calculations and decisions
» results of commissioning tests
» results of periodic inspections and measurements
» updating of fault level
» drawings showing the earthing system layout including location and size of all earth conductors and electrodes, and the location of all grid connections.

7.2   Commissioning program and safety compliance review (step 10)

Commissioning of new earthing systems is essential as a validation step for the design and installation process and for the design inputs. In most cases commissioning should measure the outputs of the earthing system in terms of produced voltages and current distributions rather than solely resistance. The commissioning should consider closely the key performance criteria identified in the hazard identification and treatment analysis phases.

Commissioning will determine the earthing system initial compliance and set a benchmark or baseline for ongoing supervision. As it is not always possible to foresee all hazard mechanisms at the design stage commissioning testing should also determine the need for any localised secondary mitigation and any additional requirements for telecommunication coordination and pipeline interference coordination or mitigation.

The earthing system commissioning procedure normally consists of six core activities. In some instances, not all activities are required:

1. visual inspection
2. continuity testing
3. earth resistivity testing
4. earth potential rise (EPR) measurement
5. current distribution measurement
6. transfer, touch and step voltage testing.

7.2.1   Visual inspection

The visual inspection typically involves checks of:

» design compliance and as-built drawing accuracy
» condition of earthing conductors and connections
» condition of earthing electrodes
» presence and condition of earthing bonds to equipment
» condition of surface layer materials if required
» condition of access fences if required
» presence of transfer hazards.

7.2.2   Continuity testing

Continuity testing is used to measure the resistance between items of plant within the main earth grid and to components that should be effectively bonded to the grid. This test is especially important in large earthing systems where visual inspection of all conductors and connections is more difficult. Adequate bonding is essential to ensure that personnel are working only on equipment that is effectively connected to the earthing system.

7.2.3   Earth resistivity testing

It is often necessary to carry out earth resistivity tests in conjunction with performance assessments to allow accurate error corrections and safety criteria determination. Even where resistivity testing was undertaken at the design stage, additional testing (however brief) may help to define measurement errors and periodic variations.

7.2.4   Injection testing

The remaining tests require the presence of a simulated power system line to ground fault. To achieve this, a circuit is established between the earthing system under test and a remote injection point. Ideally this circuit should reflect the actual fault return point. Where this is not possible post testing analysis is necessary to reflect the actual fault scenario or scenarios. This may include multiple points of return.

The simulated fault is typically made sustainable by injecting a small current, commonly between 2 and 20 amps. The effects are made measurable, even on live systems, by injecting at a frequency away from power system frequency and using frequency tuneable measuring equipment. The test is referred to as a Low Current, Off Power Frequency Injection Test.

Earth potential rise (EPR) measurement

With test current flowing through the simulated fault circuit, voltages will be present in the same locations and in proportion to those generated during a real earth fault.

The earthing system's EPR is measured by performing a fall of potential test. This test requires a test lead to be run out from the earthing system to allow a series of voltage measurements to be made between the earthing system under test and the ground. The route and distance is chosen to minimise measurement errors.

The measurements taken from the fall of potential test must be processed for the difference between test and power system frequency and for distance to remote earth. They can then be used to determine the earth system impedance and the EPR under actual fault conditions. Adjustments should also be made for mutual earth resistance and for mutual inductance as required.

Direct remote earth measurements, such as voltage measurements to remotely earthed communications or pilot wires, can also supply supplementary test data. However, with single point measurement alone it is very difficult to correctly assess and correct the many error sources that can be part of any measurement taken.

Current distribution

In the situation where fault current may leave the earthing system through paths alternate to the earth grid (such as cable sheaths or overhead earth wires), the current through those alternate paths should also be measured. This allows analysis of how fault energy is dissipated, its effect on the alternate paths (for example, cable sheath capacity) and calculation of the earth grid impedance from the total system impedance. In complex systems the results are particularly important in modelling alternate fault scenarios and in-feeds not simulated during testing.

7.2.5   Transfer, touch and step voltage testing

While test current is flowing in the fault circuit, measurements are made of actual transfer, touch and step voltages. The purpose of such measurements is to directly measure the earthing system's outputs and the compliance with the determined safety criteria.

When measuring touch and step voltages it is important to measure the prospective touch and step voltages using a high impedance voltmeter and to measure the effective or loaded touch and step voltages appearing across an appropriate resistance that represents the human body. Care should be taken not to confuse the prospective step and touch voltages (i.e. open circuit case) with the effective step and touch voltages criteria. The loaded touch and step voltage cases are more variable due to variations in contact resistance. Therefore, the loaded case is only used when necessary and precautions taken (for example, take multiple measurements, use electrode contact initially, and only use a weighted plate on moistened soil if necessary).

7.2.6   Telecommunications coordination

Where telecommunications equipment is installed within the area of influence of a high voltage earthing system consideration is required of the hazards that may be created. In such cases notification must be given to the appropriate telecommunications group.

7.2.7   Pipeline interference / coordination

Where pipelines are installed within the area of influence of a high voltage earthing system consideration is required of the hazards that may be created. These hazards must be reviewed during commissioning. In such cases notification must be given to owner / operator of the pipeline.

7.3   Ongoing monitoring and maintenance

The ongoing supervision program should monitor aspects of the installation critical to maintaining safe operation and consider any 'external risks' identified during the design phase (for example, monitoring separation distances). The condition of the earthing system components should also be examined periodically by inspection. Excavating at representative locations and visual inspection are appropriate means.

Measurement of the earthing system performance should be carried out periodically or following major changes to the installation or power system which affect the fundamental requirements of the earthing system. Such measurements should generally follow the commissioning program. Continuity tests should also be undertaken.

7.3.1   Inspection and test intervals

The asset owner or user should determine appropriate inspections and tests intervals based on knowledge of its own earthing installations and design standards, and on its understanding of environmental conditions and assessment of risk (for example, soil conditions, theft of copper).

When work has taken place that may have interfered with the earthing system, the system in that area should be inspected and checked. All parts of the earthing system exposed by excavation should be inspected for damage or deterioration.

Where there is any probability of significant corrosion of the buried earth grid, more frequent inspections of the earth grid and connections shall be carried out and replacements made where necessary.

7.4   Final documentation (step 11)

Documentation is to include the physical installation description (for example, earthing system layout drawings) as well as electrical assumptions, design decisions, commissioning data, and monitoring and maintenance requirements.

To be most effective the documentation process should be an intfor exampleral part of the overall design process, with the requirements well understood by designers, field staff and project staff from the inception of the project. Configuration management requirements (see AS/NZ 3907) appropriate for a safety critical system such as an earthing system would include identifying and including the requirements within the 'system'. It is more likely that staff will take the time to document the initial design and any 'last minute' changes.

The final stage of the design process should be a formal 'sign-off' or handover process, whereby the design engineer is able to collate all the design documentation and ongoing management requirements for inclusion in the operational support documentation and programs for the installation.

Appendix A: Fault/contact coincidence probablity calculation

This appendix provides additional detail to that provided in **Section 5.7** regarding fault/contact coincidence probability (P_{coinc}) in the following sections:

A1   coincidence probability equation derivation

A2   coincidence lookup table

A3   fault duration and rate data

A4   calculation of the coincidence probability for variations in fault and exposure rate

A5   calculation of the coincidence probability for multiple hazard sources

A6   calculation of the coincidence probability for combined hazards.

A.1   Coincidence probability equation derivation

Coincidence probability formulae for both individual and multiple fault/contact event scenarios are required in order to assess individual and societal risk exposure. The following two sections outline the derivation of the formulae used within the guide and associated software.

A.1.1   Individual fault/contact coincidence probability calculation

The coincidence probability P_{coinc} is the probability that one or more risk events will occur during time period [0,T]. This could be a result of event A and/or event B:

> event A—a person is in contact with an earthed asset when a fault occurs
>
> event B—a person contacts an earthed asset during a fault.

Events A and B have been approximated as Poisson processes. The homogeneous Poisson process describes the arrival of random, independent events that are equally likely to occur at any time and has been used to derive P_{coinc}.

The Poisson distribution is used to describe event A as follows:

$$P(X_A = x) = \frac{(\lambda T)^x e^{-\lambda T}}{x!} \qquad \text{A-1}$$

Where: λ is the arrival rate of events.

T is the time period in which the risk events could occur.

X_A represents the number of risk events occurring as a result of a person being in contact with an earthed asset.

x is the number of risk events for which the probability is being calculated.

$P(X_A = x)$ is the probability that a total of *x* risk events occurred as a result of event A during time [0, T].

The probability that no risk events will occur (x = 0) in [0, T] is:

$$P(X_A = 0) = e^{-\lambda T} \qquad \text{A-2}$$

A standard conditional probability result allows us to break down a probability, P(D) say, in terms of the conditional probability $P(D|F)$. The result states that:

$$P(D) = E\{P(D|F)\} \qquad \text{A-3}$$

Where: E{c} is the expectation of c.

This result is applied below. It is not possible to have a risk event when an individual is not in the hazard area. Hence, the time for which an individual is not in the hazard area can be ignored. If there are M exposures during [0, T] then the probability that a risk event does not occur *(X = 0)* during any of those exposures is:

$$P(X_A = 0) \ = \ E\{P(X_A = 0 \mid A_1, A_2, ...A_M)\} \qquad \text{A-4}$$

$$= \ E\{P(X_{A1} = 0 \mid A_1) \, P(X_{A2} = 0 \mid A_2)\}... \, P(X_{AM} = 0 \mid A_M)\}$$

Where: $A_1, A_2, \ldots A_M$ are the exposure events $1, 2, \ldots, M$.

$P(X_{A1} = 0|A_1)$ is the probability that no risk event will occur during exposure one.

Note that the probabilities in (A-4) can be multiplied together since we are assuming a Poisson process.

The period of consideration is restricted to times for which an individual is present in the hazard area. In this case a fault must occur for a risk event to occur. The rate of arrival of risk events (λ) will be equal to the rate at which faults occur (λ_F).

$$\lambda_F = \lambda \tag{A-5}$$

If faults are equally likely to occur at any time and the length of each of the exposures is $T_1, T_2, \ldots T_M$, then the probability that no fault will occur during any of the exposures is:

$$
\begin{aligned}
P(X_A = 0) \quad &= \; E\{P(X_{A1} = 0 \mid A_1)P(X_{A2} = 0 \mid A_2)\ldots P(X_{AM} = (0 \mid A_M)\} \\
&= \; E\{(e^{-\lambda_{F1}T_2})(e^{-\lambda_{F2}T_2})\ldots(e^{-\lambda_{FM}T_M})\} \\
&= \; E\{e^{\sum_{i=1}^{m} \lambda_{F1}T_i}\} \quad (\lambda_F = \lambda_{F1} = \lambda_{F2} = \lambda_{FM}) \\
&= \; E\{e^{-\lambda_F T_{ETot}}\} \tag{A-6}
\end{aligned}
$$

Where: T_{ETot} iss the cumulative exposure time that occurs during $[0, T]$.
λ_F is the fault rate (assumed constant).

λ_F has been approximated as being constant (faults are equally likely to occur at any time), but a time varying fault rate may be applied by using different known values of λ_F (i.e. $\lambda_{F1}, \lambda_{F2}\ldots$) and calculating directly from the above expression. Alternatively T may be divided into periods fore which λ_F is constant.

Equation (A-6) can be simplified by making the conservative approximation:

$$e^{-\lambda_F T_{ETot}} \approx \; 1 - \lambda_F T_{ETot} \tag{A-7}$$

This approximation is valid as long as $\lambda_F T_{ETot}$ is small ($\lambda_F T_{ETot} = 10^{-2}$ gives an error of $5 \times 10^{-3}\%$). The expression for $P(X_A = 0)$ simplifies to:

$$P(X_A = 0) \approx E\{1 - \lambda_F T_{ETot}\} = 1 - \lambda_F \mu_E \tag{A-8}$$

Where: μ_E is the mean cumulative time spent in the hazard area during $[0, T]$.

The period $[0, T]$ can be defined arbitrarily. If f_n is expressed as the average number of faults in one year and is μ_E is defined as the average cumulative exposure in one year, then the probability of one or more risk events for Y years is:

$$P(X_A = 0) \approx 1 - f_n \mu_E Y \tag{A-9}$$

Where: $P(X_A = 0)$ is the probability that no risk events will occur due to exposure events A.

The same process can be repeated for $P(X_B = 0)$ by applying the same process used for $P(X_A = 0)$.

The probability that no risk event will occur due to B faults is:

$$P(X_B = 0) \approx 1 - p_n \mu_F Y \tag{A-10}$$

Where: p_n is arrival rate of exposures in 1 year.

μ_F is the mean cumulative fault time per year.

X_B represents the process of a risk event occurring as a result of a person contacting an earthed asset during a fault.

Y is the number of years in $[0, T]$.

$P(X_B = 0)$ is the probability that a total of x risk events occurred as a result or process X_B during time $[0, T]$.

The coincidence probability can be determined by:

$$
\begin{aligned}
P_{coinc} &= P(X_A + X_B \geq 1) \\
&= 1 - P(X_A + X_B = 0) \\
&= 1 - P(X_A = 0)P(X_B = 0) \\
&\approx 1 - (1 - f_n \mu_E Y)(1 - p_n \mu_F Y) \\
&\approx 1 - 1 + f_n \mu_E Y + p_n \mu_F Y - f_n p_n \mu_E \mu_F Y \\
&\approx f_n \mu_E Y + p_n \mu_F Y
\end{aligned}
\qquad \text{A-11}
$$

The average cumulative exposure time (μ_E) and the average cumulative fault duration (μ_F) can be expanded:

$$
\begin{aligned}
P_{coinc} &\approx f_n \mu_E Y + p_n \mu_F Y \\
&\approx f_n (p_n t_E) Y + p_n (f_n t_F) Y \\
&\approx f_n p_n (t_F + t_e) Y
\end{aligned}
\qquad \text{A-12}
$$

Where: t_E is the average duration of the average exposure (in years).

t_F is the average duration of the average fault (in years).

p_n is the rate at which exposures occur (exposures or presences/year)

f_n is the rate at which faults occur (faults per year).

If the unit of time for t_E and t_F is converted into seconds (rather than years), and the period of time over which the calculation is made is in years then:

$$
P_{coinc} = \frac{f_n \times p_n \times (f_d + p_d) \times T}{365 \times 24 \times 60 \times 60} \times CRF
\qquad \text{A-13}
$$

Where: p_d is the average duration of the average exposure (in seconds).

f_d is the average duration of the average fault (in seconds).

p_n is the rate at which exposures occur (exposures or presences/year).

f_n is the rate at which faults occur (faults per year).

T is the number of years (exposure duration) = 1 year.

CRF is Coincidence reduction factor (see **Section 5.6.9.2**) (set to 1 normally).

## A.1.2   Group coincidence probability calculation

(A) Single event coincidence probability

This section provides an alternative (equivalent) expression for coincidence probability that is used in the pursuant group coincidence probability calculation.

Presence and fault coincidence may initially be viewed as two independent processes. The dependencies and time and seasonal correlations will be addressed in a later section. **Figure A1** and the following analysis assumes:

$$
\begin{aligned}
f_d &= \text{mean fault duration.} \\
p_d &= \text{mean presence duration.} \\
f_d &< p_d \\
T &= \text{duration under consideration.}
\end{aligned}
$$

At least one each of fault and presence events occurs during the time T. As time T is usually set to one year, this assumption is usually valid for most substations. The value of T may be increased to allow for those locations/installations whose fault frequency is less than one per year (for example, transmission and distribution assets).
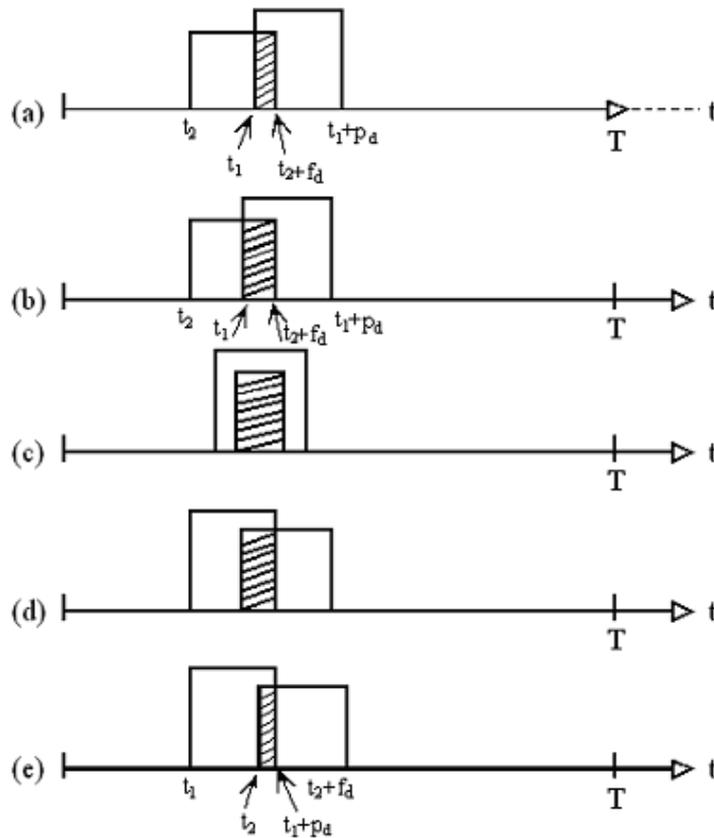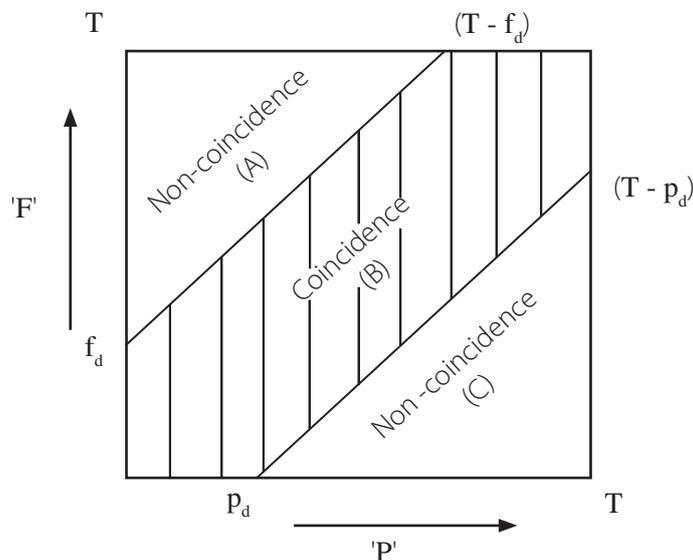
Figure A1: Coincidence probability scenarios

Case (c) covers direct coincidence probability (i.e. total overlap) which is only a subset of all five cases. The range for case (a) through to case (e) covers all instances of coincidence (including partial overlap).

For case (c) $P(\text{presence}) \times P(\text{fault}) = \dfrac{f}{T} \times \dfrac{p}{T} = \dfrac{f \times p}{T^2}$ A-14

To determine the total coincidence probability the situation may be represented by a Borel field diagram as shown in **Figure A2** following (see Papoulis [26], and Ross [25]). The P axis represents Presence occurrence (units of time), while the F axis represents fault occurrence (units of time).

Figure A2: Borel field representation of coincidence probability of two independent time events

For coincidence to occur it is required that:

$$P \leq F + p_d$$
$$F \leq P + f_d$$

Area B = {coincidence times}

Area B = $\{-p_d \leq F - P \leq f_d\}$

Probability of coincidence   = $\dfrac{\text{Area B}}{\text{Total Area}}$

$$P_c = \frac{\{-p_d \leq F - P \leq f_d\}}{T^2}$$

Non-coincidence probability   = $\dfrac{\text{Area A + Area C}}{\text{Total Area (A+B+C)}}$

$$P_{NC} = \frac{\text{Area A + Area C}}{T^2}$$

$$= \frac{(T - f_d)^2}{2T^2} + \frac{(T - p_d)^2}{2T^2}$$

$$= \frac{T^2 - 2Tf_d + f_d^2}{2T^2} + \frac{T^2 - 2Tp_d + p_d^2}{2T^2}$$

$$= \frac{1}{2} - \frac{f_d}{T} + \frac{f_d^2}{2T^2} + \frac{1}{2} - \frac{p_d}{T} + \frac{p_d^2}{2T^2}$$

$$= 1 - \frac{f_d + p_d^2}{T} + \frac{f_d^2 + p_d^2}{2T^2} \qquad \text{A-15}$$

Coincidence probability   =   Area 'B' / Total Area

$$P_C = 1 - (\text{Non-coincidence probability}) \qquad \text{A-16}$$

$$= \frac{f_d + p_d}{T} + \frac{f_d^2 + p_d^2}{2T^2}$$

This derivation is valid for short duration contacts and fault events. It is not appropriate to be used for continuous exposure or fault conditions.

This basic form is then taken in the following section and revised to manage a desired failure or arrival rate, multiple incidents, as the well as non stationary nature of the fault/presence process (i.e. a non-homogenous Poisson process).

(B) Multiple event/multiple contact/multiple people coincidence probability

To extend the derived formulae which are applicable for an individual for one presence and one fault in time **T**, Equation A-16 is rewritten using the definitions below.

$$P_c = \frac{1}{K}\left\{ \frac{f_d + p_d}{T} - \frac{f_d^2 + p_d^2}{2KT^2} \right\} \qquad \text{A-17}$$

Where: f_d = fault duration (in seconds)

        p_d = presence duration (in seconds)

        T = time period for calculation (years)

        K = constant to convert seconds into year time base

          = 365 x 24 x 60 x 60   A-18

Thus the probability that an individual will not be in contact with an earth fault generated voltage at the same time as a fault occurs can be written as:

$$P_{NC1} = 1 - P_c \qquad\qquad\qquad\qquad \text{A-19}$$

When the individual has a pattern of behaviour which equates to multiple contacts with items associated with a fault in time T, the probability of non coincidence with a single fault can be written as:

$$P_{NCmulti\text{-}presences} = P_{NC}{}^{P_nT}$$
$$= (1 - P_C)^{P_nT} \qquad\qquad\qquad \text{A-20}$$

Where: $p_n T$ = number of contacts over time T

p_n = number of contacts / year

Hence the probability of coincidence for an individual with multiple presences and a single fault in time T can be written as:

$$P_{Cmulti\text{-}presences} = 1 - P_{NC\ multi\text{-}presences}$$
$$= 1 - (1 - P_C)^{P_nT} \qquad\qquad\qquad \text{A-21}$$

For a population of N people, the probability that exactly i will be coincident with a fault occurring in time T is:

$$P_{Ni} = \binom{N}{i} P_{multi\text{-}presences}{}^{i} \ \text{x} \ \left(1 - P_{C\ multi\text{-}presences}\right)^{N-i} \qquad \text{A-22}$$

Where the number of N distinct outcomes taken i at a time is:

$$\binom{N}{i} = \frac{N!}{i!(N-i)!}$$

For a population of N people, the probability that anything other than i people will be coincident with a fault occurring in time T is:

$$P_{N2} = 1 - P_{Ni}$$
$$= 1 - \binom{N}{i} P_{C\ multi\text{-}presences}{}^{i} \ \text{x} \ \left(1 - P_{C\ multi\text{-}presences}\right)^{N-i} \qquad \text{A-23}$$

If there is a known average fault rate, rather than a single fault occurrence in time T, the probability that from **N** people, anything other than **i** people will be coincident during ANY fault is:

$$P_{N2f} = \left[1 - \binom{N}{i} P_{C\ multi\text{-}presences}{}^{i} \ \text{x} \ \left(1 - P_{C\ multi\text{-}presences}\right)^{N-i}\right]^{f_nT} \qquad \text{A-24}$$

Where: $f_n T$ = average number of faults in time T
f_n = average number of faults/year.

Taking the complement of this value gives the probability that from a population of size **N**, exactly **i** people will be coincident with ANY fault in time **T**:

$$P_{Nif} = 1 - \left[1 - \binom{N}{i} P_{C\ multi\text{-}presences}{}^{i} \ \text{x} \ \left(1 - P_{C\ multi\text{-}presences}\right)^{N-i}\right]^{f_nT} \qquad \text{A-25}$$

Finally, in order to present group probabilities in a form consistent with the F-N curves, the expected number of times (**EV**) that from a population of size **N**, at least **i** people are coincident with any fault in time **T** is:

$$EV = \sum_{i=j}^{N} 1 - \left[1 - \binom{N}{i} P_{C\ multi\text{-}presences}{}^{i} \ \text{x} \ \left(1 - P_{C\ multi\text{-}presences}\right)^{N-i}\right]^{f_nT} \qquad \text{A-26}$$

A.2   Coincidence lookup table

A range of standard exposure scenarios have been incorporated within the following lookup **Table A-1**. The table provides a coincidence multiplier for an individual fault duration which may be used to calculate P_{coinc} (as per Equation A-13).

$$P_{coinc} = \text{Coincidence multiplier x fault frequency/year} \\ \text{x Exposure duration (years) CRF} \qquad\qquad \text{A-27}$$

Where

P_{coinc} = Probability of coincidence of a fault and simultaneous contact occurring.

Coincidence Location Factor (multiplier) = Factor in lookup table (see **Table A1** in **Appendix A**).

$$= \frac{p_n\,(f_d + p_d)}{365 \ \text{x} \ 24 \ \text{x} \ 60 \ \text{x} \ 60}$$

Fault Frequency = Number of fault occurrences expected to yield a hazard event in the period of 1 year. **Table A2** in **Appendix A** gives typical fault rates.

Exposure duration = Number of years over which an individual is likely to be exposed to a given hazard scenario.

= 1 year

CRF = Coincidence reduction factor

= An empirical factor by which coincidence is expected to be reduced as a result of a specific mitigation strategy (for example, warning signs, barbed wire). See **Section 5.7.5** for more detail of the use of a CRF.

= 1 initially unless specific mitigation strategies applied.

While the access assumptions have been specified to be reasonably conservative, a designer should confirm that they accept that the values quoted are reasonable. In other cases the user must state and document their own access assumptions.

A.3   Fault duration and rate data

Faults on towers and cables

To assist with calculations, where more accurate data is not available, some typical data for overhead line fault rates and protection fault clearing times can be found in **Table A2** and **Table A3**, respectively. **Table A4** listing backup protection clearing times has been included for use when considering conductor and connection thermal requirements.

When considering faults on overhead lines, if the line length of interest is known, the average number of faults per unit time on overhead lines in **Table A1** can be used to estimate the rate at which hazardous voltages will occur on a particular tower.

The rate at which risk events occur for a given structure f_n can be calculated as follows, where the number of hazardous structures per fault refers to the number of interconnected structures which could be considered to contribute to a 'hazardous' condition on the structure being examined.

$$f_n = \frac{\text{No. of Faults on Line in Time Period}}{\text{Time Period (in years)}} \ \text{x} \ \frac{\text{No. of hazardous structures per fault}}{\text{No. of transmission structures in line}} \qquad \text{A-28}$$

The fault rates for underground cables are much lower than for overhead lines. Typical underground cable fault rates are two to three per 100 km for 11 to 33kV and less than 1 for higher voltages. The average fault duration $f_{d'}$ can be estimated from values given in **Table A2**. Note that for close in faults, earth fault current is high and

Table A1: Coincidence location factor (multiplier) lookup ble

Location	Access Assumptions	Coincidence multiplier ($*10^{-4}$) for fault duration (sec)													
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.5	2	3	4
Backyard	Inside backyard with regular contact of up to 8 times/wk (contact duration 4 sec) 416 contacts/year	0.541	0.554	0.567	0.580	0.594	0.607	0.620	0.633	0.646	0.660	0.726	0.791	0.923	1.06
Urban interface	Within 100m of houses, where people visit occasionally, up to 100 contacts/year (contact duration 4 sec.)	0.130	0.133	0.136	0.140	0.143	0.146	0.149	0.152	0.155	0.159	0.174	0.190	0.222	0.254
Remote	Remote location where a person may contact up to 10 times per year for up to 4 sec.	0.0130	0.0133	0.0136	0.0140	0.014	0.0146	0.0149	0.0152	0.0155	0.0159	0.0174	0.0190	0.0222	0.0254
MEN	Regular contact of between 5 and 6/day with items connected to the MEN (contact duration 4 sec) 2000 contacts/year	2.60	2.66	2.73	2.79	2.85	2.92	2.98	3.04	3.11	3.17	3.49	3.81	4.44	5.07

The contact duration estimating process is necessarily quite imprecise, as very little or no actual data is available. While tables pertaining to 'what people do' all day are available they usually relate to general movement, and are insufficiently accurate for the purpose of assessing duration contact. Therefore, it is important that the sensitivity of the response to contact frequency and duration be understood when making decisions regarding exposure rates.

the protection operates quickly. However, for faults further out along the feeder, additional line impedance limits the fault current which takes longer to be cleared by the protection system. Consequently, different fault locations need to be considered to determine the worst case EPR and clearing time combination.

Table A2: Typical overhead line fault rates

System Voltage (phase to phase)	Overhead Line Fault Rate (faults/100km/year)
LV	20-150
11kV-33kV	5-10 shielded, 10-40 unshielded
66kV	2-5
100kV-132kV	1-4
220kV-275kV	<1.0
330kV	<0.5
400kV	<0.5
500kV	<0.5

NOTE 1:   The higher outage rates occur in northern Australia where there is more frequent high wind and lightning storm activity.

NOTE 2:   The lower outage rates occur in southern Australia and New Zealand where there is less frequent high wind and lower lightning activity.

Table A3: Typical primary protection clearing times

System Voltage (phase to phase)	Primary Protection Clearing Time
LV	2sec
11kV-33kV	1sec
66kV	0.5sec
100kV-132kV	220msec
251kV-275kV	120msec
330kV	120msec
400kV	120msec
500kV	100msec

NOTE: The primary protection clearing times for >100kV are based on National Electricity Rules fault clearing time requirements for remote end.

Table A4: Typical backup protection clearing times

System voltage (phase to phase)	Backup protection clearing time
LV	1-2sec
11kV-33kV	1-2sec
66kV	1sec
100kV-<250kV	430msec
250kV-275kV	250msec
330kV	250msec
400kV	175msec
500kV	175msec

NOTE: The backup protection fault clearing times for >100kV are based on National Electricity Rules CB Fail clearing time requirements.

Faults associated with major substations

The hazard scenarios associated with a given substation are driven by faults on both the primary and secondary networks terminating at the substation.

Primary faults—events associated with faults on the incoming powerlines or within the HV equipment or yard.

Secondary faults—events associated with faults on the downstream power network, typically sourced via a transformer(s) in the substation.

The resultant fault frequency is based upon:

» A summation of available feeder fault rates.

» Wherever possible the line fault rates should reflect data sourced over an extended period.

» Although a fault may be tripped and (possibly) reclosed by a pole mounted recloser and not the feeder breaker, all secondary faults are seen by the substation. In some cases over 200 faults per year are seen by some rural substations.

» While fault frequency must reflect all fault occurrences, the resultant EPR is often quite low due to the high impedance nature of many faults (for example, line falling on tree or cross arm).

Example A1: Jogger

Problem: A jogger goes for a run every day of the week. At the halfway point of each run the jogger touches a metal gate next to a 275kV tower for 1 s. Risk events occur at the pole once every 120 years (i.e. fault rate 0.83/100 km/year, with average tower spacing of 100 m and say five towers each side contribute to 'significant' EPR of the structure near the gate), and create a touch voltage hazard on the gate for 1 s.

Solution: The risk associated with this scenario may be calculated directly using Equation 1 as shown. The average length of an exposure p_d is approximately 1 s, the average length of a fault f_d is 1s, and the number of exposures per year that occur p_n is 365. The rate at which risk events occur is:

$$f_n = \frac{1 \text{ risk event}}{120 \text{ years}} = 8.33 \times 10^{-3} \text{ risk events per year}$$

The coincidence probability per year is therefore:

$$P_{coinc} = f_n p_n (f_d + p_d) \frac{T \times CRF}{365 \times 24 \times 60 \times 60}$$

$$= (8.33 \times 10^{-3})(365)(1+1) \frac{1}{365 \times 24 \times 60 \times 60}$$

$$= 8.33 \times 10^{-3} \times 365 \times 6.34.10^{-8}$$

$$= 1.93 \times 10^{-7}$$

This individual risk level is below the tolerable level of 10^{-6} defined in **Section 4.4.6**. Consequently, no further risk treatment action is necessary.
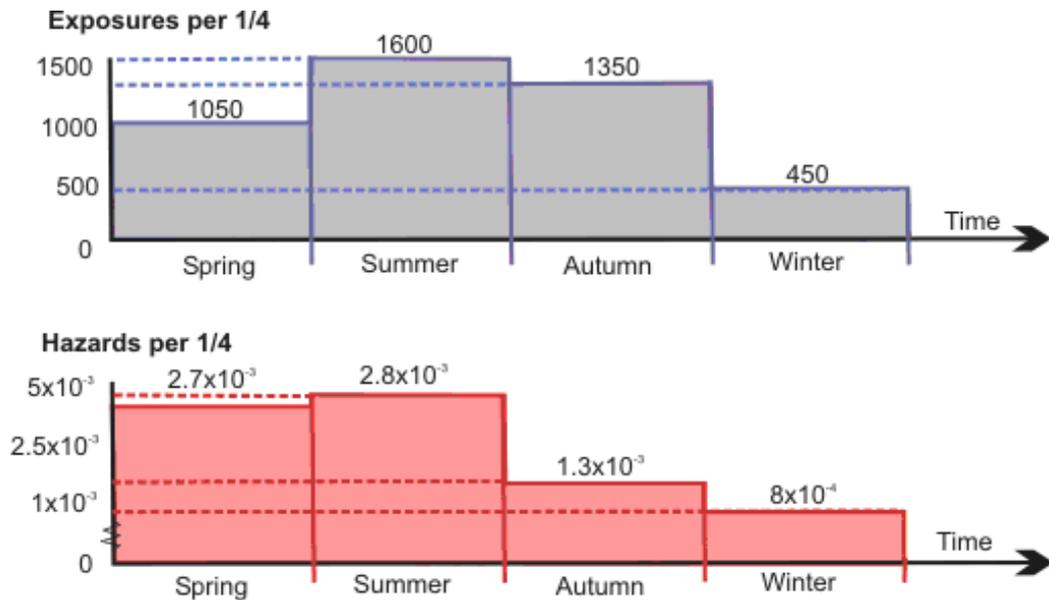
A.4 Calculation of the coincidence probability for variations in fault and exposure rate

The fault rate may vary with the time of day (for example, during daylight hours) or season (for example, winter), and the exposure factor often varies significantly according to the time of day or season. In order to adjust for such variations, rather than use the conservative highest rate, the probability of coincidence may be calculated separately for each period of time over which the fault or exposure rate is constant.

The risk calculation may therefore be divided into Regions of the lowest common length of time for which both the fault and exposure rates are approximately constant. The coincidence probability for a single year is the sum of the coincidence probabilities for each of the individual periods over each year.

Example A2: Tourist attraction near river

Problem: A conductive (or earthed) power pole is located next to a popular tourist attraction near a river. Tourists visit the attraction most regularly during the warmer holiday months between late spring and early autumn. Risk events also occur most frequently during this period as a result of insulation failure. The average length of exposures and faults are 1 s and 0.2 s respectively. The average number of hazards and exposures per season are shown in **Figure A4**.

Figure A4: Variations in fault rate and exposure rate over the year

Solution: The coincidence probability may therefore be determined for each season independently and the final value calculated as the sum of the coincidence probabilities from each of the individual periods. If the average fault and exposure lengths are 0.2 s and 1 s then the probability of coincidence for each season is:

Spring

Exposures occur approximately 12 times per day (p_n = 1050 per ¼) and last ~1 s on average. Risk events are estimated to occur in spring once in every 377 years on average (p_n = 2.7 x 10^{-3} per ¼) and last approximately 1 s. The coincidence probability occurring in spring is therefore:

$$P_{c,Sprg} = f_n p_n (f_d + P_d) \ \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= (2.7 \times 10^{-3})(1,050)(1 + 1) \ \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= 2.7 \times 10^{-3} \times 1,050 \times 2.53 \times 10^{-7}$$

$$= 7.2 \times 10^{-7}$$

Summer

Exposures occur approximately 18 times per day (p_n = 1600 per ¼) and last ~1 s on average. Risk events are estimated to occur in spring once every 364 years and last approximately 1 s. The coincidence probability occurring in spring is therefore:

$$P_{c,Sumr} = f_n p_n f_d (f_d + p_n) \ \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= (2.8 \times 10^{-3})(1,600)(1+1) \ \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= 2.8 \times 10^{-3} \times 1,600 \times 2.53 \times 10^{-7}$$

$$= 1.1 \times 10^{-6}$$

Autumn

Exposures occur approximately 15 times per day (p_n = 1350 per ¼) and last ~1 s on average. Risk events are estimated to occur in spring once every 364 years on average (f_n = 2.8 **x** 10-3 per ¼) and last approximately 1 s. The coincidence probability occurring in autumn is therefore:

$$P_{c,Autm} = f_n p_n (f_d + p_d) \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= (1.3 \times 10^{-3})(1,350)(1+1) \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= 1.3 \times 10^{-3} \times 1,350 \times 2.5 \times 10^{-7}$$

$$= 4.5 \times 10^{-7}$$

Winter

Exposures occur approximately 5 times per day (p_n = 450 per ¼) and last ~1 s on average. Risk events are estimated to occur in spring once every 1333 years (f_n = 7.5 **x** 10-4 per ¼) and last approximately 1 s. The coincidence probability occurring in winter is therefore:

$$P_{c,wntr} = f_n p_n (f_d + p_d) \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= (8 \times 10^{-4})(450)(1+1) \frac{4}{365 \times 24 \times 60 \times 60}$$

$$= 8 \times 10^{-4} \times 450 \times 2.53 \times 10^{-7}$$

$$= 9.1 \times 10^{-8}$$

The total probability of fatality for the year is therefore:

$$P_{coinc} = P_{c,Spring} + P_{c,Summer} + P_{c,Autumn} + P_{c,winter}$$

$$= 7.2 \times 10^{-7} + 1.1 \times 10^{-6} + 4.5 \times 10^{-7} + 9.1 \times 10^{-8}$$

$$= 2.4 \times 10^{-6}$$

This does not differ significantly from the probability of coincidence obtained for the average values over the entire year. Exposures occur (on average over the whole year) 12 times per day (p_n = 4450 per year) and last ~1 s on average. Risk events are estimated to occur once every 132 years (p_n = 7.6 **x** 10-3 per year) and last approximately 1 s. The coincidence probability calculated from these average values is therefore:

$$P_{coinc} \, avg = (7.6 \times 10^{-3})(4,450)(1 + 1) \frac{1}{365 \times 24 \times 60 \times 60}$$

$$= 7.6 \times 10^{-3} \times 4,450 \times 6.34 \times 10^{-8}$$

$$= 2.1 \times 10^{-6}$$

Only small variations in fault and exposure rates are apparent in this example. As a result little difference exists between the seasonally adjusted coincidence probability (P_{coinc} = 2.4 **x** 10-6) and the coincidence probability calculated from average fault and exposure characteristics (P_{coinc} = 2.1 **x** 10-6). This risk level is above the tolerable level of 10-6 and falls in the Intermediate Risk category defined in **Section 4.4.6**. Consequently, risk treatment measures must be investigated to reduce the risk to as low as reasonably practicable.

A.5   Calculation of the coincidence probability for multiple hazard sources

Independent faults may cause overlapping hazard zones to exist. In such cases the risk associated with asset must be calculated independently to determine the overall risk for each Region according to the fault rate. The risk associated with a hazard zone is only independent if the areas do not overlap, otherwise the hazard Regions must be divided according to the amount of overlap which exists between the areas.
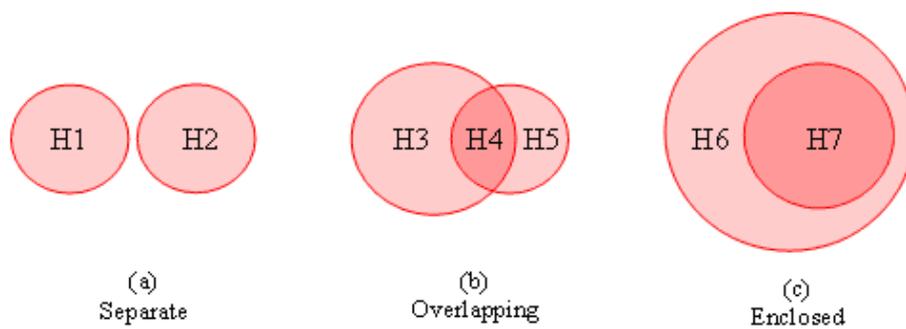
Figure A5: Multiple hazard zones resulting from independent substation faults

If hazard zones overlap as shown in (b), the overlapped Region (H4) will contain fault rate contributions from both sources, resulting in a higher coincidence probability in that Region. In such cases the coincidence probability should be calculated separately for each Region with a different fault rate. The occurrence of overlapping hazard zones is restricted to risk events which occur independently. Overlapping hazard zones are therefore a rare occurrence usually restricted to risk events arising from step voltage hazards.

A.6   Calculation of the coincidence probability for combined hazards

The methods presented in the preceding sections illustrate the methods for calculating the coincidence probability for specific cases. However, hazards are rarely simple and the risk analysis may require a combination of these approaches to be undertaken. In such cases the coincidence probability must be calculated separately for each case. For example, two hazards with overlapping hazard Regions for which the exposure and fault rates vary separately should first be separated and then each Region should be analysed separately according to *Appendix A-3*.

Appendix B: Fibrillation risk analysis

This appendix provides the following background to the fibrillation risk component of the overall risk analysis process:

B1—limits for ventricular fibrillation

B2–development constant fibrillation characteristics

B3–constant fibrillation characteristic curve families.

B.1　Voltage limits for ventricular fibrillation

Voltage limits for ventricular fibrillation of humans is based on the probabilistic physiological data provided in IEC 60479-1:2005 (similar to AS/NZS 60479.1-2002 but with updated data). The fibrillation current limit needs to be converted into voltage limits for comparison with the calculated step and touch voltages, taking into account the impedances present in the body current path. The voltage limits shall take into account the following factors:

»　proportion of current flowing through the Region of the heart

»　body impedance along the current path

»　resistance between the body contact points and return paths (for example, series resistance of footwear, or crushed rock), and

»　earth fault duration.

The sequence to be followed to determine the voltage limits is shown in **Figure B1**.
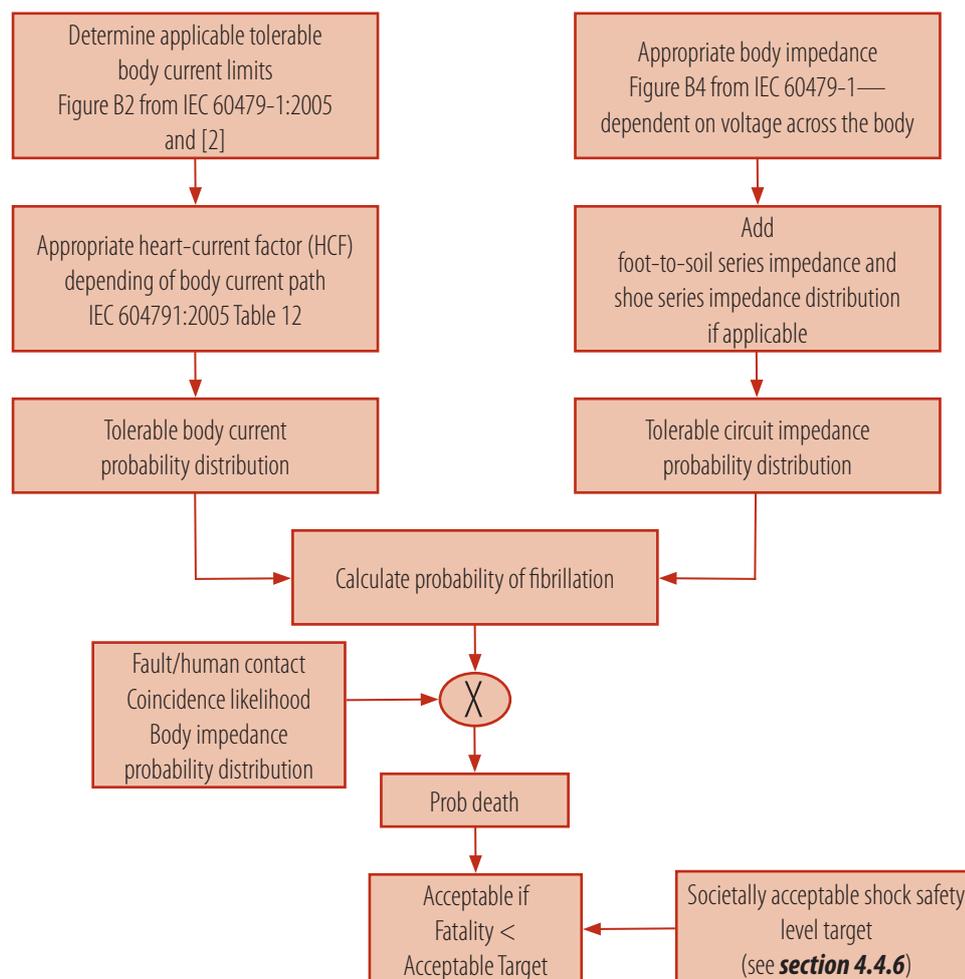
Figure B1: Procedure for calculating voltage limits

NOTE 1: Body impedance depends on voltage across body.

NOTE 2: If additional resistance between bare hands and/or feet is considered in the formulation, then the voltage must be clearly denoted as a prospective touch voltage and tested accordingly (refer to Section 7.2.5 regarding measurements).

The following sections detail the calculation of tolerable prospective touch and step voltage limits. These calculations are based on the procedure from **Figure B1**.

B.1.1   Fibrillation currents

The IEC 60479-1 standard contains a number of body current curves. There are three curves of interest when considering fibrillation currents. These are curve c1 which corresponds to a Neglibible probability of fibrillation, curve c2 which corresponds to a five percent probability of fibrillation and curve c3 which corresponds to a 50 percent probability of fibrillation. A 95 percent curve can be found in [2] and matched to the final c2 and c3 locations. Fitting a probability function across the 5, 50 and 95 percent curves enables the probabilistic analysis outlined in this Appendix to be undertaken. As the IEC 60479 -1 standard does not define the probability of fibrillation for curve c1 it is not usually included in the construction of probability density functions.

Curves c1, c2 (5 percent) and c3 (50 percent) and the additional c4 (95 percent) curve are shown in **Figure B2**. These curves apply to a current path of left hand to both feet.
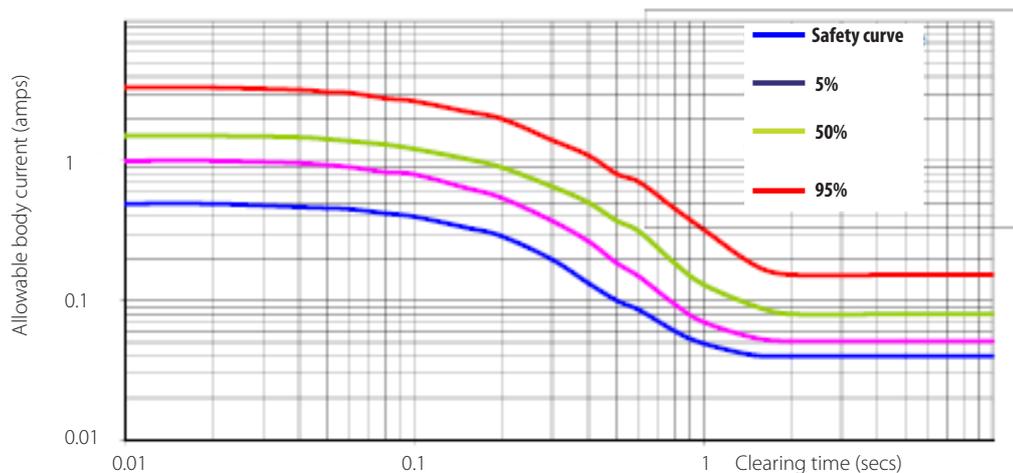
Figure B2: Allowable body current curves c1, c2 and c3 and c4

Table B1: Body Current Curve Boundary Descriptions

| Boundaries	Physiological Effects
Above curve c1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
c1 - c2	Probability of ventricular fibrillation increasing up to about 5%
c2 - c3	Probability of ventricular fibrillation up to about 50%
c3 - c4	Probability of ventricular fibrillation up to 95%
Beyond curve c4	Probability of ventricular fibrillation above 95%
330kV	<0.5
400kV	<0.5
500kV	<0.5

Table B2 (from *IEC60479-1*) provides details of heart current factor (HCF) or relative current density for a range of contact configurations. The HCF may be used to scale allowable body current criteria shown in **Figure B2** according to the contact configuration. For example, when considering the current path hand to hand the allowable body current values which are normalised for LH to foot content are divided by 0.4 (i.e. increased by 250 percent).

Table B2: Relative Current Densities (or HCF) in the vicinity of the heart for different conditions

Current Path	Heart Current Factor
LH to LFT, RF or Feet; both hands to both feet.	1.0
LH to RH	0.4
RH to LF, RF or both feet	0.8
Back to RH	0.3
Back to LH	0.7
Chest to RH	1.3
Chest to LH	1.5
Seat to LH, RH or both hands	0.7
Foot to Foot	0.04

B.1.2   Shock circuit

For step and touch voltage shock situations, parameters which are significant for the step and touch voltage circuits are shown in **Figure B3**. The parameters are further detailed in the following sections.
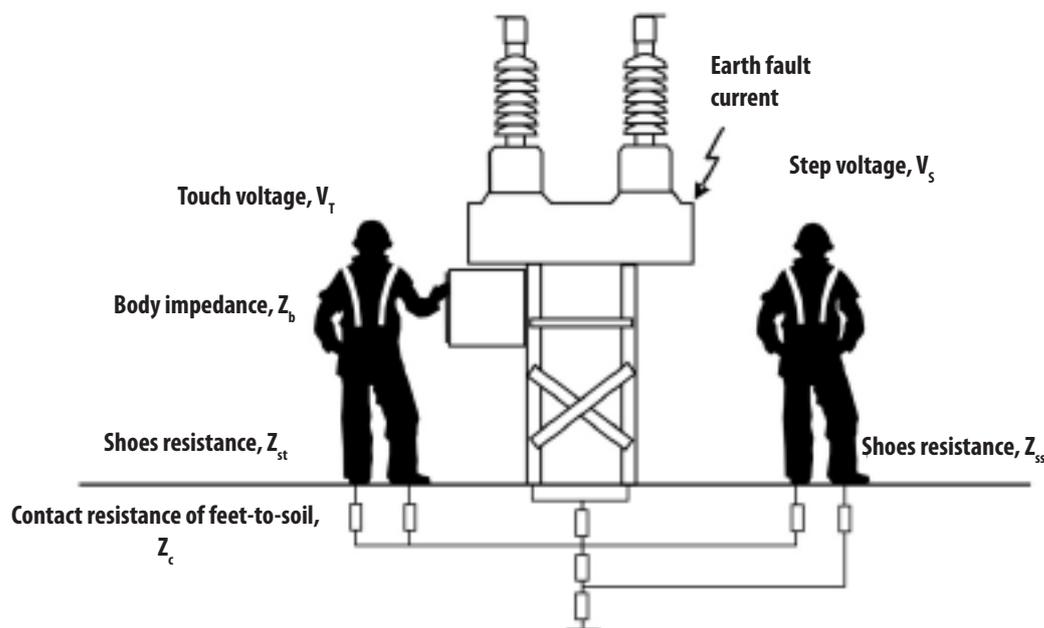
Figure B3: Step and touch voltage circuits parameters

For step and touch voltages, the relevant circuit parameters are:

» The body impedance, Z_b.

» The resistance of shoes, Z_{ss} or Z_{st}.

» The contact resistance of feet-to-soil, Z_c.

» Hand contact resistance.

The hand contact resistance should be taken as zero (i.e. assume bare-hands in all situations).

B.1.2.1   The body impedance

The body impedance depends on the voltage across the human body. The body impedance also depends on the current path through the body. For example, the hand to feet impedance (represented as 1.5 Z_{ip} in **Figure 3** in *IEC 60479-1*) is lower than the hand to hand impedance or the foot to foot impedance (both represented by 2 Z_{ip}). Since body impedances values in *IEC 60479-1* are for the hand to hand path (or foot to foot), it follows that the hand to feet impedance (i.e. for touch voltage) is 75 percent of the quoted values and the foot to foot impedance (for step voltages) are the same as the quoted values. **Table B3** summarises the resistance path factors (RPF's) and **Figure B4** shows the resistance characteristics from *IEC60479* for hand to hand or foot to foot contact paths (for large area dry and water wet contact).

Table B3: Body resistance path factors (RPFs) from IEC60479

Current Path	Resistance Path Factor
Hand to hand, foot to foot	1.0
Hand to both feet	0.75
Both hands to both feet	0.5
Hand to trunk	0.5
Both hands to trunk	0.7
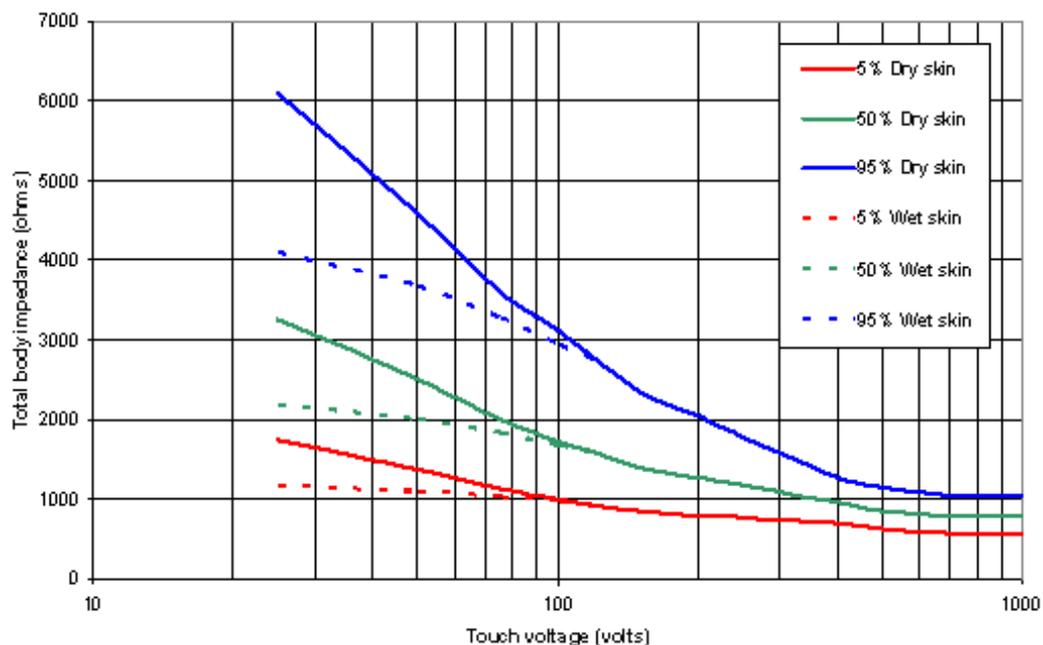
Figure B4: Body resistance large contact areas dry and water wet conditions

IEC 60479-1:2005 contains body impedance data for dry, water-wet and saltwater-wet conditions and also for three contact areas. For the purposes of this Guide, the body impedances for dry and water-wet conditions and for the large contact surface area are considered appropriate. However, it should be noted that the data for dry and water-wet conditions are very similar especially for fault durations below 1.5 s and touch voltages above 125 volts (see **Figure B4**).

The calculation of step and touch voltage limits uses body impedances which depend on the voltage across the body and considers the current path through the body. The probability distribution of the body impedance is also considered.

B.1.2.2   Resistance of shoes

Footwear provides additional series resistance in the shock circuit. Resistance of shoes vary greatly depending on the type of shoe and on whether the shoe is dry or wet. In addition to having a resistance, a shoe will also exhibit a flashover or breakdown voltage. The ability of a shoe to withstand voltage depends on the type of shoe, on the amount of wear and on whether the shoe is dry or wet. Resistance of shoe may vary from 500 Ω to 3000 kΩ while the withstand voltage may vary between 500 V up to 20kV. Low withstand voltage is typically associated with wet shoes.

Various publications allow for a range of shoe resistances as follows:

» BS 7354:1990—Substation earthing allows a shoe resistance of 4000 Ω to be used for substation earthing design. BS 7354 acknowledges that the withstand voltage of worn footwear has not been well researched. This Guide also recommends a limiting value of 5kV for touch and step voltages.

» BS EN 50341-1 uses a shoe resistance of 2000 Ω for calculating touch voltage limits for locations where people are expected to be wearing shoes.

» ITU K.33 standard allow the use of the following shoe resistances (see **Table B4**) for calculating the voltage limits.

Table B4: ITU K.33 footwear resistance

Type and state of shoes	Shoe resistance (kΩ)	
	Leather sole	Elastomer sole
Dry shoes	3000	2000
Wet or damp shoes, hard soil	5	30
Wet or damp shoes, loose soil	0.25	3

» Typical Public Footwear—A range of footwear resistances were used in the probabilistic analysis behind the derivation of EC5 (NSW Electricity Council precursor to ENA(C(b)-1) criteria in the late 1980s). More recently published data based upon HV testing of shoes [1] led to the addition of voltage withstand characteristics to the data shown in **Table B5** following. These values will be referred to as 'typical public footwear' and used throughout this Guide when appropriate.

Table B5: Typical public footwear characteristics

Case	Description	Resistance (ohms)	Voltage withstand (volts) [1]	Population percentage
1	Bare feet	0	0	10
2	Dry new leather	5000000	7000	4
3	Dry new black rubber	5000	5000	4
4	Dry new elastomer	30000000	20000	4
5	Dry used leather	1000000	5000	16
6	Dry used black rubber	1000	2500	16
7	Dry used elastomer	6000000	15000	16
8	Wet new leather	10000	1000	3
9	Wet new black rubber	500	1000	2
10	Wet new elastomer	100000	8000	3
11	Wet used leather	5000	500	8
12	Wet used black rubber	500	750	6
13	Wet used elastomer	50000	4000	8

In the absence of any new data the typical public footwear distribution cited in **Table B5** has been used in probabilistic analysis. If additional conservation is required then, a single value of 2000 Ω can be used.

For specific cases involving electrical workers in and around substation/transmission assets, electrical footwear as outlined in **Table B6** may be used in the analysis.

Table B6: Electrical worker footwear characteristics

Case	Description	Resistance (ohms)	Voltage withstand (volts) [1]	Population percentage
1	Dry used black rubber	1000	2500	35
2	Dry used elastomer	6 000 000	15 000	35
3	Wet used black rubber	500	750	15
4	Wet used elastomer	50 000	4000	15

When considering the effect of shoe resistances, the touch voltage circuit will include the resistance of two shoes in parallel while the step voltage circuit will include the resistance of two shoes in series.

B.1.2.3   Contact resistance of feet-to-soil

The contact resistances between the feet and the soil may appreciably increase the resistance of the shock circuit, especially if a thin layer of high resistivity material is used on the surface.

For soil with a surface resistivity, ρ_E, the contact resistance maybe calculated as follows from *ENA EG(1)* and *IEEE80*:

For step voltages,

$$Z_{cs} = 6\,\rho_E \qquad\qquad \text{B-1}$$

For touch voltages,

$$Z_{ct} = 1.5\,\rho_E \qquad\qquad \text{B-2}$$

As described in **Section 5.8.4**, thin layers of high resistivity material can be used to reduce the current flowing through the human body. For a thin layer of high resistivity material on top of the soil, a de-rating factor, C_s is required to account for the difference in magnitude between the resistivity of the thin layer (ρ_1) and the resistivity of the underlying soil (ρ_E), and also to account for the thickness of the layer (h_s).

$$C_s \;=\; 1 - \frac{0.09\left(1 - \dfrac{\rho_E}{\rho_1}\right)}{2h_s + 0.09}$$

$$\text{B-3}$$

The contact resistance is then calculated as follows:

For step voltages,

$$Z_{cs} = 6\,C_s\,\rho_1 \qquad\qquad \text{B-4}$$

For touch voltages,

$$Z_{ct} = 1.5\,C_s\,\rho_1 \qquad\qquad \text{B-5}$$

B.1.2.4   Contact resistance of surface layers

The two main surface layer materials in common usage are crushed rock and asphalt. The same series resistance formulations used for the soil top layer (see previous **Section B.1.2.3**) may be applied to these materials. These materials exhibit a wide range of electrical properties both initially and over time and any design requiring their use for safety reasons should take care to ensure the installation matches the required specification. The following points outline some experience to date in the application of these materials:

B.1.2.4.1   Crushed rock

Crushed rock is only considered appropriate for use within a secured area, and commonly serves multiple roles of series resistance, vehicle driveway and walkway, and weed control layer. Therefore, the specification must consider electrical properties and trafficability. It is insufficient to leave the specification open as quarries may provide material that has too large a range of gravel size (i.e. too many fines (poor electrical quality), and too large size (poor trafficability)), and poor electrical resistivity performance.

A typical specification would include figures such as:

» Gravel size: 30 to 50 mm
» Electrical properties: 3000 ohm-m.

Prior to accepting delivery of the full consignment of material some utilities carry out a brief testing process [1].

B.1.2.4.2 Asphalt

Asphalt may also be used to limit body current flow and allow trafficability of vehicles and people. Unfortunately asphalt exhibits highly variable electrical properties as shown in HV testing research [1]. Therefore care must be taken in the specification of asphalt for body current limiting purposes. Key aspects to be considered include:

» **Preparation:** Use of compacted road base (and possibly plastic underlay for weed control).

» **Material:** Well compacted hot mix at least 50mm thickness compacted (as cold mix electrical properties compromised in wet condition).

» **Electrical properties**: As it is difficult to type test a batch of hot asphalt, conservative values of resistance and voltage withstand are often used. In the attached fibrillation tables (see **Section B.3**) the following values are assumed:

  » Asphalt Resistivity—10 000 ohm m

  » Asphalt Voltage withstand—3kV.

B.1.3 Touch voltage circuit

A typical touch voltage shock circuit for the situation depicted in **Figure B3** is shown in **Figure B5**.
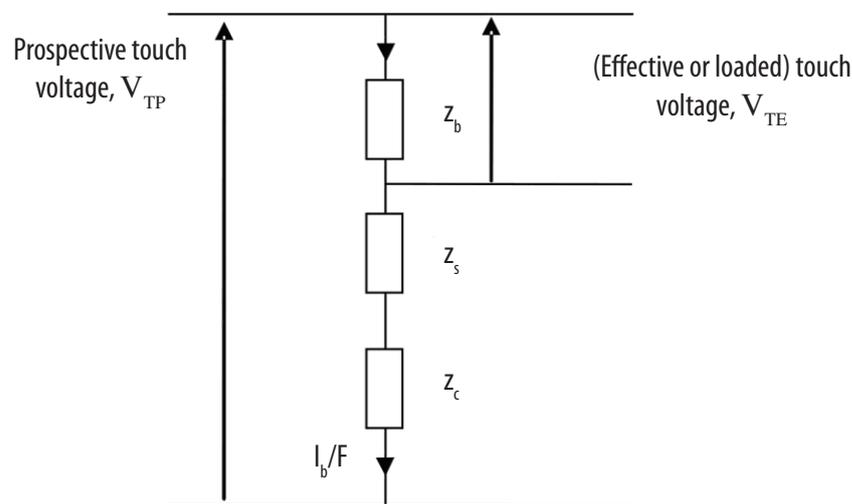
Figure B5: Touch voltage shock circuit

The prospective touch voltage, V_{TP}, for a fault duration, t, may be determined by the acceptable body current, Ib/HCF multiplied by the sum of the various impedances considered in the shock circuit. The factor, HCF, is the heart-current factor as detailed in **Table B2** (from Section 5.9 of *IEC 60479-1:2005*). The heart-current factor permits the calculation of currents through paths other than left hand to feet which represent the same danger of ventricular fibrillation as that corresponding to Ib left hand to feet shown in **Figure B3**.

$$V_{TP} \ = \ \frac{I_b}{HCF} \ (Z_b + Z_{st} + Z_{ct})$$

B-6

For touch voltages, a current path of left hand to feet is assumed. According to **Table B2** from IEC 60479-1:2005, HCF=1 for touch voltages.

$$Z_{ct} \ = \ 1.5 \, \rho_E$$

B-7

If Z_{1s} is the resistance of one shoe, then:

$$Z_{st} \ = \ \frac{Z_{1s}}{2}$$

B-8

$$V_{TP} = I_b \ (Z_b + Z_{st} + Z_{ct})$$ B-9

Prospective touch voltage limits can be calculated by substituting the relevant body impedance, soil resistivity and the IEC 60479-1 body current limits. Equation B-9 can be rewritten as follows:

$$V_{TP} = I_b Z_b + I_b \ (Z_{st} + Z_{ct}) \qquad \text{or}$$

$$V_{TP} = V_{TE} + I_b \ (Z_{st} + Z_{ct})$$ B-10

The term $I_b Z_b$ is the effective (or loaded) touch voltage, V_{TE}.

To calculate the prospective touch voltage limit for particular fault duration, Equation B-10 can be used. The following **Section B2** outlines how probabilistic analysis may be applied to derive constant fibrillation characteristic curves (shown in **Section B3**).
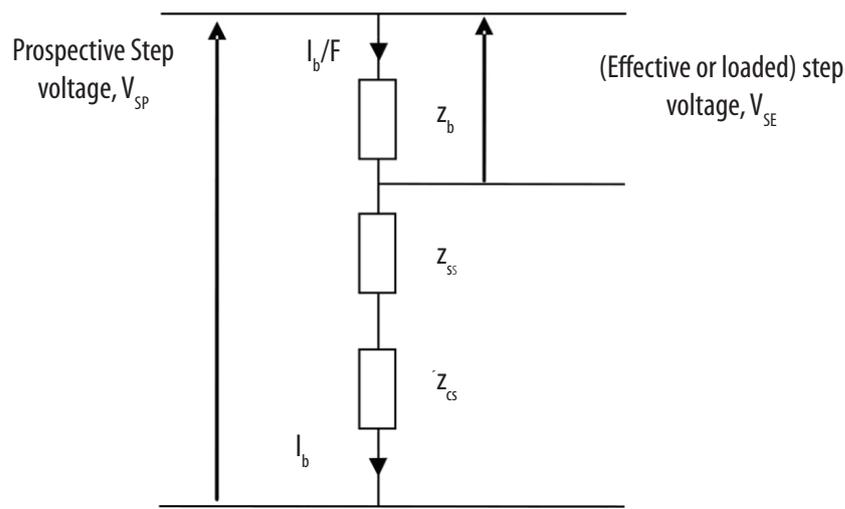
Figure B6: Step voltage shock circuit

B.1.4   Step voltage circuit

A typical step voltage shock circuit for the situation depicted in **Figure B3** is shown in **Figure B6**.

The prospective step voltage, V_{SP}, for a fault duration, t, may be determined by the acceptable body current, I_b/HCF, multiplied by the sum of the various resistances considered in the shock circuit. The factor, **HCF**, is the heart-current factor as detailed in **Table B2** (from Section 5.9 of *IEC 60479-1:2005*).

$$V_{SP} = \frac{I_b}{HCF} \ (Z_b + Z_{ss} + Z_{cs})$$

B-11

$$Z_{CS} = 6\rho_s$$ B-12

If Z_{1s} is the resistance of one shoe, then:

$$Z_{SS} = 2\,Z_{1s}$$ B-13

$$V_{SP} = \frac{I_b}{HCF} \ (Z_b + Z_{ss} + Z_{cs})$$

B-14

$$V_{SP} = \frac{I_b}{HCF}\,Z_b + \frac{I_b}{HCF} \ (Z_{ss} + Z_{cs}) \qquad \text{or}$$

$$V_{SP} = V_{SE}\ \frac{I_b}{HCF} (Z_{ss} + Z_{cs})$$ B-15

For a foot-to-foot path, the heart-current factor of 0.04 is given in **Table B2** (from *IEC 60479-1:2005*). This implies that 25 times more current flowing through the foot to foot path is required to create

the same risk of ventricular fibrillation compared to the current flowing in the left hand to feet path. The current is lowered further still by the added effect of having two sets of footwear and/or foot-to-ground resistances in series.

B.2 Developing constant fibrillation voltage/time characteristics

Most allowable voltage curves have a probability of fibrillation that is non linear and dependent upon distribution of clearing times [6]. This adds an extra undesired variable when assessing a particular installation, and does not provide equity across power systems.

The aim of this section is to describe a method for creating an allowable voltage curve (with respect to clearing time) such that it will have a specific and constant probability of fibrillation with respect to clearing time, if that voltage vs clearing time characteristic were applied to a body. Two methods are outlined, one based on a Monte Carlo sampling approach and the second based upon direct convolution of cumulative probability functions.
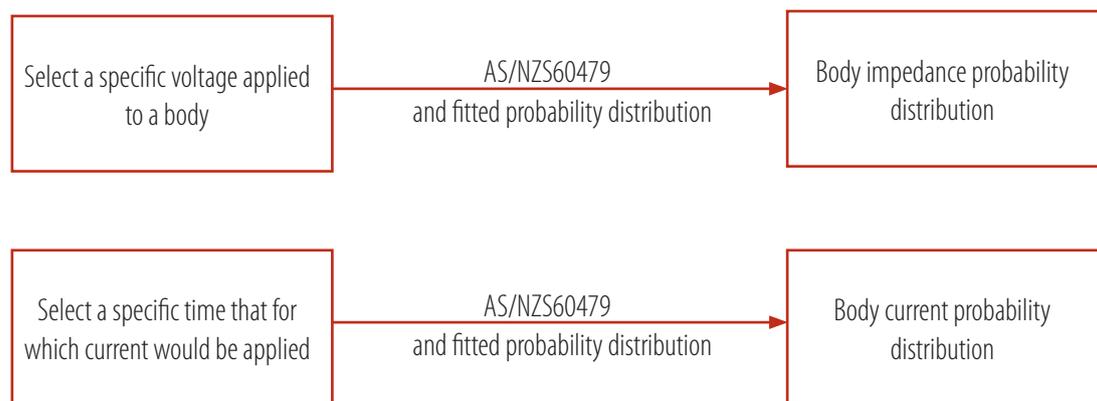
Figure B7: Process for generating body impedance and body current distributions

B.2.1 Monte Carlo sampling approach

Figure B9 shows the first stages of the process being the selection of a single voltage value and a specific time for which to apply the current. The selection of these parameters then allows the creation of probability distributions for body impedance and body current.

Figure B9 demonstrates the process of calculating a probability of fibrillation for a particular applied voltage and time pair. This process can now be adjusted to find the voltage that corresponds to a particular fibrillation probability for a specific duration that the voltage is applied to a body, this revised process is shown in **Figure B8**.
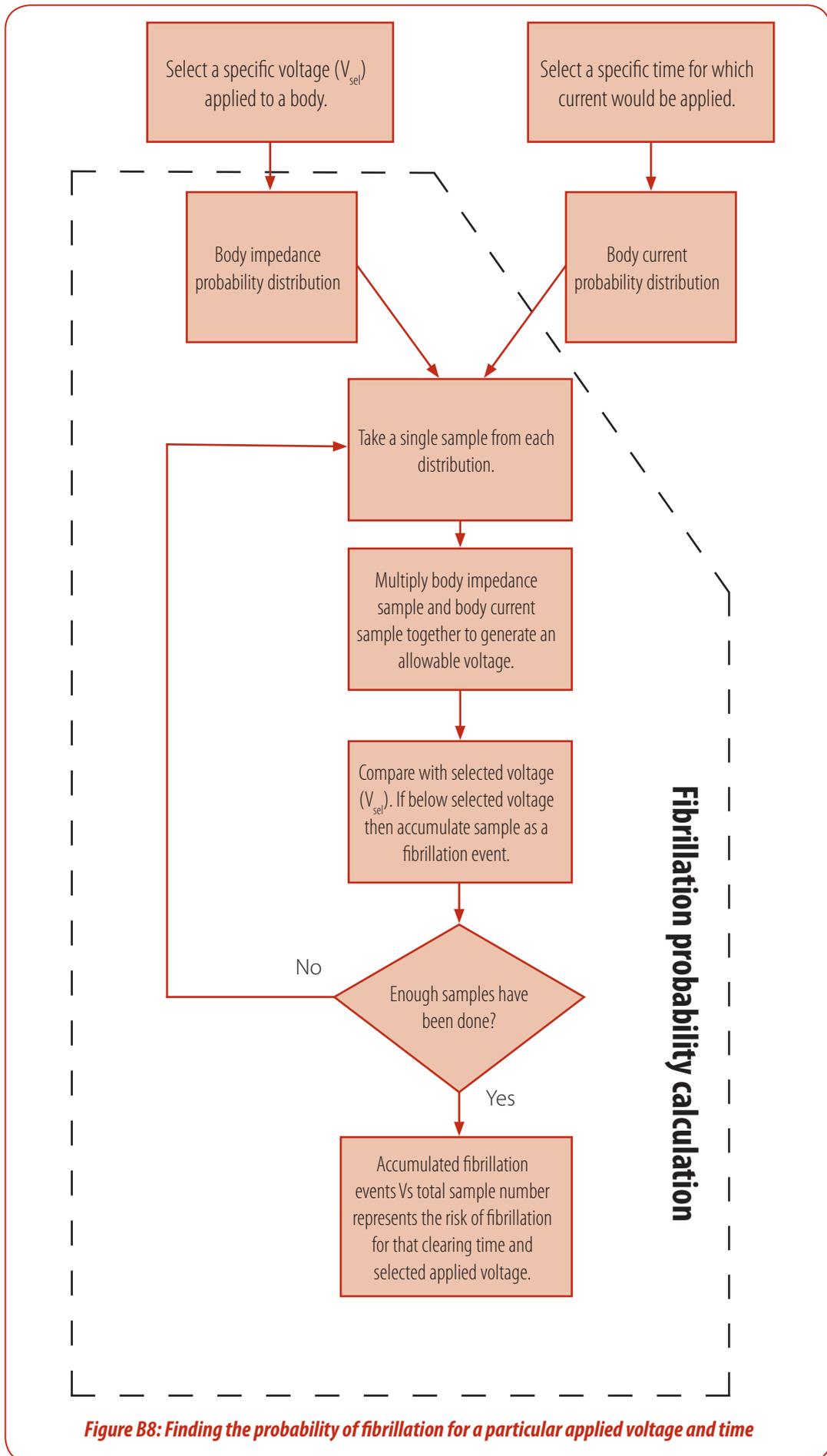
Figure B10 outlines the process of calculating a voltage vs time characteristic for a particular target probability.

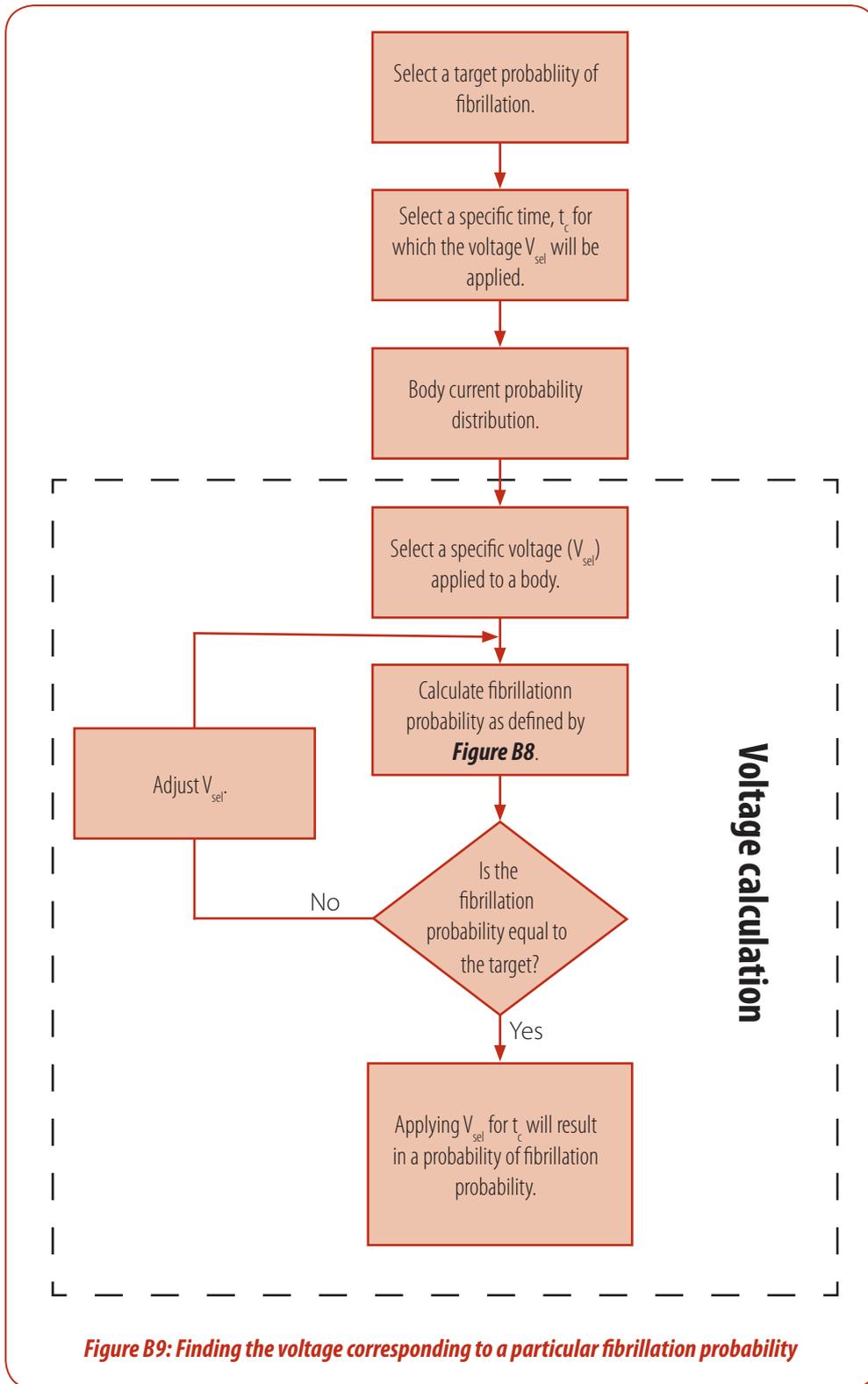### B.2.2 Cumulative probability distribution function convolution

To calculate the probability of a particular touch or step voltage hazard causing fibrillation the strength of the hazard must be compared with the ability of a person to withstand the hazard. This is done by comparing the allowable current cumulative distribution function (CDF) (i.e. withstand strength) with the applied or possible current CDF (i.e. hazard strength). A CDF is another representation of a probability distribution function (PDF) where the change in height between two points on the CDF 'x' axis is equal to the area between the same two points on the 'x' axis of the PDF.
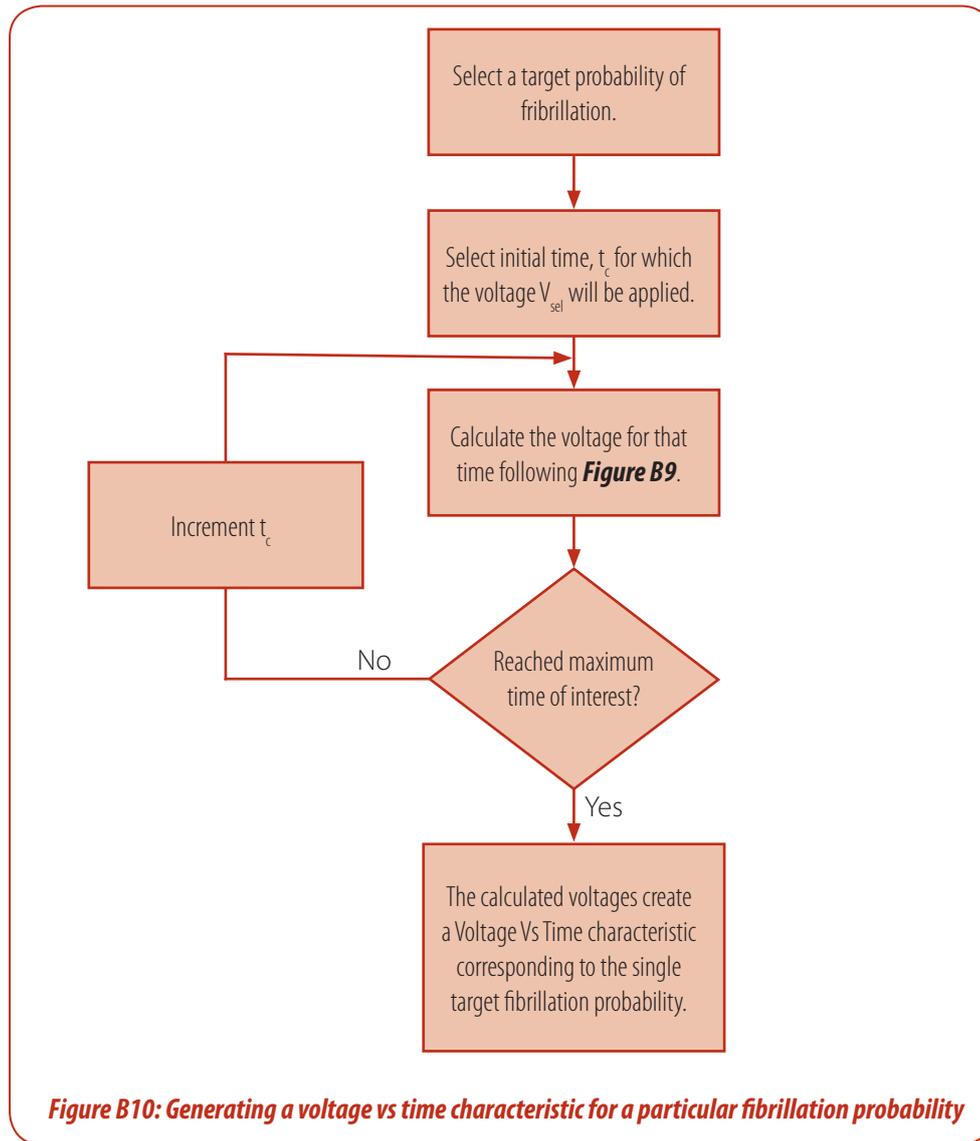
The possible current CDFs are calculated based on the body impedance CDFs. The following considerations besides body impedance must be included in the calculation of possible currents:

» current pathway through the body

Select a specific voltage (V$_{sel}$) applied to a body.

Select a specific time for which current would be applied.

Body impedance probability distribution

Body current probability distribution

Take a single sample from each distribution.

Multiply body impedance sample and body current sample together to generate an allowable voltage.

Compare with selected voltage (V$_{sel}$). If below selected voltage then accumulate sample as a fibrillation event.

Enough samples have been done?

No

Yes

Accumulated fibrillation events Vs total sample number represents the risk of fibrillation for that clearing time and selected applied voltage.

Fibrillation probability calculation

Figure B8: Finding the probability of fibrillation for a particular applied voltage and time

Select a target probabliity of fibrillation.

Select a specific time, t_c for which the voltage V_{sel} will be applied.

Body current probability distribution.

Select a specific voltage (V_{sel}) applied to a body.

Calculate fibrillationn probability as defined by *Figure B8*.

Adjust V_{sel}.

Is the fibrillation probability equal to the target?

No

Yes

Applying V_{sel} for t_c will result in a probability of fibrillation probability.

Voltage calculation

Figure B9: Finding the voltage corresponding to a particular fibrillation probability

Figure B10: Generating a voltage vs time characteristic for a particular fibrillation probability

- » contact impedance
- » additional series impedance such as shoes and flashover characteristics
- » ground resistance and presence of crushed rock layer
- » wet or dry conditions.

Using Ohm's Law:

$$I_{possible} \quad = \quad \frac{V_{Applied}}{Z_{Path\ Impedance}}$$

B16

The probability of fibrillation may then be calculated for a given applied voltage and clearing time by comparing the two CDFs:

$$P_{fibrillation}\ (V_{app}, t_c) = \sum_{n=1}^{n=100} \sum_{m=1}^{m=100} \left(\frac{\frac{n}{100} \times \frac{m}{100}\ (I_{possible}(V_{app}) > I_{allowable}(t_c))}{\frac{n}{100} \times \frac{m}{100}} \right)$$

B17

Equation B17 is the sum of all the possible combinations of probabilities for when $I_{possible} > I_{allowable}$ divided by the total number of possible combinations of probabilities. This calculation is essentially the same as the convolution of the $I_{possible}$ and $I_{allowable}$ probability distribution functions (PDF)s.

B.3   Constant fibrillation characteristic curve families

Following the processes outlined in the foregoing two sections constant fibrillation voltage/time characteristic curve families have been developed to cover the following scenarios:

» contact configuration—touch, step and hand to hand voltages
» upper layer soil resistivity—50, 100, 500, 1000, 2000, 5000 ohm.m
» surface layer materials—crushed rock, asphalt
» additional series impedances—footwear (typical public and electrical footwear)
» moisture—wet or dry hands.

The following figures B11-1 to B11-24 for constant fibrillation probability may be used in the manual criteria derivation process described in **Section 5.7**. **Table B7** summarises the characteristics upon which each of the figures are based.

*Table B7: Constant fibrillation probability curve scenario summary*

| Figure	Contact configuration	Footwear	Wet/dry body	Surface soil resistivity/ohm.m	Surface layer	Figure number
B11-1	Prospective Touch	None	Wet	50	Soil	B11-1
B11-2			Dry	50		B11-2
B11-3		Typical Public		50		B11-3
B11-4				100		B11-4
B11-5				500		B11-5
B11-6				1000		B11-6
B11-7				5000		B11-7
B11-8		Electrical		50		B11-8
B11-9		Typical Public		50	Soil, crushed rock slab	B11-9
B11-10				50	Soil, asphalt	B11-10
B11-11		Electrical Worker		50	Soil, crushed rock/slab	B11-11
B11-12				50	Asphalt	B11-12
B11-13	Prospective Step	No Footwear	Wet	50	Soil	B11-13
B11-14		Typical Public	Dry	50		B11-14
B11-15				100		B11-15
B11-16				500		B11-16
B11-17				1000		B11-17
B11-18				5000		B11-18
B11-19		Electrical		50		B11-19
B11-20		Typical Public		50	Soil, crushed rock/slab	B11-20
B11-21				50	Soil, asphalt	B11-21
B11-22		Electrical		50	Soil, crushed rock/slab	B11-22
B11-23				50	Soil, asphalt	B11-23
B11-24	Hand to Hand	N/A	Wet	N/A	N/A	B11-24
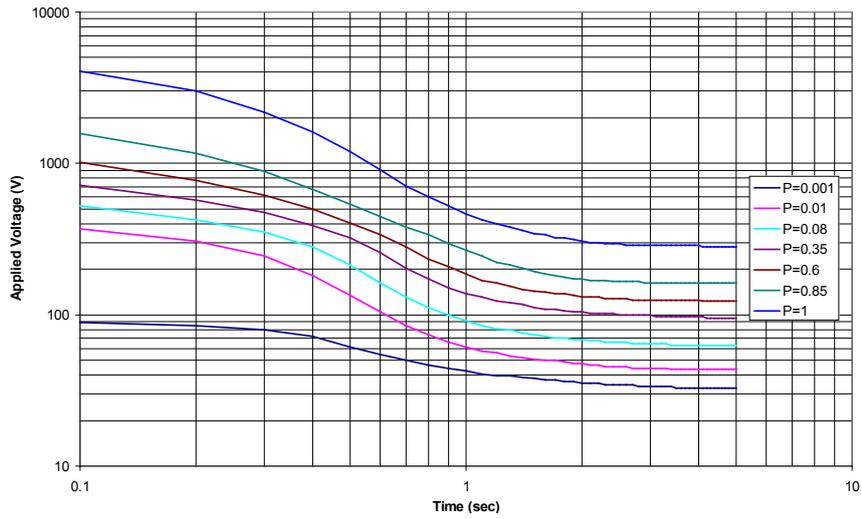
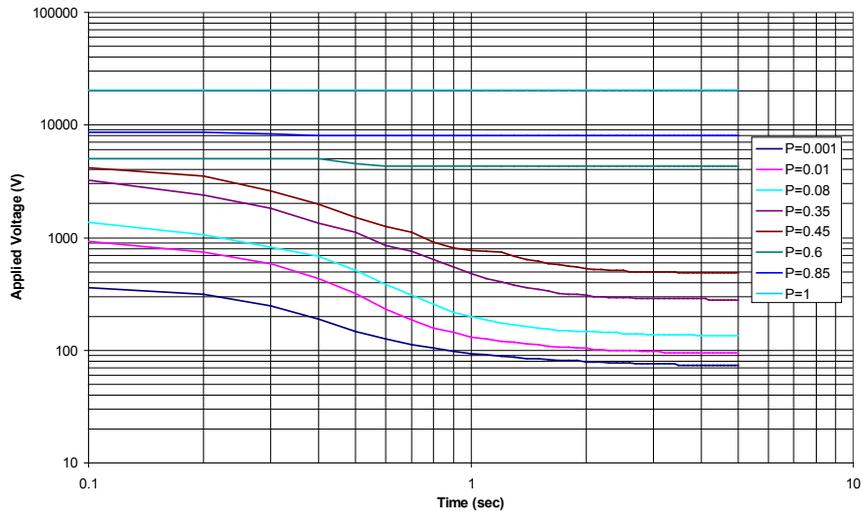*Figure B11-1: Prospective touch, no footwear, wet body, 50 ohm.m soil*
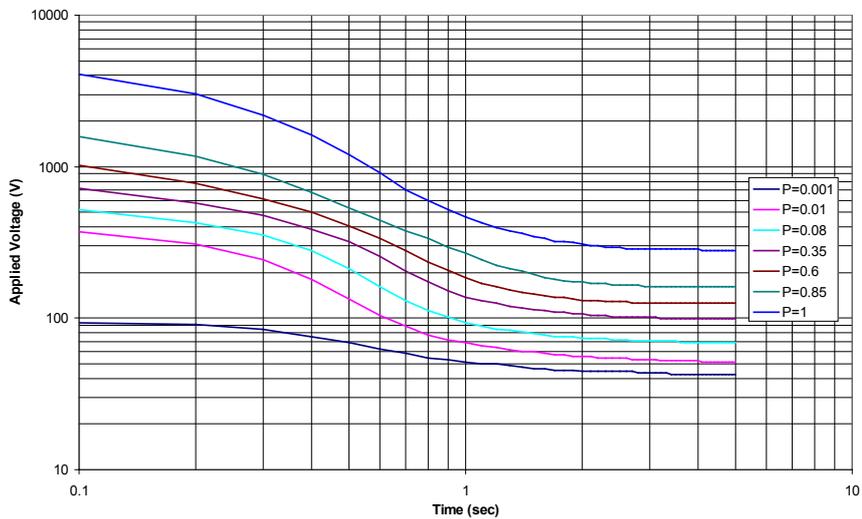
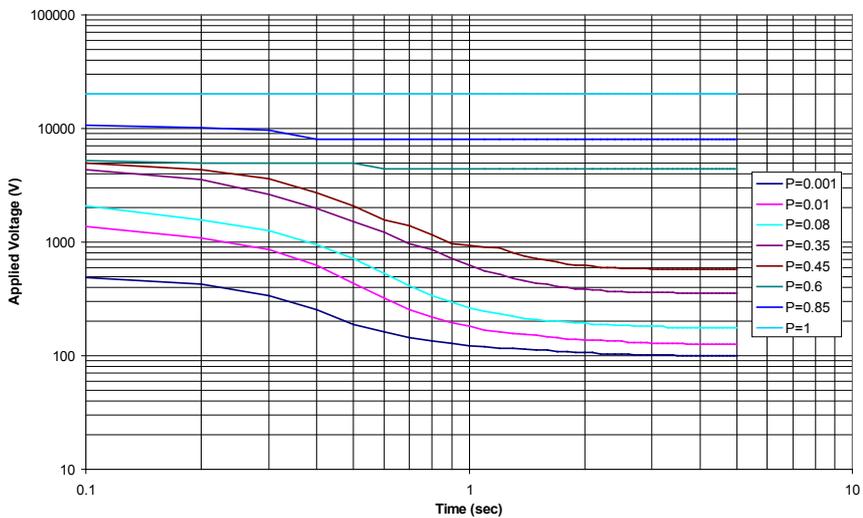*Figure B11-2: Prospective touch, no footwear, dry body, 50 ohm.m soil*
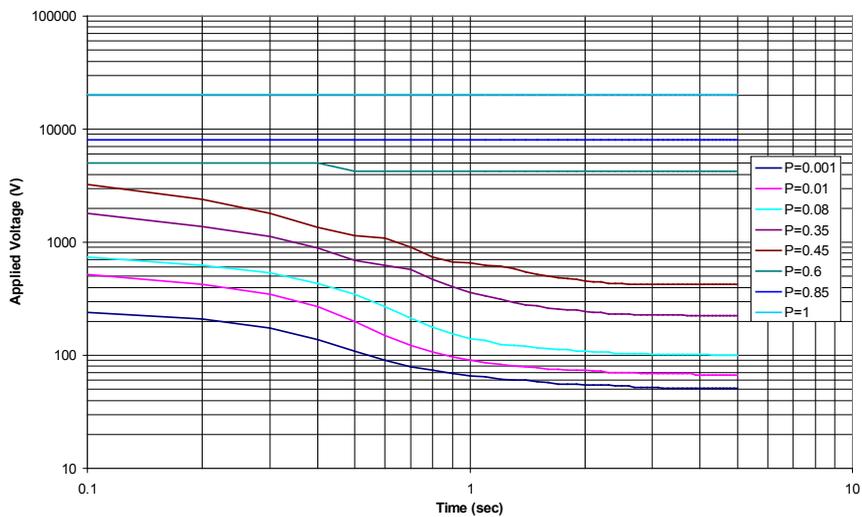
Figure B11-3: Prospective touch, typical public footwear, dry body, 50 ohm.m soil
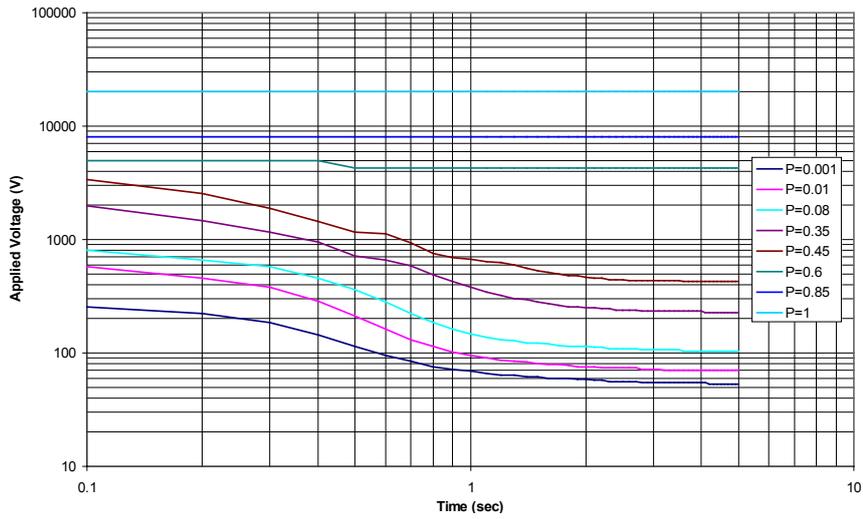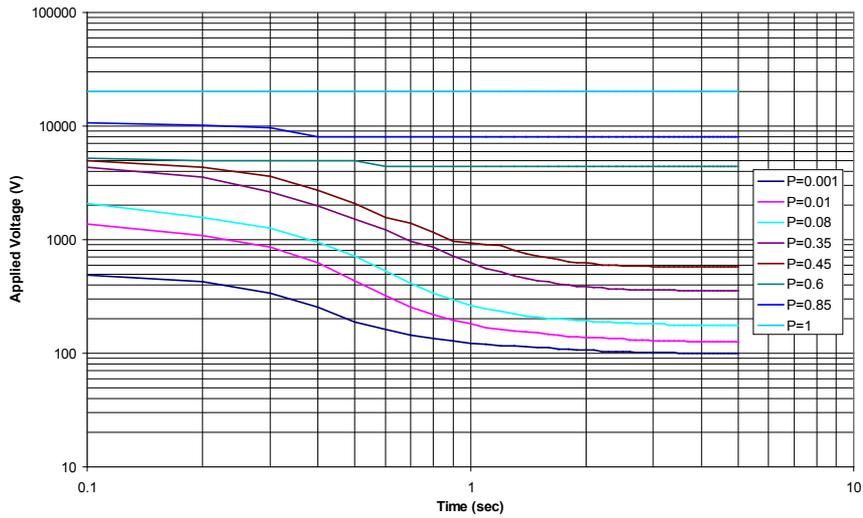
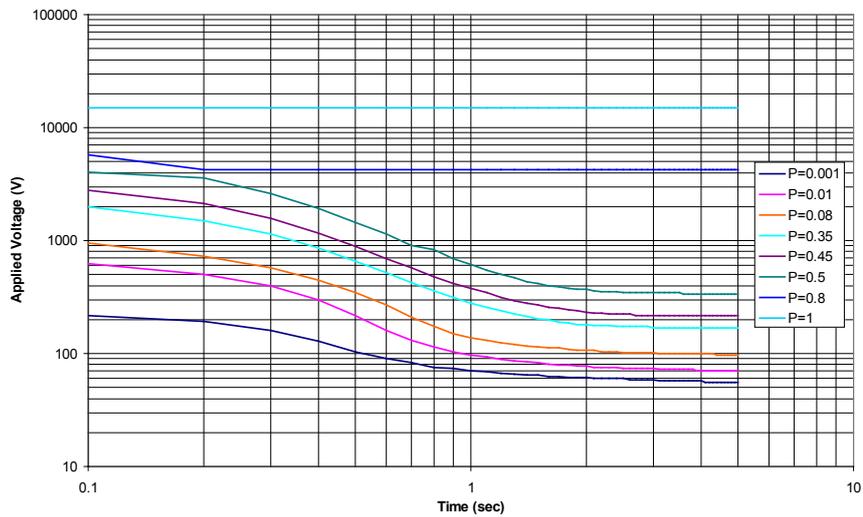*Figure B11-4: Prospective touch, typical public footwear, dry body, 100 ohm.m soil*

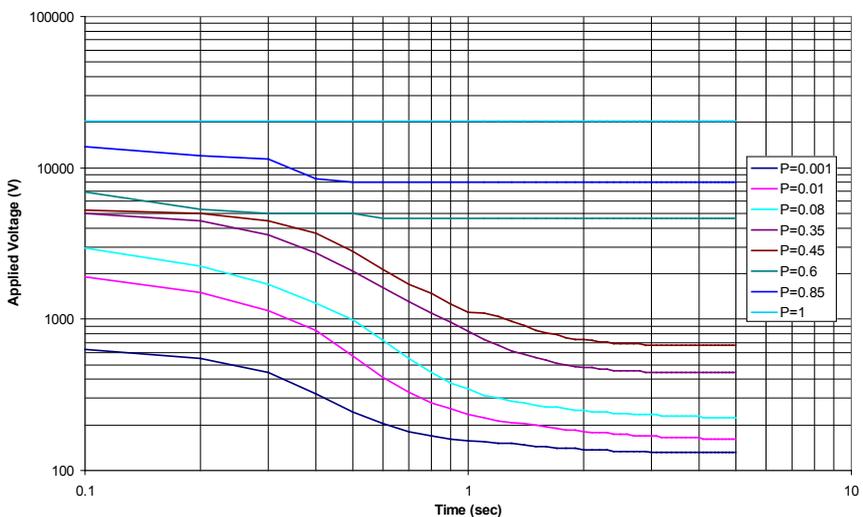*Figure B11-5: Prospective touch, typical public footwear, dry body, 500 ohm.m soil*

Figure B11-6: Prospective touch, C(b)-1 footwear, dry body, 1000 ohm.m soil

Figure B11-7: Prospective touch, typical public footwear, dry body, 5000 ohm.m soil

Figure B11-8: Prospective touch, electrical footwear, dry body, 50 ohm.m soil

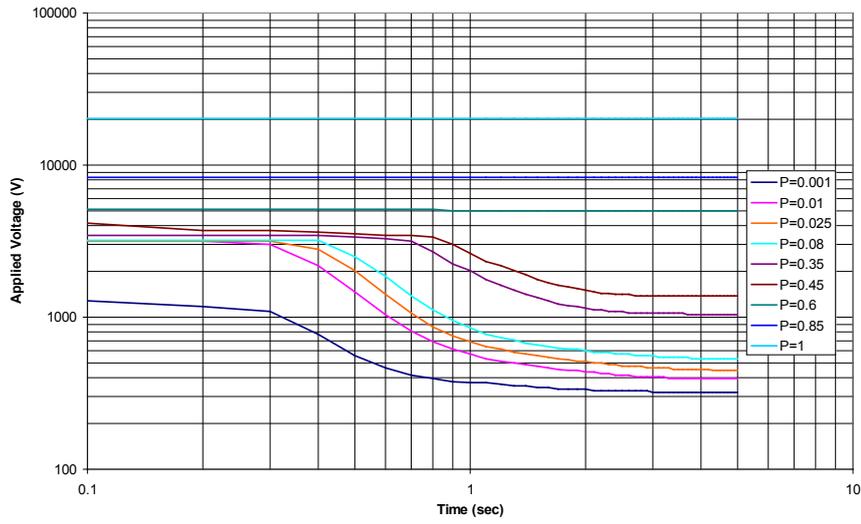*Figure B11-9: Prospective touch, typical public footwear, dry body, 50 ohm.m soil, crushed rock/slab*

Figure B11-10: Prospective touch, typical public footwear, dry body, 50 ohm.m soil, asphalt
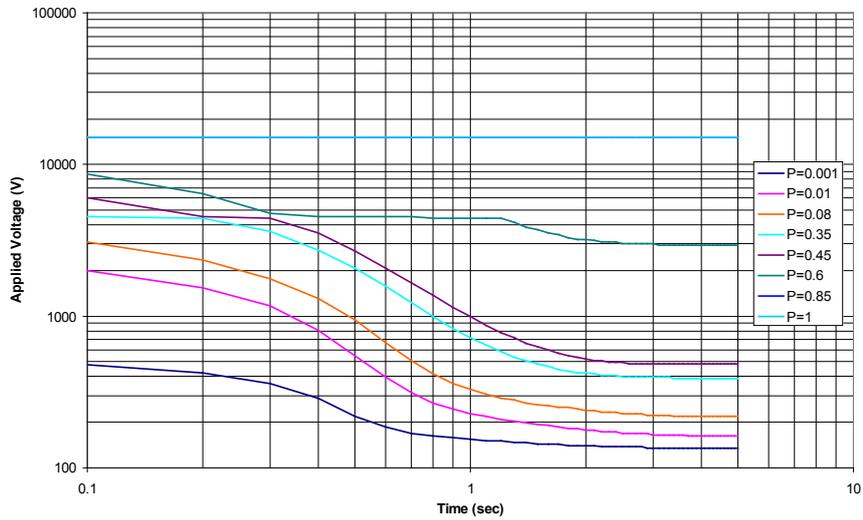

Figure B11-11: Prospective touch, electrical footwear, dry body, 50 ohm.m soil, crushed rock/slab
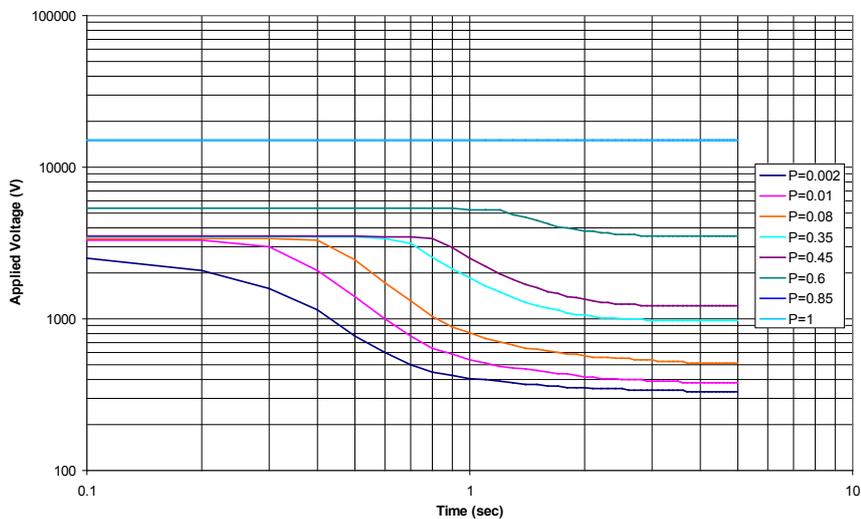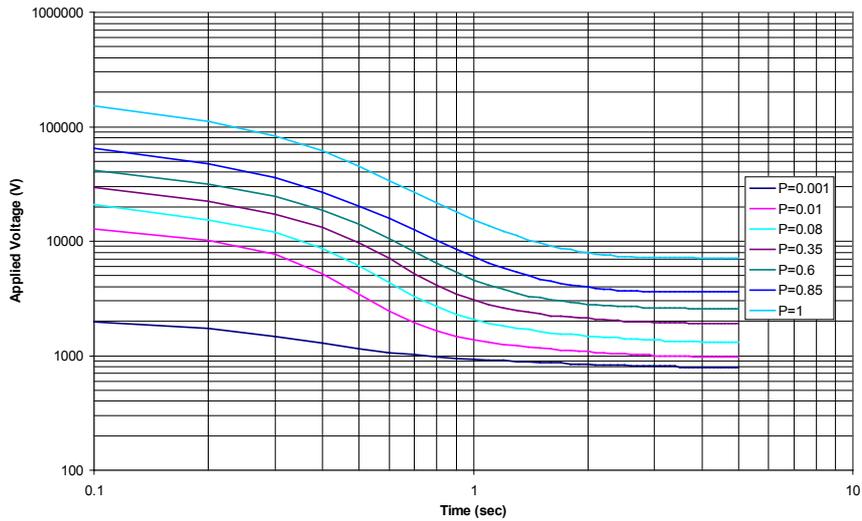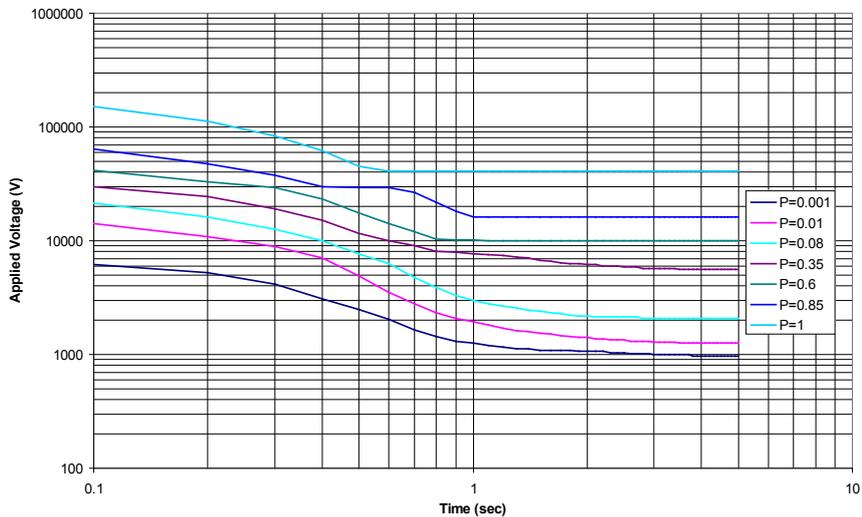

Figure B11-12: Prospective souch, electrical footwear, dry body, 50 ohm.m soil, asphalt

Figure B11-13: Prospective step, no footwear, wet body, 50 ohm.m soil

Figure B11-14: Prospective step, typical public footwear, dry body, 50 ohm.m soil

Figure B11-15: Prospective step, typical public footwear, dry body, 100 ohm.m soil

Figure B11-16: Prospective step typical public footwear, dry body, 500 ohm.m soil

Figure B11-17: Prospective step, typical public footwear, dry body, 1000 ohm.m soil

Figure B11-18: Prospective step, typical public footwear, dry body, 5000 ohm.m soil

Figure B11-19: Prospective step, electrical footwear, dry body, 50 ohm.m soil

Figure B11-20: Prospective step, typical public footwear, dry body, 50 ohm.m soil, crushed rock/slab

Figure B11-21: Prospective step, typical public footwear, dry body, 50 ohm.m soil, asphalt

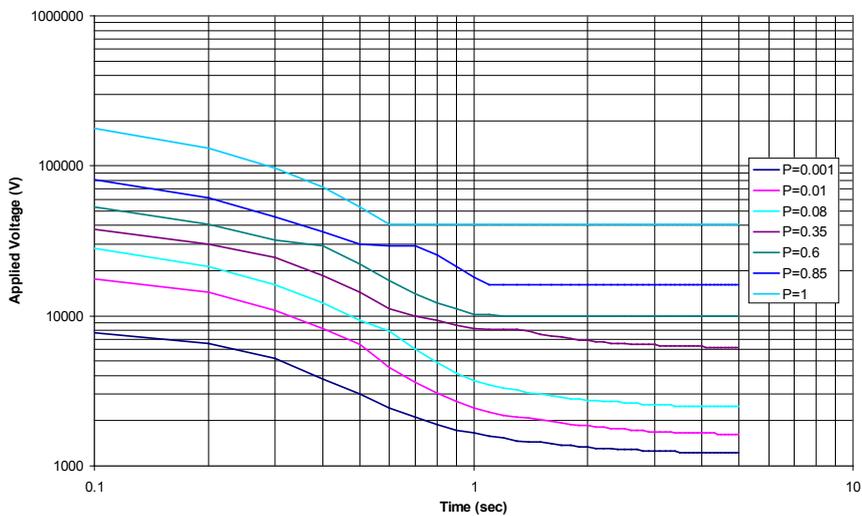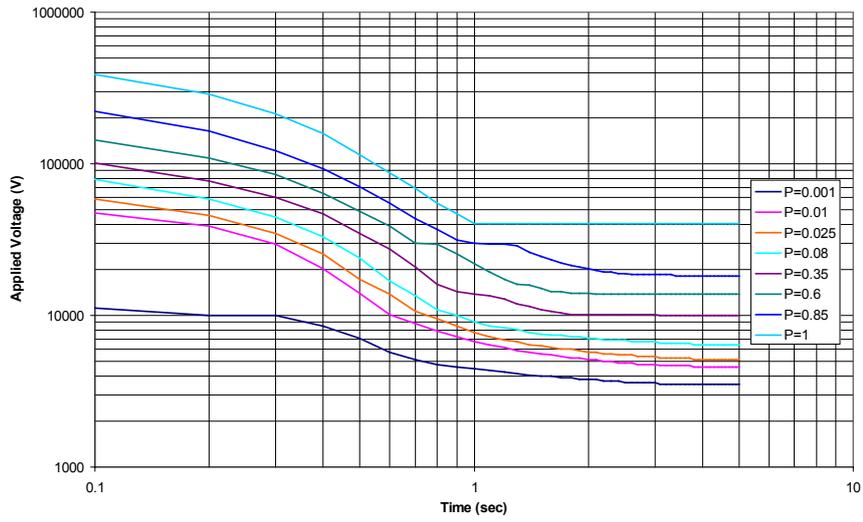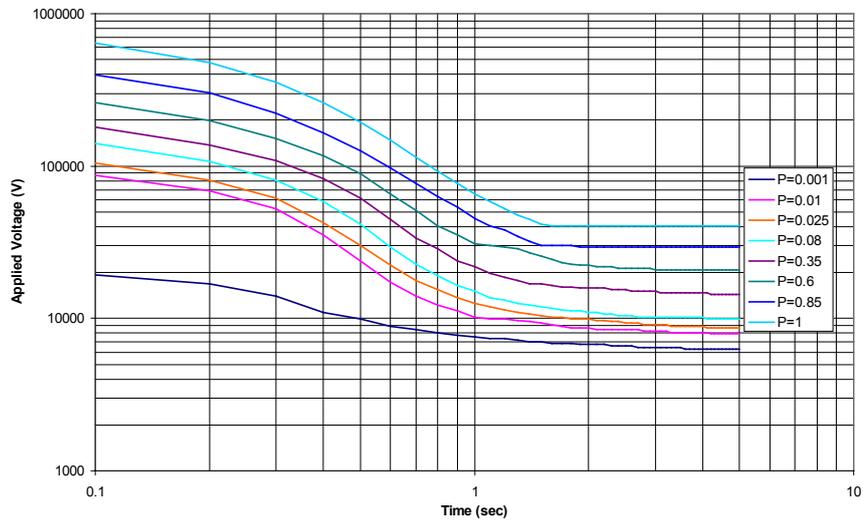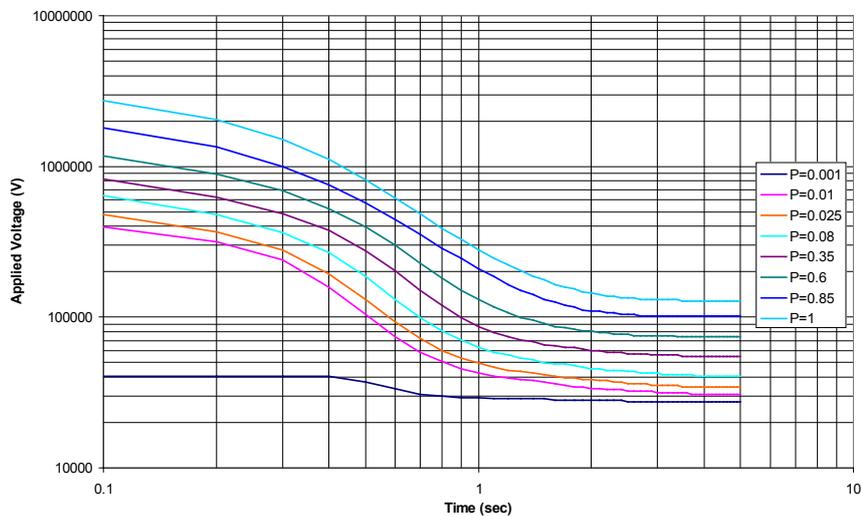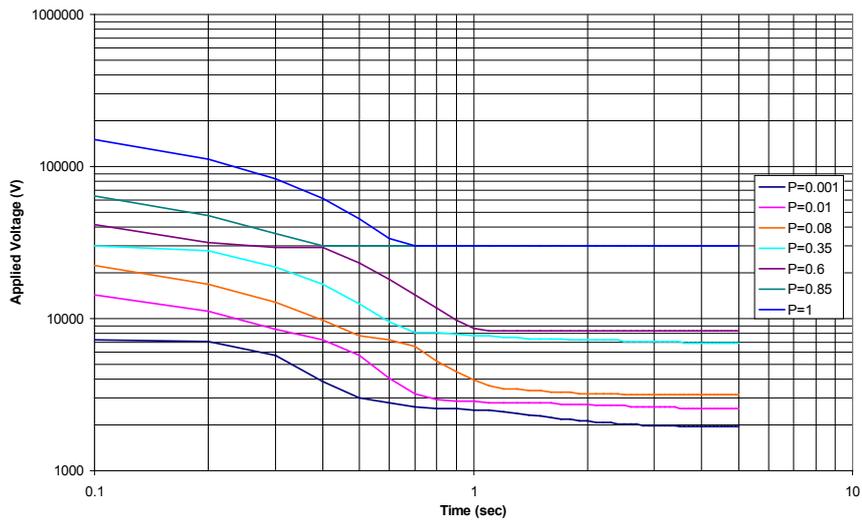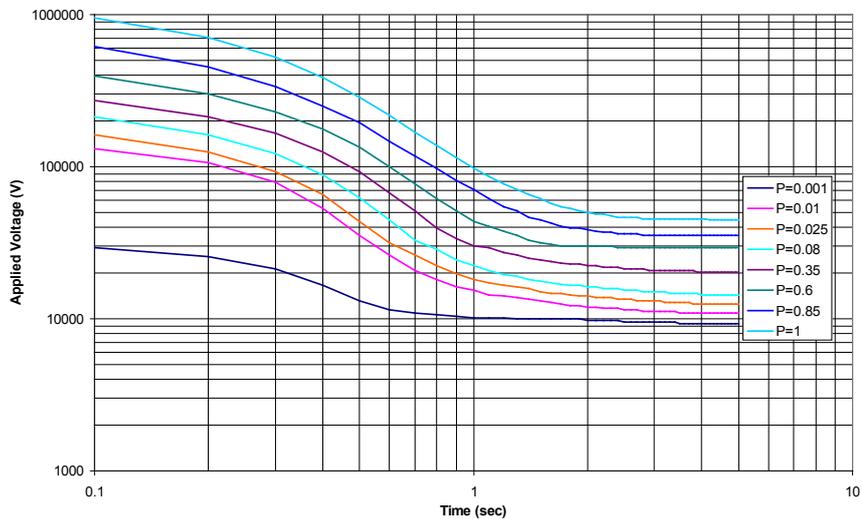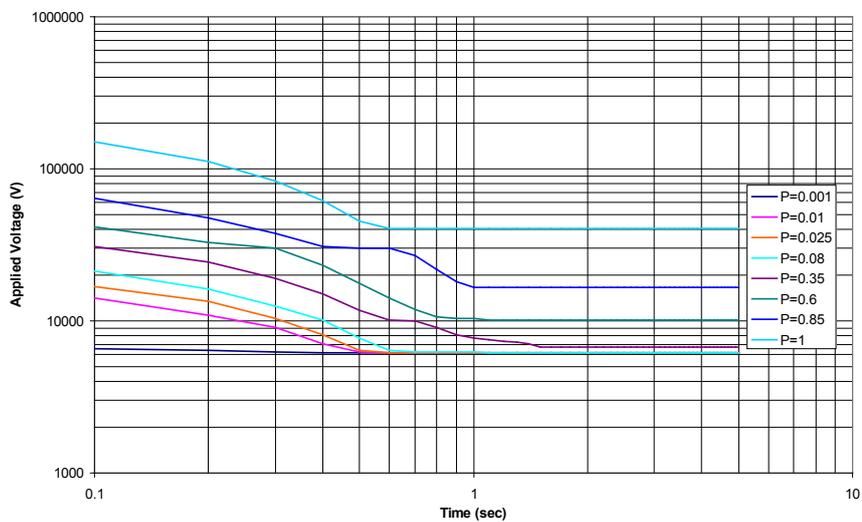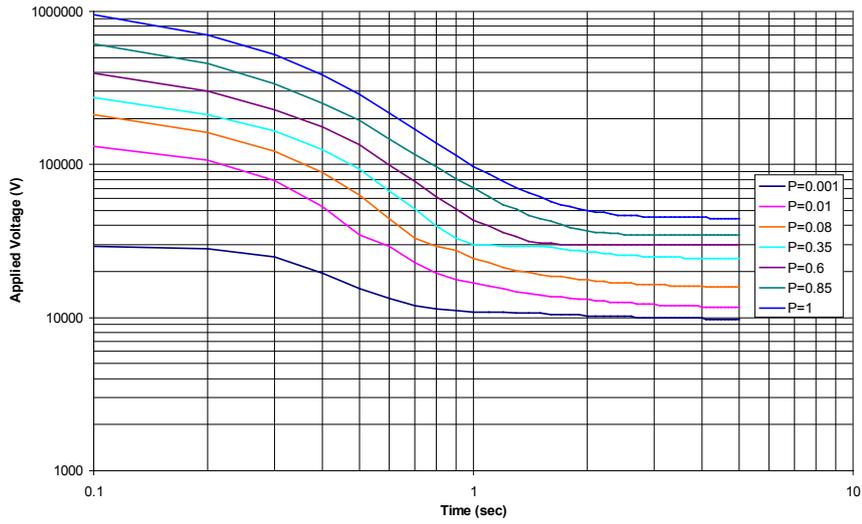*Figure B11-22: Prospective step, electrical footwear, dry body, 50 ohm.m soil, crushed rock/slab*
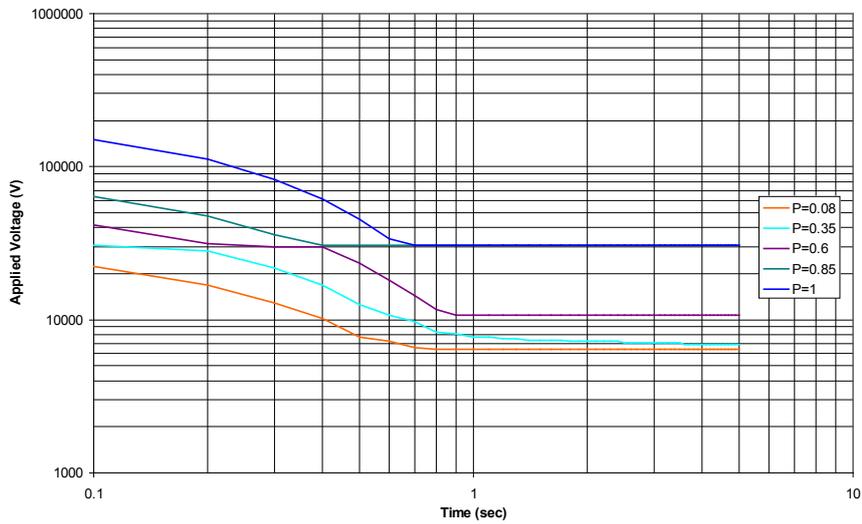
Figure B11-23: Prospective step, Electrical footwear, dry body, 50 ohm.m soil, asphalt
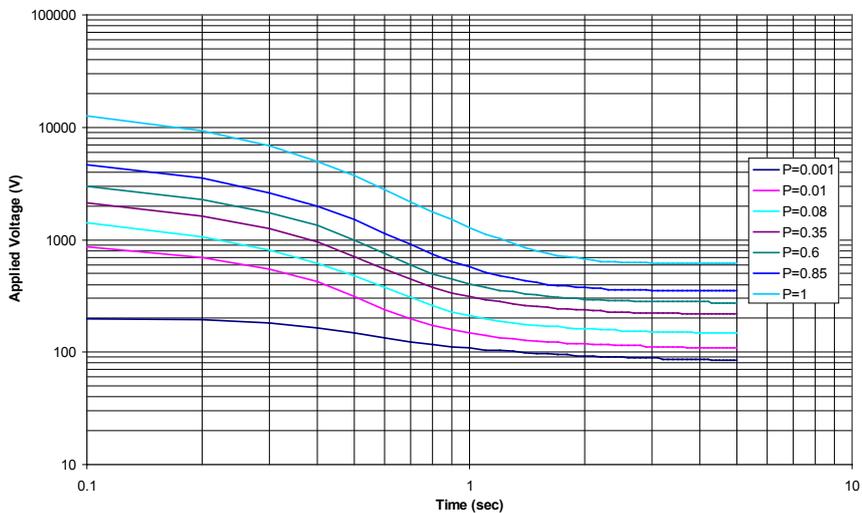
Figure B11-24: Prospective hand to hand, wet body

Appendix C: Manual probabilistic safety assessment process

This appendix provides a methodology whereby a probabilistic safety assessment may be made using a manual process. The scenarios that may be analysed include a range of series impedance cases a (for example, soil resistivity, footwear, surfacer layer, wet/dry body impedance) provided in **Appendix B.3**. The stages of the manual process are equivalent to Steps 6 A-D of the Power Frequency Design Process (see **Section 5.7**) as highlighted in **Figure C1** following.

Step 6A

Calculate coincidence probability

Is P_{coinc} < target? where target = 10^{-6}

Yes—negligible risk

No

Steps 6B and C

Determine voltage and clearing time relevant to fault scenario.

Determine series impedance applicable to ontgact scenario, e.g., crushed rock, footwear, soil resistivity.

Select famly of constant probability curves relating to series impedance.

Determine P_{fib} applicable to voltage and clearing time—if between curves, go to next highest curve.

Calculate max, required coincidence pbobability.

No—intolerable risk

Is risk acceptable?

Yes—negligible risk

Risk accepted

Reassess and modify

$P_{coinc} = P_{coinc}{}^{x}$

Coincidence reduction factor (CRF)

ALARA region—intermediate risk

Yes

Is mitigation justified?

No

Step 6D

Coincidence

Voltage/clearing time reduction or coincidence reduction?

Voltage / clearing time

Apply voltage / clearing time mitigation strategy

Figure C1: Safety criteria derivation methodology

Each of the four steps are described in more detail in the following three sections with supporting information provided in **Appendices A** and **B**.

C.1   Coincidence calculations (step 6A)

The first stage in the derivation process is to determine the likelihood of a person being present at the time of a fault occurrence (i.e. P_{coinc}). While not a customary assessment this is the logical first step based upon the major significance the coincidence probability plays in the risk profile formulation.

From Equation 1, if the maximum acceptable risk of fatality is set to a predetermined value (for example, 10^{-6} or 10^{-4} $P_{fatality}$ target), then for a known value of fibrillation probability there is a value of coincidence probability that determines whether the acceptable risk of fatality has been met. It is logical to use this value of coincidence probability as the target criteria for safety compliance.

C.1.1   Negligible or low risk and remote locations

If the coincidence probability is less than the allowable societal limits the hazard is of an acceptable level fault independent of the fibrillation probability. This condition is met for some low fault frequency cases (for example, some transmission structures without shieldwires) or for 'remote locations' where people rarely make contact. In such instances the earthing system specifications are dictated by system reliability requirements (for example, insulation coordination and protection operation) or equipment damage requirements (for example, telecommunications plant, pipeline insulations, railways signalling equipment). In some cases a standard design procedure may still be followed if the cost is low and the action expected.

C.1.2   Coincidence location factor lookup table

A simplified approach may be used if the hazard scenario meets one of the exposure descriptions given in the lookup **Table A1** provided in **Appendix A**. The coincidence multiplier is a factor in the table that combines fault and contact assumptions in order to determine the coincidence probability using Equation C-1 following:

P_{coinc} =   Coincidence location factor × fault frequency/year
                          x exposure duration **x** CRF   C-1

Where

$P_{coincidence}$ =   Probability of coincidence of a fault and simultaneous contact occurring.

Coincidence
Location Factor   =   Factor in lookup table (see **Table A1** in **Appendix A**).

                  + $$\frac{p_n \text{ x } (f_d + p_d)}{365 \text{ x } 24 \text{ x } 60 \text{ x } 60}$$ C-2

Fault Frequency   =   Number of fault occurrences expected to yield a hazard event in the period of 1 year. **Table A2** in **Appendix A** gives typical fault rates.

Exposure duration =   number of years over which an individual is likely to be exposed to a given hazard scenario.

                  =   1 year in this analysis.

CRF   =   coincidence reduction factor

                  =   an empirical factor by which coincidence is expected to be reduced as a result of a specific mitigation strategy (for example, warning signs, barbed wire). See **Section 5.6.4** for more detail of the use of a CRF in Stage 3 of the process.

                  =   1 initially unless specific mitigation strategies applied.

Table C1 following gives an excerpt of the coincidence location factor table from *Appendix A*.

Table C1: Coincidence Location Factor (Multiplier) Example

Location	Access Assumptions	Coincidence multiplier (*10⁻⁴) for fault duration (sec)				
		0.1sec	0.2sec	0.7sec	0.8sec	0.9sec
Remote	Remote location where a person may contact up to 1 time per year for up to 20 sec.	0.00637	0.00641	0.00656	0.0066	0.00663
MEN	Regular contact up to between 6 and 7/day with items connected to the MEN (contact duration 4 sec)	3.12	3.20	3.58	3.65	3.73

Example 1—Remote structure

If the location is deemed to meet the 'remote location' description, where a person may visit annually and be in an exposed position for up to 20 seconds, and the structure or effected location is expected to see less than 1 fault every 20 years, with fault duration less than 0.2 seconds, the annual coincidence probability is likely to be less than:

$$P_{coincidence} \leq 0.0064 \times 10^{-4} \times 0.05 \times 1$$
$$= 3.2 \times 10^{-8}$$

It may be seen that as the coincidence probability is much less than the lower limit of 10^{-6} that the shock criteria is acceptable independently of the fibrillation probability.

C.1.3   Coincidence calculation

For additional scenarios, or if the parameters given in the standard cases cited in *Table A1* are not applicable, the fault/contact coincidence probability may be calculated using another simplified formula given in Equation C-3 following:

$$P_{coinc} = \frac{f_n \times p_n \times (f_d + p_d) \times T \times CRF}{365 \times 24 \times 60 \times 60} \qquad \text{C-3}$$

Where

f_n	=	number of earth faults/year
f_d	=	fault duration (seconds)
p_n	=	number of presences/year
p_d	=	presence duration (seconds)
T	=	exposure duration (years)
	=	1 year
CRF	=	Coincidence reduction factor (see *Section 5.6.9.2*) (set to 1 normally)

Appendix A provides additional information regarding the calculation of fault/contact coincidence including:

» derivation of individual and societal risk coincidence probability

» coincidence multiplier table for sample exposures

» fault duration and rate tables and guidance

» non uniform arrival situations.

Example 2—Individual substation operator

The following case study will work through the three-stage process as it relates to an individual power utility operator who typically works in major substations. The following parameters are assumed:

» operator moves in and around substation equipment (for example, operating isolators and earth switches) and fence (i.e. opening gate)

» contacts: 2000/year for five sec on average

» safety shoes—use electrical footwear (see **Appendix B**)

» crushed rock surface layer

» touch voltages expected up to 500V

» clearing time 500ms or less

» fault rate 20/year—system faults not initiated by operator

» coincidence reduction factor (CRF) of unity.

As there is no matching access profile on the lookup table, use the supplied formula (from Equation (C-3)) to calculate the coincidence probability:

$$P_{Coinc} = \frac{20 \times 2000 \times (0.5 + 5) \times 1}{365 \times 24 \times 60 \times 60}$$

$$= 6.98 \times 10^{-3}$$

C-4

As the coincidence probability is higher than 10^{-6} lower risk bound, Stage 2 of the process needs to be followed.

C.2 Coincidence compliance assessment (steps 6B and 6C)

If the coincidence value calculated does not meet the 'negligible risk' target of 10^{-6} then, according to Equation (1), the fibrillation probability may be calculated and used to reduce the fatality probability. A series of voltage time curves have been derived that have constant fibrillation probability independent of fault duration based upon IEC 60479. Such constant probability (P_{fib}) curves are needed to make resolution of Equation 1 possible without additional detailed calculations, as P_{coinc} is also dependant upon fault duration. The tables of voltage time characteristics with constant P_{fib} included in **Appendix B** have been derived to cover appropriate combinations of the following cases:

» contact configuration—touch, step and hand to hand voltages

» upper layer soil resistivity—50, 100, 500, 1000, 2000, 5000 ohm.m

» surface layer materials—crushed rock, asphalt

» additional series impedances—footwear, electrical footwear

» moisture—wet or dry hands.

For situations where the voltage and clearing time give a point between two constant probability curves, the higher of the curves is used as a conservative value for the design. Then, using the value of P_{fib} determined from the graph, the target acceptable coincidence probability ranges (based on a target $P_{fatality}$ target range of 10^{-6} to 10^{-4}) maybe calculated as per Equation C-5.

$$P_{Target\ Concidence} \leq \frac{10^{-6}}{P_{fib}} < ALARA\ region \leq \frac{10^{-4}}{P_{fib}}$$

C-5

Hence the upper bound on the target coincidence probability can be defined as:

$$P_{Target\ Concidence} \leq \frac{10^{-6}}{P_{fib}}$$

C-6

If the probability of coincidence $P_{coinc} < P_{Upper\ target\ required\ coincidence}$ then the design process is complete. If the probability of coincidence is in the ALARA region (see **Section 4.4**) then it is necessary to consider what mitigation is required.

As the expected coincidence probability is higher than 10^{-6} it is necessary to determine the probability of fibrillation in order to calculate the maximum required value of coincidence probability. To do this the constant fibrillation probability curves corresponding to electrical footwear and crushed rock are used as shown in **Appendix B**.
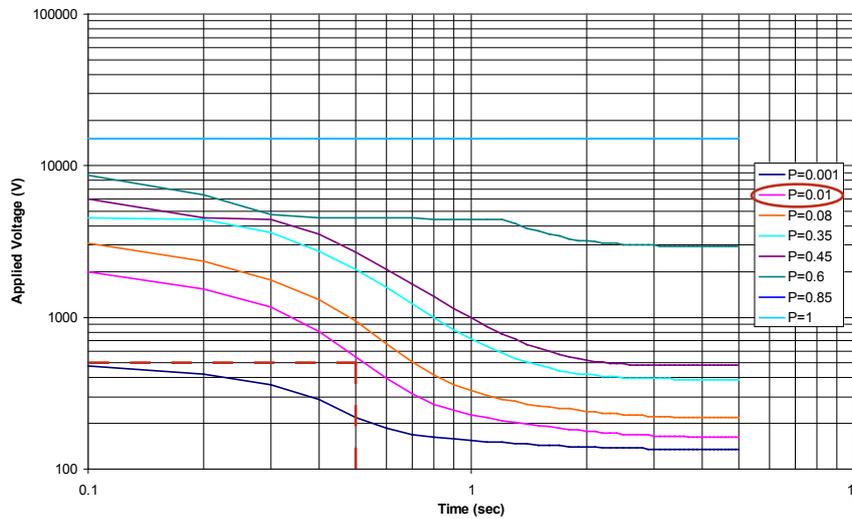
Figure C2: Constant probability of fibrillation—electrical worker footwear,
50 ohm.m soil, crushed rock, 100% dry

The 500 volt/0.5 second point lies just below the 0.01 fibrillation probability curve (in **Figure C2**). Target acceptable coincidence probability range is therefore calculated using Equation 5 to be between:

$$P_{\text{Target Concidence}} \leq \frac{10^{-6}}{0.01} < \text{ALARA region} \leq \frac{10^{-4}}{0.01}$$

C-7

$$P_{\text{Target Concidence}} \leq 10^{-4} < \text{ALARA region} \leq 10^{-2}$$

C-8

As the calculated coincidence probability of 6.98×10^{-3} is within the ALARA region, it is necessary to consider mitigation in the design. Therefore move on to Step 6C of the procedure and consider what options are appropriate.

C.3 Hazard mitigation assessment (step 6D)

If compliance is not achieved in steps 6B and 6C then the two main mitigation options usually followed are to either reduce the presented voltage or clearing time, or reduce the probability of coincidence. A third alternative relates to extreme cases where either the cost of mitigation is prohibitive or prudence would dictate applying mitigation nonetheless.

The design is complete if P_{coinc} (see Equations **Appendix A**) meets the target value.

$$P_{\text{coinc}} < P_{\text{Upper target coincidence}}$$

C-9

For cases where the preceding condition is not met (i.e. in ALARA region) a risk cost benefit analysis outlined in **Section 5.7.5** and **Appendix F** should be used.

Appendix D: Worked examples

To illustrate the principles of risk based earthing design, two worked examples are presented as detailed below. The first demonstrates an individual/societal risk analysis for a 'gathering' type event implemented through software, while the second considers the individual risk through the manual process outlined in **Appendix C**.

D.1   Societal gathering case study

To demonstrate software-aided risk based earthing design, the following case study is outlined below.

The case study involves an existing 132kV steel lattice tower 10m from a metallic fence surrounding a sporting ground. Events are held at the ground 30 times/year for a duration of three hours. There are potentially 100 people exposed to fault situations at each event.

Firstly the touch voltage scenarios will be assessed. Ninety (90) percent of the population do not contact the fence adjacent to the tower more than 12 times/event while the average person will contact four times/event. The duration of each contact is 30 seconds. Faults occur at the tower at the rate of 0.045/year with a clearing time of 200msec. The maximum touch voltage on the fence was calculated as 600V.

This information can be entered into **Argon** [28], using the 'Time dependent—gathering' Time Base options (selected under the 'Tool' menu), as shown in **Figure D1** following.
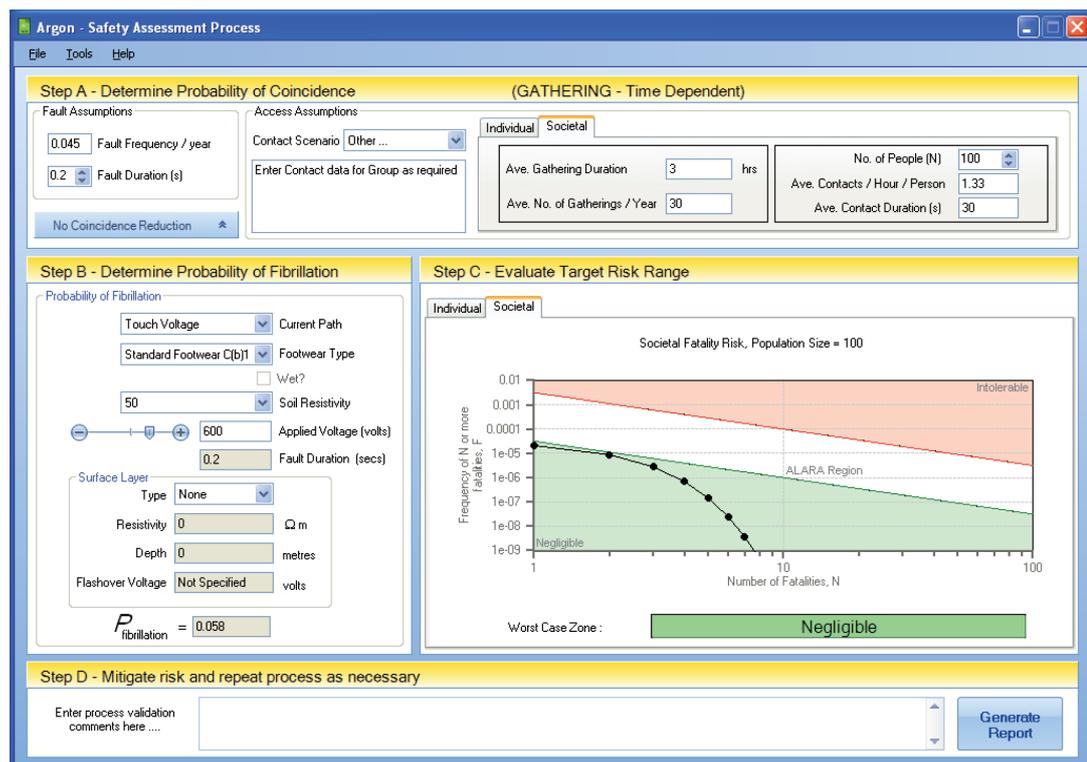
Figure D1: Argon societal gathering risk assessment

From the **Argon** [28] output for the touch voltage case illustrated, all points on the F-N curve sit below the ALARA region in the Negligible risk region.

To ensure that no individual is exposed to a greater risk than that acceptable under the individual targets, it is also necessary to consider the above information for the individual case. See **Figure D2** following for the **Argon** input screen.

The probability of fatality for the individual touch voltage case is 9×10^{-7} which puts the case in the negligible risk category. No further risk mitigation is required.

Figure D2: Argon individual gathering risk assessment

The risk associated with step voltages in the vicinity of the tower should also be assessed. Using a conservative estimation of a typical person taking 100 steps each (0.5 secs duration) in the tower vicinity with an average applied step voltage of 5000 volts, the societal risk and individual levels also lie in the negligible risk region. No hand-to-hand contact scenarios were identified in the areas.

D.2   33kV concrete pole case study

To illustrate the principles of risk based earthing design following the simplified method presented in this Guide, a simple case study is detailed below.

The case study involves an existing 33kV concrete pole located close to a bus stop. This pole was identified as potentially carrying an EPR risk for people using the bus stop. The bus stop is typically used by people travelling to work and it can therefore be assumed that footwear is worn around the pole.

Step 1—Gathering data

» The prospective earth fault current at the source substation is 7 kA.
» The resistance to earth of the 33kV pole was measured as 20 Ω.
» The resistivity of the top soil layer was measured as 50 Ω-m.
» The earth fault clearing time is 0.5 s.
» The earth fault frequency for the line is five per year.
» The line consists of 200 poles.

Step 3—Maximum EPR

Using parameters associated with the earth fault current path for an earth fault at the pole, the EPR on the pole was calculated as 6kV.

Step 5—Step A safety criteria methodology

The only hazardous components at the pole are the touch voltages onto the concrete pole. The risk can be assessed by calculating the coincidence probability.

$$P_{coinc} = f_n p_n (f_d + p_d) \frac{1}{365 \times 24 \times 60 \times 60}$$

The frequency of earth faults for the line with 200 poles is five faults per year. Therefore:

$$f_n = \frac{1}{200} = 0.025$$

If for the purpose of this case study, we assume that the pole is being touched once a day for one minute (i.e. someone leans against the pole) for five days of the week (i.e. for 260 days per year), $p_n = 260$.

$$P_d = 5 \text{ minutes} \times 60 \text{ seconds} = 300 \text{ seconds}$$

$$P_{coinc} = f_n p_n (f_d + p_d) \frac{1}{365 \times 24 \times 60 \times 60} = \frac{(0.025)(260)(0.5 + 300)}{(365 \times 24 \times 60 \times 60)} = 6 \times 10^{-5}$$

Since only one person is typically affected, $N^2 = 1$ and the end target is unaffected.

As $P_{coinc} > 10^{-6}$, the probability of fibrillation must be calculated using Step 6B of the Safety Criteria Methodology.

Calculate actual step and touch voltages

The actual maximum step voltage was calculated as approximately 2000 V.

The actual touch voltage on the pole was calculated as approximately 3000 V.

For step voltage:

The constant characteristic fibrillation curve family most closely relating to the site conditions is shown in **Figure D3**. The expected step voltage of 2000V (for 0.5 secs) is plotted on **Figure D3** to determine the equivalent fibrillation probability.
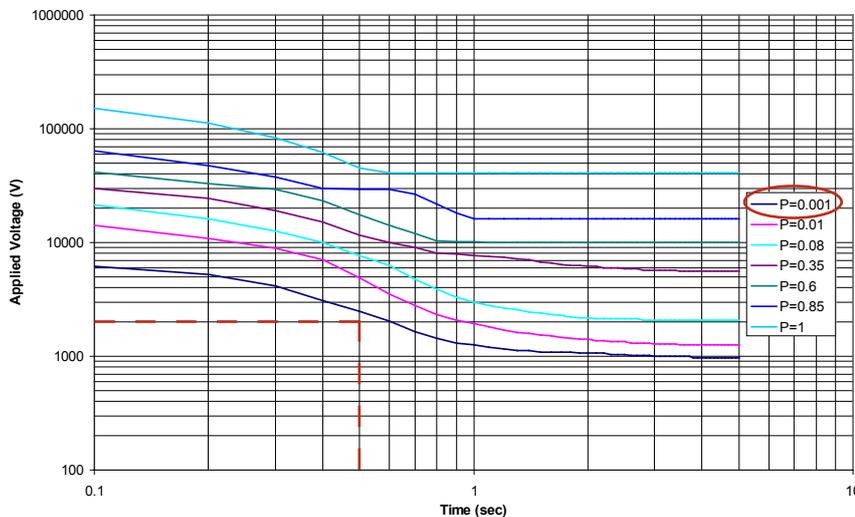
Figure D3: Step voltage, typical public footwear, Dry Body Impedance, Soil Res 50 Ohm.m

$$P_{fibrillation} <= 0.001$$

Calculate target coincidence range:

$$P_{Target\ Concidence} \leq \frac{10^{-6}}{p_{fib}} < ALARA\ region \leq \frac{10^{-4}}{p_{fib}} \qquad \text{D-1}$$

$$P_{Target\ Concidence} \leq \frac{10^{-6}}{0.001} < ALARA\ region \leq \frac{10^{-4}}{0.001} \qquad \text{D-2}$$

$$P_{Target\ Concidence} \leq 1 \times 10^{-3} < ALARA\ region \leq 0.1 \qquad \text{D-3}$$

As $P_{coinc} = 6 \times 10^{-5}$, the risk lies in the negligible risk zone for step voltage hazards.

For touch voltage:

The expected touch voltage of 2000V for 0.5 secs is shown on **Figure D4** following.
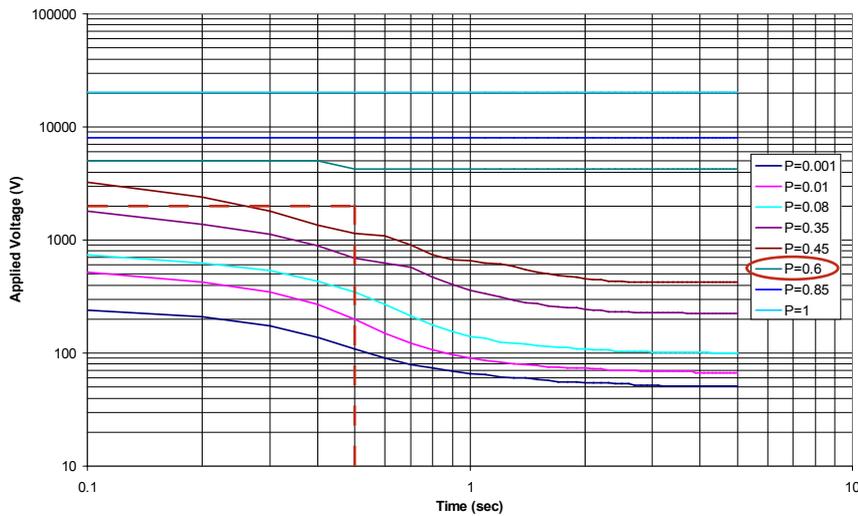
Figure D4: Touch voltage, typical public footwear, Dry Body Impedance, Soil Res 50 Ohm.m

$$P_{fibrillation} < 0.6$$

Calculate target coincidence range according to the following equation:

$$P_{Target\ Coincidence} \leq \frac{10^{-6}}{p_{fib}} < ALARA\ region \leq \frac{10^{-4}}{p_{fib}}$$

D-4

$$P_{Target\ Coincidence} \leq \frac{10^{-6}}{0.6} < ALARA\ region \leq \frac{10^{-4}}{0.6}$$

D-5

$$P_{Target\ Coincidence} \leq 1.67\ x\ 10^{-6} < ALARA\ region \leq 1.67\ x\ 10^{-4}$$

D-6

As $P_{coinc} = 6\ x\ 10^{-5}$, the risk is classified as being in the ALARA region or Intermediate Risk and should be minimised unless the risk reduction is impractical or the costs are grossly disproportionate to the level of safety gained.

Sensitivity analysis

It is often useful to change the input parameters to determine the level of sensitivity of the compliance outcome to these inputs. This can be achieved simply when using software such as **Argon** [28]. It is thus possible to determine upper and lower bounds on the contact frequency and duration corresponding to the ALARA region.

Risk cost benefit analysis

A cost benefit analysis should be carried out to provide input to the mitigation justification process. The following values provide an illustration of the present value (PV) process (see **Appendix F**). The various input parameters should be validated within the context of the duty holding utility or corporation. The PV calculation provides one input to the risk cost benefit analysis process.

Calculate the present value (PV) of the liability:

VoSL = $10 000 000

Liability per year = 10 000 000 **x** 6 **x** 10^{-5} = $600

PV = $13 000 (assuming an asset lifespan of 50 years and a discount rate of four percent).

Steps 7 and 8: Risk treatment option assessment

Examples of risk treatment options are:

- » installing an underslung earth wire on the line
- » installing a gradient control conductor and an asphalt layer around the pole
- » installing an insulating barrier around the pole to prevent people from touching the pole
- » moving the pole
- » moving the bus stop.

A few of the above risk treatment options are discussed below to illustrate the principles.

Installing an underslung earth wire on the line

A study has shown that an underslung earth wire would reduce the EPR on the pole to 600 V. The resulting touch voltage on the pole would then reduce to 300 V which is below the tolerable touch voltage limit. The cost of this risk treatment option has been determined to be approximately $200 000. Comparing the cost of risk treatment to the present value of the liability indicates that the cost of this risk treatment option is grossly disproportionate to the safety gained. The earth wire may only reduce the risks associated with the terminating substations which could be factored into the process. In addition future changes in land use along the line may indicate additional value for this option. An alternative would be the use of an overhead shield wire mounted on raiser brackets, which would provide the added value of increasing reliability if the line was subject to lightning strikes.

Installing a gradient control conductor and an asphalt layer around the pole

With a gradient control conductor installed at a distance of one metre around the pole, the touch voltage still exceeds the touch voltage limit. However, if asphalt is installed around the pole, the touch voltage limit increases to 2500 V with the result that the touch voltage is lower than the limit. The cost of this risk treatment option is $10 000 and is below the present value of the liability. There may be some additional ongoing costs associated with maintenance of the asphalt.

Installing an insulating barrier around the pole to prevent people from touching the pole

An insulating barrier could be installed around the pole to prevent people from being able to touch the pole. Such an insulating barrier could take the form of a wooden enclosure or a fibreglass jacket. The cost of this risk treatment option is $5000 and is significantly below the present value of the liability. There may be some additional ongoing costs associated with maintenance of the insulating barrier.

Additional risk treatment options may be considered as required. Clearly, economically viable risk treatment options exist for this case and one of the options should be implemented. The cheapest risk treatment option may not be the best option. Other considerations may dictate which risk treatment option is selected. For example, an underslung earth wire may be the best option if a number of other EPR issues exist along the line.

For other cases, the costs and practicality of the selected risk treatment option may be such that there is some residual risk after treatment is applied. This residual risk may be negligible and therefore acceptable. Alternatively, the residual risk may be in the intermediate category and would require further risk cost benefit analysis. The risk cost benefit analysis may be applied using the amount by which the probability of fatality has been reduced to determine whether further risk treatment is required.

Appendix E: Probabilistic safety criteria case studies

A series of standard (or predetermined) prospective touch voltage/clearing time curves have been developed to cover approximately the same key design cases as existing in standards today. This is aimed at providing engineers with design curves complete with their boundary conditions well identified. For each case study the following information has been included: curve details (figure and equation) and assumptions governing the range of applicability. If the boundary conditions do not meet the case under investigation the 'by hand' method (see *Appendix C*) or **Argon** [28] software may be used to generate appropriate design curves.

The following comments provide information regarding the background behind the selected curves:

Conservatism: Wherever possible a conservative approach has been followed in order to widen the range of applicable conditions for a given curve type.

Touch duration: Contact duration of four (4) seconds has been taken as a general case, except where otherwise mentioned.

Surface soil resistivity: A low soil resistivity value of 50 ohm-m has been used.

Standard public footwear: A typical distribution of footwear resistance (see *Appendix B.1.2.2*, *Table B5*) has been selected in all cases except that of bare feet at swimming pools, and electrical worker footwear (see *Appendix B.1.2.2*, *Table B6*) inside substations.

Surface layer materials: Crushed rock with a resistivity of 3000 ohm-m and thickness of 100mm has been used within substations.

Contact configuration: The curves relate to prospective touch voltages, however, they can be applied very conservatively to prospective step voltages.

Risk targets: All curves relate to a 'negligible risk' level as defined for individual and societal risk as appropriate (see *Section 4.4.6*). An exception is 'backyard' and 'MEN' access under zone substation secondary fault conditions, where a curve corresponding to an individual risk limit of 1 in 100 000 has also been shown.

Contact scenarios: The representative contact scenarios selected are:

» **Remote**—A location where the contact frequency is sufficiently low that the fault/contact coincidence probability is less than the target fatality probability. In that case there is no touch voltage target required.

» **Urban interface**—Asset outside normal public thoroughfare with low frequency of direct contact by a given person.

» **Backyard**—An area with a contactable metallic structure (for example, fence, gate) subject to fault induced voltage gradients. This metallic structure is not an HV asset but becomes live due to earth fault current flow through the soil.

» **MEN contact**—Contact with LV MEN interconnected metalwork (for example, household taps) under the influence of either LV MEN voltage rise and/or soil potential rise.

Power system asset categories—The power system assets have been divided into the following categories:

» **Transmission assets**—overhead lines and cables and associated infrastructure (for example, poles, earth pits) with system voltages of 66kV and above.

» **Distribution assets**—Overhead lines and cables with system voltages less than 66kV, and distribution transformers with LV secondary.

» **Transmission substations**—Major substations with secondary voltages of 66kV and above.

» **Zone substations**—Major substations with secondary voltages less than 66kV.

Fault frequencies and durations: The fault frequencies and durations used are listed with each curve. They are conservatively based upon the fault data given in *Appendix A-3*.

Curve shape selected: A conservative curve match has been selected based upon **Argon** [28] generated

curves corresponding to the cases under consideration. For clearing time conditions outside those tabulated (i.e. < 0.1 secs and > five secs) the curve match equations are not valid. For times less than 100m secs use the value tabulated for 100 m secs. For times greater than five secs apply a tangent to extrapolate the curve.

The following table summarises the cases provided and the acronyms used to describe each case. Each case is characterised by a particular combination of fault rate, contact probability and series resistance. The aquatic cases are for wet body, all other cases are dry.

Table E1: Case study descriptions

Case		Description	Acronym
E-1	Transmission (≥66kV) and distribution assets (< 66kV)	Contact with transmission asset in urban interface location.	TU
		Contact with distribution asset in urban interface location.	DU
		Contact with metalwork in a backyard effected by either transmission or distribution asset.	TDB
		Contact with MEN connected metalwork (around house) where MEN or soil is effected by either transmission or distribution assets.	TDMEN
		Contact with metalwork associated with an aquatic centre that operates five months of the year.	AQ5
		Contact with metalwork associated with an aquatic centre that operates twelve 12 months of the year.	AQ12
E-2	Transmission substations (≥66kV secondary)	Backyard near major substation with primary side fault.	MSPB
		Backyard near transmission substation with secondary side fault.	TSSB
		MEN contact near transmission substation with secondary side fault.	TSSMEN
E-3	Zone substations (< 66kV secondary)	Backyard near major substation with primary side fault.	MSPB
		Backyard near zone substation with secondary side fault.	ZSSBI
		MEN contact near zone substation with secondary side fault.	ZSSMEN
E-4	Inside major substations	Inside transmission substation.	TSI
		Inside zone substation.	ZSI

E.1 Transmission and distribution assets

The following series of curves (in **Figure E1**) relate to acceptable prospective touch voltages associated with earthfault events on transmission and distribution assets. The transmission cases relate to lines and cables with system voltages of 66kV and above, and distribution lines and substations, with fault frequency assumptions given in **Table E2**.
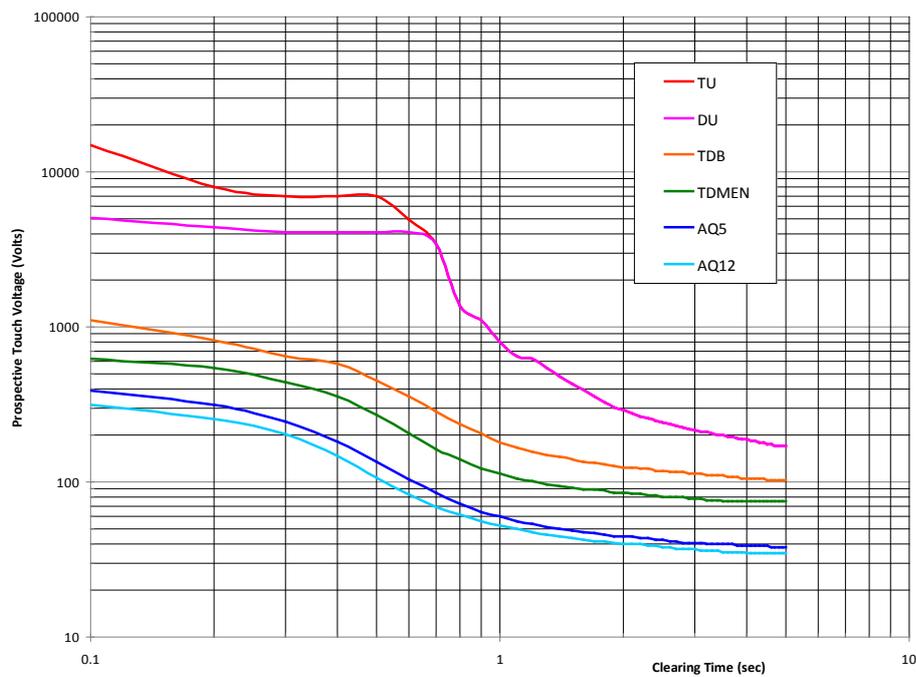
Figure E1: Transmission and distribution asset prospective touch voltage criteria

The following two tables describe the basis of each prospective touch voltage curve shown above. Note that individual risk contact frequency and durations are based upon a 'typical maximally' exposed individual (i.e. 90-95 percent confidence limit).

Table E2: Curve generation data

Curve		Fault frequency/yr	Contact Scenario	Footwear
Transmission Urban	TU	0.1	Urban-100 contacts/yr for 4 sec for clearing times to 1sec (≥66kV)	Standard
			135 contacts/yr for 4 sec clearing times above 1 sec (<66kV)	
Distribution Urban	DU	0.1	135 contacts/yr for 4 sec	Standard
Transmission distribution backyard	TDB	0.1	Backyard-416 contacts/yr for 4 sec	Standard
Transmission distribution MEN	TDMEN	0.1	MEN-2000 contacts/yr for 4 sec	Standard
Aquatic 5 months/yr	AQ5	0.1	Aquatic-as per societal based gathering with a population size of 50	None/wet
Aquatic all year	AQ12	0.1	Aquatic-as per societal based gathering with a population size of 50	None/wet
Remote	N/A	0.1	Less than 60 off (4 sec) contacts for 1 sec fault duration, or less than 75 off (4 sec) contacts for 0.2 sec fault duration	N/A

The following points provide an outline of the assumptions behind the fault rates used in **Table E2**.

- » **Transmission assets**: 2 km long transmission section (for example, asset interconnected by 10 spans each up to 200m in length with an overhead earth wire) contributing at a fault rate of 5 faults/100km/year yielding 1 fault per 10 years.

- » **Distribution assets**: A fault rate of 1 fault per 10 years relates to a range of distribution assets including:
  - » 1km of isolated underground cable @ 10 faults/100km/yr
  - » 2 by 500m of underground cable feeding a substation @ 10 faults/100km/yr

» 1 km line section (for example, 10 by 100m) with an earth wire shielded @ 10 faults/100km/yr

» 2 by 100m spans without an earth wire @ 40 faults/100km/yr

» 2 by 100m spans without an earth wire and pole mounted substation @ 40 faults/100km/yr.

» **Aquatic centres:** A fault rate of one fault per 10 years relates to 500m of underground cable and associated substation.

» **Remote assets:** Assets may be considered as 'remote' if they do not require a certain touch voltage to comply with the risk targets (i.e. coincidence probability below risk target).

The following table details the voltage/time points used in the generation of the allowable curves.

Table E3: Data points used in generation of curves

Curve		Voltage	Clearing Time (sec)
Transmission Urban <1 sec	TU	8000	0.2
Transmission Urban >1 sec	TU	800	1
Distribution Urban	DU	800	1
Transmission distribution backyard	TDB	181	1
Transmission distribution MEN	TDMEN	121	1
Aquatic 5 months/yr	AQ5	60	1
Aquatic all year	AQ12	52	1

The following table provides the equations that may be used to generate the curves.

Table E4: Curve generation equations

Prospective touch voltage characteristic equation	
TU	$(A+B \times \ln(t)+C \times(\ln(t))^2+D \times (\ln(t))^3+E \times(\ln(t))^4+F \times (\ln(t))^5)/$ $(1+G \times \ln(t)+H \times (\ln(t))^2+I \times (\ln(t))^3+J \times(\ln(t))^4+K \times(\ln(t))^5)$
DU	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4+F \times t^5)/(1+G \times t+H \times t^2+I \times t^3+J \times t^4+K \times t^5)$
TDB	$(A+B \times t^{0.5}+C \times t+D \times t^{1.5}+E \times t^2)/(1+F \times t^{0.5}+G \times t+H \times t^{1.5}+I \times t^2)$
TDMEN	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4)/(1+F \times t+G \times t^2+H \times t^3+I \times t^4+J \times t^5)$
AQ5	$(A+B \times t^{0.5}+C \times t+D \times t^{1.5}+E \times t^2)/(1+F \times t^{0.5}+G \times t+H \times t^{1.5}+I \times t^2+J \times t^{2.5})$
AQ12	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4+F \times t^5)/(1+G \times t+H \times t^2+I \times t^3+J \times t^4+K \times t^5)$

	TU	DU	TDB	TDMEN	AQ5	AQ12
A	799.42725	8220.3651	97.645156	-649.67186	698.77353	495.31069
B	-151.06911	-16049.118	-795.84933	16189.957	-2119.495	-924.04026
C	2134.7725	-3233.5941	2480.8153	-20833.832	2500.9396	799.79951
D	-2465.5817	22189.669	-3353.6563	-7164.2576	-1252.7575	1923.7987
E	957.22069	-17347.089	1882.7004	50476.952	227.96264	-910.51476
F	-54.963953	8373.5787	-8.6985271	-16.765657	0.067719264	102.10042
G	2.439744	6.8997717	27.772071	255.8065	-7.9995184	5.7831848
H	2.1390046	-48.174695	-38.682025	-743.73193	15.571508	-34.926711
I	-0.37795247	109.8737	20.292411	852.87544	-9.7021929	85.548089
J	-0.062680222	-118.88136		-12.438076	1.9941212	-32.281391
K	0.072177248	51.807561				3.3629346

Societal risk assessment

The societal risk associated with each of the assets has also to be assessed for each hazard scenario with the assumptions and conclusions shown in **Table E5**. Note that the exposure conditions are based upon average exposure frequency and duration estimates for the susceptible group of people, and the number of exposed people is based upon the number who could reasonably be expected to be able to make simultaneous contact with affected metalwork.

Table E5: Societal risk assessment assumptions

Curve		Av. contacts/ person/yr	Av contacts duration (secs)	Av gathering duration (hrs)	Av. no. gatherings/yr	Max. no. people for < 10e-6 risk
Transmission Urban <1 sec	TU	75 Year	4	N/A	N/A	41
Transmission Urban >1 sec	TU	75 Year	4	N/A	N/A	41
Distribution Urban	DU	75 Year	4	N/A	N/A	43
Transmission distribution backyard	TDB	312 Year	4	N/A	N/A	42
Transmission distribution MEN	TDMEN	1500 Year	4	N/A	N/A	42
Aquatic 5 months/ yr	AQ5	7/gathering	2	10	150	43
Aquatic all year	AQ12	7/gathering	2	10	365	43

Assumptions

» Contacts are based on the expected behaviour of an average person. This has been approximated as 75 percent of the number of contacts for a worst case single individual.

» Aquatic contacts are 7 per person per gathering. This is 7 contacts per person over a 10 hour gathering duration.

Application notes

» Assets directly connected to major substations need to comply with the criteria listed in the section for faults associated with the asset, as well as the appropriate major substation criteria for voltages transferred to the asset under substation EPR conditions.

» The fault rates chosen are above average for higher transmission voltage assets to simplify the criteria generated. This does not preclude a utility from reassessing its own asset class and deriving less stringent criteria if necessary.

» Whenever safety criteria are selected (either standard curves or using **Argon** [28] software) it is important that appropriate technical review be undertaken (for example, peer and/or manager review and signoff). For alternative curves generated within **Argon** it is also important that adequate sensitivity analysis be undertaken and assumptions and decisions documented in a generated report.

» A surface soil resistivity of 50 ohm-m has been used for all contact cases outside a major substation fence. This is quite a conservative value as in many instances the higher surface soil resistivity would add series impedance allowing higher perspective touch voltages. **Figure E2** provides and example of the transmission/distribution MEN contact criteria for a range of soil resistivities.
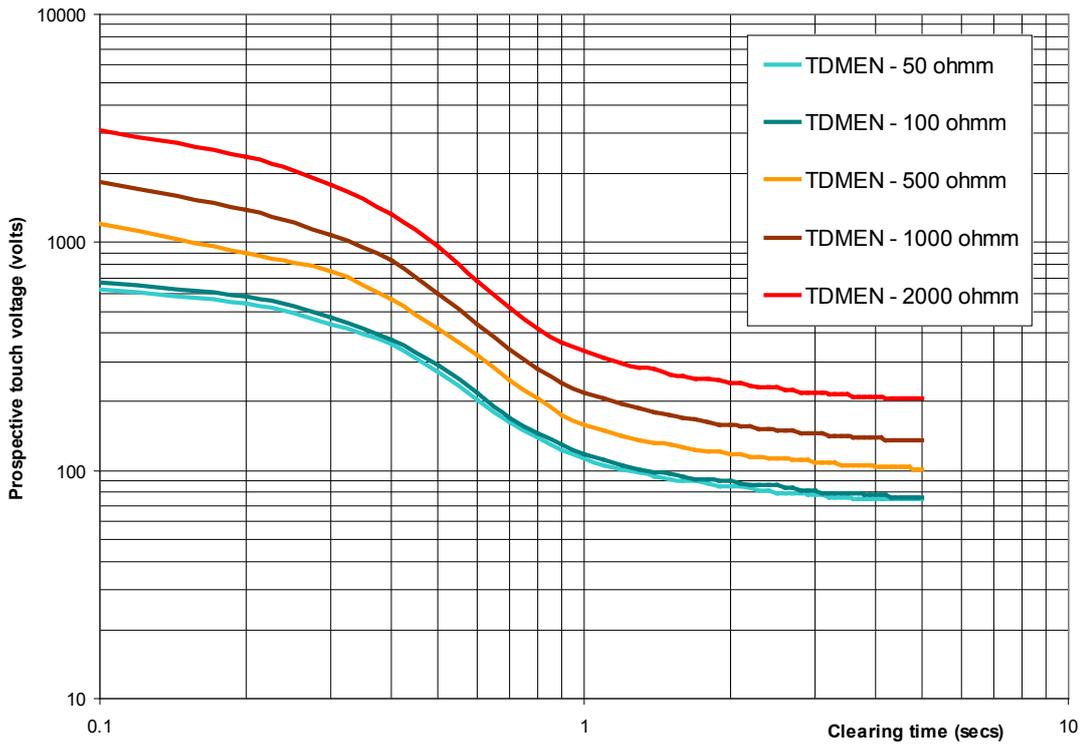
Figure E2: Surface soil resistivity effect on TDMEN prospective touch voltage contact case

E.2   Transmission substations

The following series of curves relate to acceptable prospective touch voltages associated with earthfault events on transmission substations, and hazard scenarios beyond the fence. The transmission cases relate to system voltages of 66kV and above, with fault frequency assumptions given in *Table E6*. The hazard scenarios to be managed within the transmission substation perimeter fence are handled separately in *Appendix E4*.

Figure E3: Transmission asset prospective touch voltage criteria

The following two tables describe the basis of each prospective touch voltage curve shown above. Note that individual risk contact frequency and durations are based upon a 'typical maximally' exposed individual (i.e. 90 to 95 percent confidence limit).

Table E6: Curve generation data

Curve		Fault frequency/yr	Contact scenario	Footwear
Major substation primary backyard	MSPB	0.1	Backyard-416 contacts/ yr for 4 sec	Standard
Transmission substation secondary backyard	TSSB	5	Backyard-416 contacts/ yr for 4 sec	Standard
Transmission substation secondary MEN	TSS MEN	5	MEN-2000 contacts/yr for 4 sec	Standard

The following points provide an outline of the assumptions behind the fault rates listed in *Table E7*.

» **Major substation primary (transmission or zone substation):** 1 fault per 10 years.

» **Transmission substation secondary:** A fault rate of 5 faults per year conservatively relates to 100km of 66kV (or above) lines allowing for up to 5 faults/100km/yr.

The following table details the voltage/time points used in the generation of the allowable curves.

Table E7: Data points used in generation of curves

Curve		Voltage	Clearing time (sec)
Major substation primary backyard	MSPB	817	0.2
Transmission substation secondary backyard	TSSB	353	0.2
Transmission substation secondary MEN	TSSMEN	167	0.2

The following table provides the equations that may be used to generate the curves.

Table E8: Curve generation equations

Curve	Prospective touch voltage characteristic equation
MSPB	$(A+B \times t^2+C \times t^4+D \times t^6+E \times t^8)/(1+F \times t^2+G \times t^4+H \times t^6+I \times t^8)$
TSSB	$(A+B \times Ln(t)+C \times Ln(t)^2+D \times Ln(t)^3+E \times Ln(t)^4+F \times Ln(t)^5)/(1+G \times Ln(t)+H \times Ln(t)^2+I \times Ln(t)^3+J \times Ln(t)^4+K \times Ln(t)^5)$
TSSMEN	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4)/(1+F \times t+G \times t^2+H \times t^3+I \times t^4+J \times t^5)$

	MSPB	TSSB	TSSMEN
A	1241.258	75.68182	201.3427
B	-4848.43	-43.9751	-1199.97
C	28118.07	19.48004	2566.167
D	50914.76	-66.1741	-3298.33
E	-1488.67	40.51125	3434.546
F	11.65353	-4.42428	-6.04267
G	-95.9901	-0.04563	18.8067
H	496.1288	-0.48785	-47.4951
I	-13.7814	-0.35768	58.25748
J		0.209505	2.793045
K		0.045215	

Societal risk assessment

The societal risk associated with each of the assets has also to be assessed for each hazard scenario with the assumptions and conclusions shown in **Table E9**. Note that the exposure conditions are based upon average exposure frequency and duration estimates for the susceptible group of people, and the number of exposed people is based upon the number who could reasonably be expected to be able to make simultaneous contact with affected metalwork.

Table E9: Data points used in generation of curves

Curve		Av. contacts/person/year	Av contacts duration (secs)	Max. no. people for < 10e-6 risk
Major substation primary backyard	MSPB	75/Year	4	41
Transmission substation secondary backyard	TSSB	75/Year	4	41
Transmission substation secondary MEN	TSSMEN	75/Year	4	43

Assumption

Contacts are based on the expected behaviour of an average person. This has been approximated as 75 percent of the number of contacts for a worst case single individual.

As the number of exposed people is expected to be less than the societal 10^{-6} criteria (see **Table E9**), the governing case is that of the individual risk criteria.

Application notes

Whenever safety criteria are selected (either standard curves or using **Argon** [28] software) it is important that appropriate technical review be undertaken (for example, peer and/or manager review and signoff). For alternative curves generated within **Argon** it is also important that adequate sensitivity analysis be undertaken and assumptions and decisions documented in a generated report.

E.3   Zone substations

The following series of curves (see **Figure E4**) relate to acceptable prospective touch voltages associated with earthfault events on zone substations, and hazard scenarios beyond the fence. The primary fault cases are common with the transmission substations, while the secondary fault cases relate to system voltages of below 66kV. The hazard scenarios to be managed within the substation perimeter fence are handled separately in **Appendix E4**.
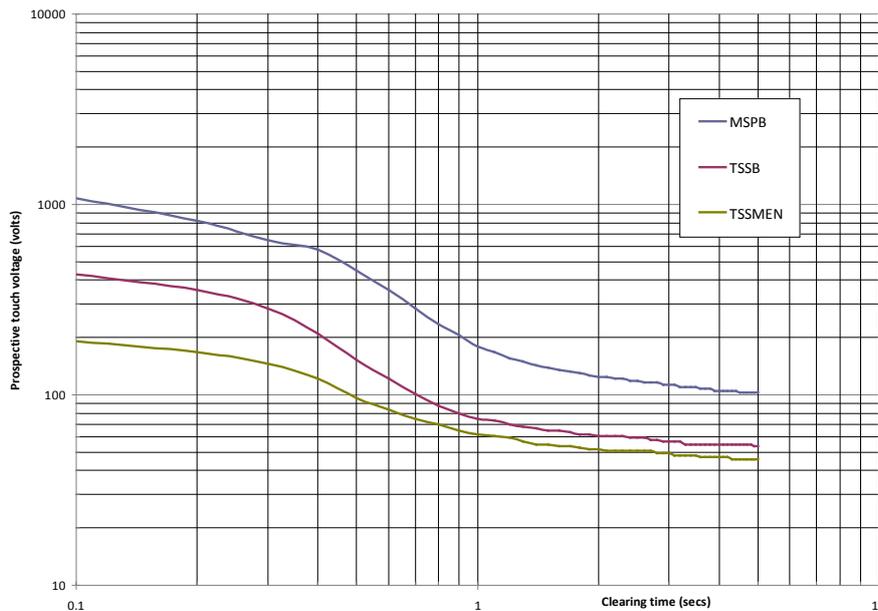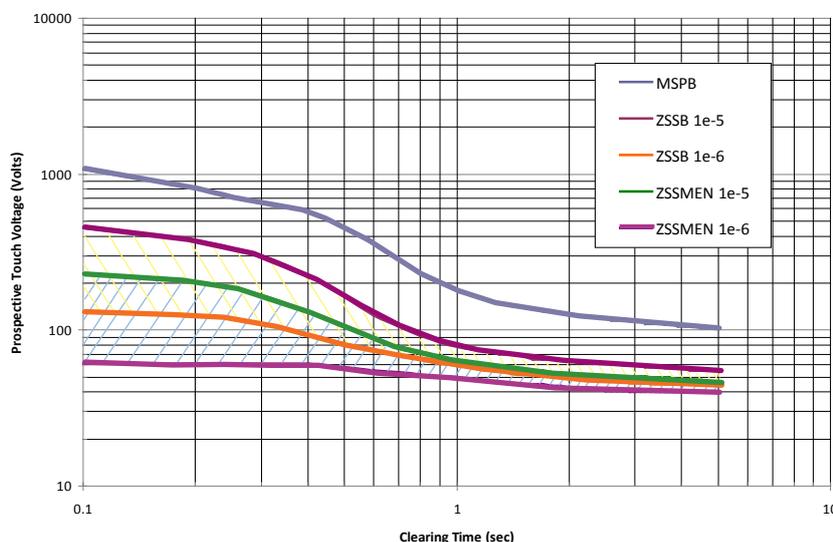

Figure E4: Zone substation prospective touch voltage criteria

The following two tables describe the basis of each prospective touch voltage curve shown above. Note that individual risk contact frequency and durations are based upon a 'typical maximally' exposed individual (i.e. 90 to 95 percent confidence limit).

Table E10: Curve generation data

Curve		Fault frequency/yr	Contact scenario	Footwear
Major substation primary backyard	MSPB	0.1	Backyard-416 contacts/ yr for 4 sec	Standard
Zone substation secondary backyard (P fatality = 1e-5)	ZSSB 1e-5	40	Backyard-416 contacts/ yr for 4 sec	Standard
Zone substation secondary backyard (P fatality = 1e-6)	ZSSB 1e-6	40	Backyard-416 contacts/ yr for 4 sec	Standard
Zone substation secondary MEN (P fatality = 1e-5)	ZSSMEN 1e-5	40	MEN-2000 contacts/yr for 4 sec	Standard
Zone substation secondary MEN (P fatality = 1e-6)	ZSSMEN 1e-6	40	MEN-2000 contacts/yr for 4 sec	Standard

The following points provide an outline of the assumptions behind the fault rates listed in **Table E10**.

» **Major substation primary (transmission or zone substation):** 1 fault per 10 years

» **Zone substation secondary:** A fault rate of 40 faults per year conservatively relates to 100km of <66kV lines allowing for up to 40 faults/100km/yr. This value is higher than that experienced at many urban cable networks, but lower than that experienced at some rural substations with long overhead lines. Refer to Application notes at the end of this section for more discussion.

The following table details the voltage/time points used in the generation of the allowable curves.

Table E11: Data Points used in generation of curves

Curve		Voltage	Clearing time (sec)
Major substation primary backyard	MSPB	817	0.2
Zone substation secondary backyard (P fatality = 1e-5)	ZSSB 1e-5	162	0.5
Zone substation secondary backyard (P fatality = 1e-6)	ZSSB 1e-6	82	0.5
Zone substation secondary MEN (P fatality = 1e-5)	ZSSMEN 1e-5	105	0.5
Zone substation secondary MEN (P fatality = 1e-6)	ZSSMEN 1e-6	58	0.5

The following table provides the equations that may be used to generate the curves.

Table E12: Curve generation equations

	Prospective touch voltage characteristic equation
MSPB	$(A+B \times t^2+C \times t^4+D \times t^6+E \times t^8)/(1+F \times t^2+G \times t^4+H \times t^6+I \times t^8)$
ZSSB 1e-5	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4)/(1+F \times t+G \times t^2+H \times t^3+I \times t^4+J \times t^5)$
ZSSB 1e-6	$(A+B \times Ln(t)+C \times Ln(t)^2+D \times Ln(t)^3+E \times Ln(t)^4)/$ $(1+F \times Ln(t)+G \times Ln(t)^2+H \times Ln(t)^3+I \times Ln(t)^4+J \times Ln(t)^5)$
ZSSMEN 1e-5	$(A+B \times t+C \times t^2+D \times t^3+E \times t^4+F \times t^5)/(1+G \times t+H \times t^2+I \times t^3+J \times t^4+K \times t^5)$
ZSSMEN 1e-6	$(A+B \times t^2+C \times t^4+D \times t^6+E \times t^8)/(1+F \times t^2+G \times t^4+H \times t^6+I \times t^8)$

	MSPB	ZSSB 1e-5	ZSSB 1e-6	ZSSMEN 1e-5	ZSSMEN 1e-6
A	1241.2581	414.47239	58.704212	241.82759	60.120211
B	-4848.4271	-1624.8778	-64.790797	-561.29412	275.67652
C	28118.067	4370.8166	9.3195529	854.39356	415.81948
D	50914.762	-7009.3324	-14.235582	-85.405692	-123.54387
E	-1488.6715	8665.1363	17.744609	-204.28229	12.860762
F	11.65353	-6.4730161	-0.75856407	55.953719	4.0397975
G	-95.990136	38.73057	-0.37320234	-2.0399516	10.805298
H	496.1288	-109.23281	-0.03023277	3.7776532	-3.0940403
I	-13.781359	132.21093	0.27792391	7.436951	0.32026358
J		4.9045266	0.02769612	-6.8814069	
K				1.4292578	

Societal risk assessment

The societal risk associated with each of the assets has also to be assessed for each hazard scenario with the assumptions and conclusions shown in **Table E8**. Note that the exposure conditions are based upon average exposure frequency and duration estimates for the susceptible group of people, and the number of exposed people is based upon the number who could reasonably be expected to be able to make simultaneous contact with affected metalwork.

Table E13: Data Points used in Generation of Curves

Curve		Average contacts/ person/yr	Average contacts duration (secs)	Maximum number people for risk
Major substation primary backyard	MSPB	312	4	43 (<10e-6)
Zone substation secondary backyard (P fatality = 1e-5)	ZSSB 1e-5	312	4	43 (<10e-5)
Zone substation secondary backyard (P fatality = 1e-6)	ZSSB 1e-6	312	4	45 (<10e-6)
Zone substation secondary MEN (P fatality = 1e-5)	ZSSMEN 1e-5	2000	4	53(<10e-5)
Zone substation secondary MEN (P fatality = 1e-6)	ZSSMEN 1e-6	2000	4	56 (<10e-6)

As the number of exposed people is expected to be less than the societal 10^{-6} criteria (see **Table E13**), the governing case is that of the individual risk criteria.

Application notes

» The two curves delineating the risk range of 10^{-6} to 10^{-5} are used in this instance on account of the relatively low allowable voltages resulting from a combination of higher fault and contact frequencies found in the vicinity of a zone substation.

» It is expected that the risk profile for many substations will lie in this part of the ALARA region and require the designer to undertake either:

  » some form of risk cost benefit analysis to justify the level of mitigation considered 'reasonable' for a given substation, or

  » deriving their own set of curves based upon a different fault frequency, or

  » evaluate the fault current levels more closely to take into consideration a more 'reasonable' expected EPR value. It would be seen to be reasonable to take the current corresponding to the 90 percent confidence limit. Studies have shown that it is not unusual to reduce the 'bus plus 1ohm' fault impedance by 60 to 70 percent when more realistic line and fault impedances are incorporated.

» It is expected that for some maintenance or construction activities a special assessment of the risk exposure may be warranted (for example, replacing fences, extending an operating yard). It may be appropriate that training and work methods put in place to protect workers in these instances (see **Section 6.2**).

» Whenever safety criteria are selected (either standard curves or using **Argon** [28] software) it is important that appropriate technical review be undertaken (for example, peer and/or manager review and signoff). For alternative curves generated within **Argon** it is also important that adequate sensitivity analysis be undertaken and assumptions and decisions documented in a generated report.

E.4   Inside major substations

The following series of curves (see **Figure E5**) relate to acceptable prospective touch voltages associated with earthfault events on major transmission and zone substations, for hazard scenarios within the fence. The contact scenarios are associated with utility staff (for example, operators, technicians) involved in carrying out their normal duties, and therefore it is considered reasonable that the risk associated with their aggregated exposure across all substations be kept within acceptable limits.

The primary fault cases have been evaluated and considered to contribute very little to the risk profile, therefore the secondary fault cases are considered as the defining cases.
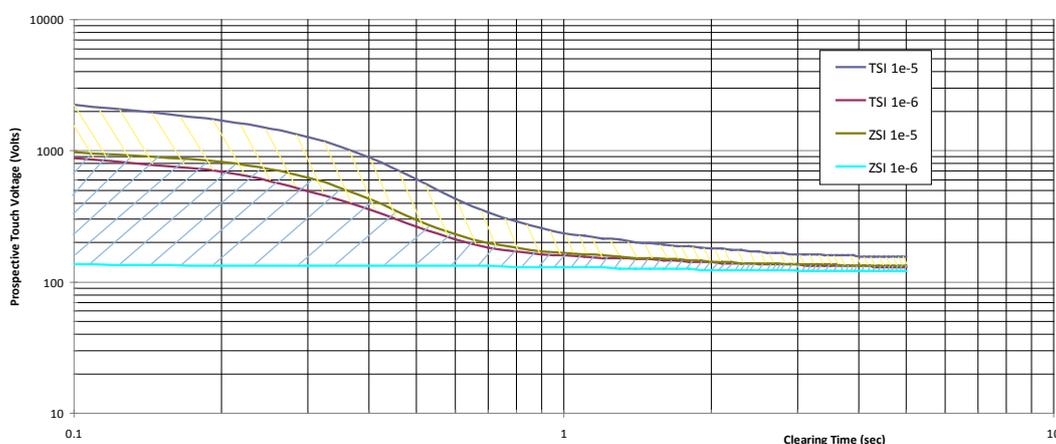
Figure E5: Allowable prospective touch voltages within substation perimeter fence

The following two tables describe the basis of each prospective touch voltage curve shown above.

» **Contact scenarios**: 1000 contacts with metalwork per year, with no equipotential earth mat or gloves. This is only a percentage of the full number of contacts. It is the number of contacts that occur without mitigation measures such as earthmats. However, it was decided that the risk levels were such that:

» equipotential operating mats be installed, and

» gates have asphalt under foot, and/or open inwards.

» **Underfoot series impedance**: 50ohmm topsoil with 100mm of 3000ohmm crushed rock.

» **Footwear**: Electrical footwear (see *Appendix B.1.2.2*).

» **Individual risk contact frequency and durations**: Based upon a 'typical maximally' exposed individual (i.e. 90 to 95 percent confidence limit).

Table E14: Curve generation data

Curve		Fault frequency/yr
Transmission substation inside (P fatality = 1e-5)	TSI 1e-5	5
Transmission substation inside (P fatality = 1e-6)	TSI 1e-6	5
Zone substation iInside (P fatality = 1e-5)	ZSI 1e-5	40
Zone substation inside (P fatality = 1e-6)	ZSI 1e-6	40

The following points provide an outline of the assumptions behind the fault rates listed in **Table E14**.

» **Transmission substation secondary**: A fault rate of 5 faults per year conservatively relates to 100km of 66kV (or above) lines allowing for up to 5 faults/100km/yr.

» **Zone substation secondary:** A fault rate of 40 faults per year conservatively relates to 100km of <66kV lines allowing for up to 40 faults/100km/yr. This value is higher than that experienced at many urban cable networks, but lower than that experienced at some rural substations with long overhead lines. Refer to Application notes at the end of this section for more discussion.

The following table details the voltage/time points used in the generation of the allowable prospective touch voltage curves.

Table E15: Data points used in generation of curves

Curve		Voltage	Clearing Time (sec)
Transmission substation inside (P fatality = 1e-5)	TSI 1e-5	1710	0.2
Transmission substation inside (P fatality = 1e-6)	TSI 1e-6	650	0.2
Zone substation inside (P fatality = 1e-5)	ZSI 1e-5	298	0.5
Zone substation inside (P fatality = 1e-6)	ZSI 1e-6	133	0.5

The following table provides the equations that may be used to generate the curves.

Table E16: Curve generation equations

Prospective touch voltage characteristic equation	
TSI 1e-5	$(A+B \times t^2 + C \times t^4 + D \times t^6 + E \times t^8 + F \times t^{10})/(1+G \times t^2 + H \times t^4 + I \times t^6 + J \times t^8 + K \times t^{10})$
TSI 1e-6	$(A+B \times t + C \times t^2 + D \times t^3 + E \times t^4)/(1+F \times t + G \times t^2 + H \times t^3 + I \times t^4)$
ZSI 1e-5	$(A+B \times t + C \times t^2 + D \times t^3 + E \times t^4 + F \times t^5)/(1+G \times t + H \times t^2 + I \times t^3 + J \times t^4 + K \times t^5)$
ZSI 1e-6	$A+B \times t + C/t + D \times t^2 + E/t^2 + F \times t^3$

	TSI 1e-5	TSI 1e-6	ZSI 1e-5	ZSI 1e-6
A	2569.545	637.94153	1110.8979	141.67741
B	1197.681	-572.49703	-3007.2425	-14.724067
C	17499.51	2714.9907	3480.5229	-1.9700353
D	79372.2	-10805.961	-1447.8536	3.6573951
E	3154.154	13995.845	2727.496	0.15442975
F	92.91638	-7.1746418	-478.7441	-0.32081732
G	15.05919	51.04948	-1.7566906	
H	-50.4536	-121.8715	3.7172855	
I	440.98	114.44089	-5.7402292	
J	26.95798		20.567474	
K	0.450135		-3.6778086	

Societal risk assessment

The societal risk associated with each of the assets has also to be assessed for each hazard scenario with the assumptions and conclusions shown in **Table E17**. Note that the exposure conditions are based upon average exposure frequency and duration estimates for the susceptible group of people, and the number of exposed people is based upon the number who could reasonably be expected to be able to make simultaneous contact with affected metalwork.

Table E17: Data points used in generation of curves

Curve		Av. contacts/ person/year	Av contact duration (secs)	Max. no. people for risk
Transmission substation inside (P fatality = 1e-5)	TSI 1e-5	750	4	5 (<10e-5)
Transmission substation inside (P fatality = 1e-6)	TSI 1e-6	750	4	64 (<10e-6)
Zone substation inside (P fatality = 1e-5)	ZSI 1e-5	750	4	3 (<10e-5)
Zone substation inside (P fatality = 1e-6)	ZSI 1e-6	750	4	45(<10e-6)

Assumption

Contacts are based on the expected behaviour of an average person. This has been approximated as 75 percent of the number of contacts for a worst case single individual.

As the number of exposed people is expected to be less than the societal 10^{-6} criteria (see **Table E9**), the governing case is that of the individual risk criteria.

As the number of exposed people is expected to be less than the societal 10^{-6} criteria (see **Table E17**), the governing case is that of the individual risk criteria.

Application notes

Whenever safety criteria are selected (either standard curves or using **Argon** [28] software) it is important that appropriate technical review be undertaken (for example, peer and/or manager review and signoff). For alternative curves generated within **Argon** it is also important that adequate sensitivity analysis be undertaken and assumptions and decisions documented in a generated report.

Appendix F: ALARA design process

F.1   Introduction

If the risk analysis deems the risk, associated with the fault/contact coincidence and applied voltage, to lie within the ALARA region an assessment of mitigation options is required. In some cases, even if the absolute level of risk associated with a given exposure scenario is very low, it may still be prudent to undertake remedial action. Conversely the cost and/or practicability may make any mitigation measure difficult to justify. The following questions provide a means for examining the issues from a range of perspectives:

» Is the level of risk above an acceptable value?

» Has the variable nature of the input parameters been assessed? For example, the actual fault current may be lower than the 'planning value' on account of additional fault resistance.

» Does a risk cost-benefit analysis (RCBA) yield a positive result considering 'all-of-life' costs? A positive result is achieved if many people are affected or it is a high exposure location, and the hazard may be mitigated with reasonable cost. The use of cost benefit analysis may provide a mechanism for gauging the relative value of the risk reduction options, however, it should not be used as the only arbiter in decision making [11-14].

» Does the remedial action lower the fear level of the public or raise their confidence in the utility (for example, use of brick boundary fences)?

» Is there another reason to justify the expense? Examples might include:

» Need to maintain corporate image,

» More than one person may die at a time,

» Contravention of a legally binding statute,

» Operational imperatives at risk (for example, continuity of supply).

It may be necessary to break down individual hazard scenarios into stages of mitigation in order to gain an adequate understanding of the value of each step in the process. The RCBA process is summarised in the following section. This process enables better targeting of expenditure to zones of need. **Figure F1** summarizes the ALARA region design process.

F.2   Risk cost benefit analysis

Risk cost benefit analysis can be applied to assess equipment damage, livestock loss, property damage and the cost of public deaths. In some cases it may also be prudent to include indirect as well as direct costs in a risk cost benefit analysis. These indirect costs may include legal costs and less tangible items such as cost to reputation and corporate public image.

Where risk has been determined to be in the ALARA region then it will sometimes be appropriate to carry out a risk cost benefit analysis (RCBA) to establish the relative cost of risk treatment or the value of the risk reduction options. In the 'Low risk' case a RCBA will also help establish whether any possible risk treatment option is justifiable, whilst in some 'high risk' cases, 'gross disproportionality' in the cost of treatment compared to the risk may in exceptional cases need to be investigated. For business risk decisions a benefit/cost ratio of two or more is considered favourable. In the earthing risk context, the benefit is in avoiding an electrocution (for example, value of life) while the cost is the cost of a successful mitigation strategy. In particular, the benefit/risk ratio is the ratio of the benefit (value of life) NPV/cost of mitigation NPV. In the case of human safety, to carry out such an analysis, it is necessary to use a 'value of life' figure—normally referred to as the value of statistical life (VoSL).

Various studies of VoSL carried out around the world [20-23] show that values varying between approximately $2 million and $20 million have been used in various countries including Australia. Abelson [20] stated that given research findings as a whole and values employed in Europe, $3 million to $4 million would appear to be a plausible VoSL for a healthy prime age individual in Australia at present. Miller [23] proposed an alternative Australian perspective, depending upon nature of the hazard scenario. The selection of a VoSL value for carrying out RCBAs when evaluating

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                    ┌─────────────────────────────────────┐
                    │              Given                  │
                    │  Negligible Limit < P_fatality <    │
                    │        Intolerable Limit            │
                    └─────────────────────────────────────┘
                                   │
                    ┌─────────────────────────────────────┐
           ┌───────▶│ Determine the next best mitigation  │
           │        │ based on combination of             │
           │        │   •   lower EPR, V_t, t_c           │
           │        │   •   lower coincidence             │
           │        │   •   increase series impedance     │
           │        └─────────────────────────────────────┘
           │                       │
           │        ┌─────────────────────────────────────┐
           │        │         Calculate P_death           │
           │        └─────────────────────────────────────┘
           │                       │
           │              ◇ Should the mitigation be
           │                undertaken independent of cost?
         Y │                (e.g. based on a legal risk,
           │                responsible behaviour,
           │                publicity test, strategic
           │                advantage)  ─────────────────────┐ Y
           │                       │ N                       │
           │        ┌─────────────────────────────────────┐  │
           │        │ Undertake a risk cost benefit       │  │
           │        │ analysis (RCBA)                     │  │
           │        │ (possibly VoSL or VOSL)             │  │
           │        └─────────────────────────────────────┘  │
           │                       │                          │
           │              ◇ Should the mitigation be          │
           │                undertaken based on RCBA? ────────┤ Y
           │                       │ N                        │
           │              ◇ Are there more options            │
           └──────────────  to consider?                      │
                                   │ N                        │
                    ┌──────────────────────┐    ┌─────────────────────────┐
                    │ No further           │    │ Undertake proposed      │
                    │ mitigation required  │    │ mitigation              │
                    └──────────────────────┘    └─────────────────────────┘
```
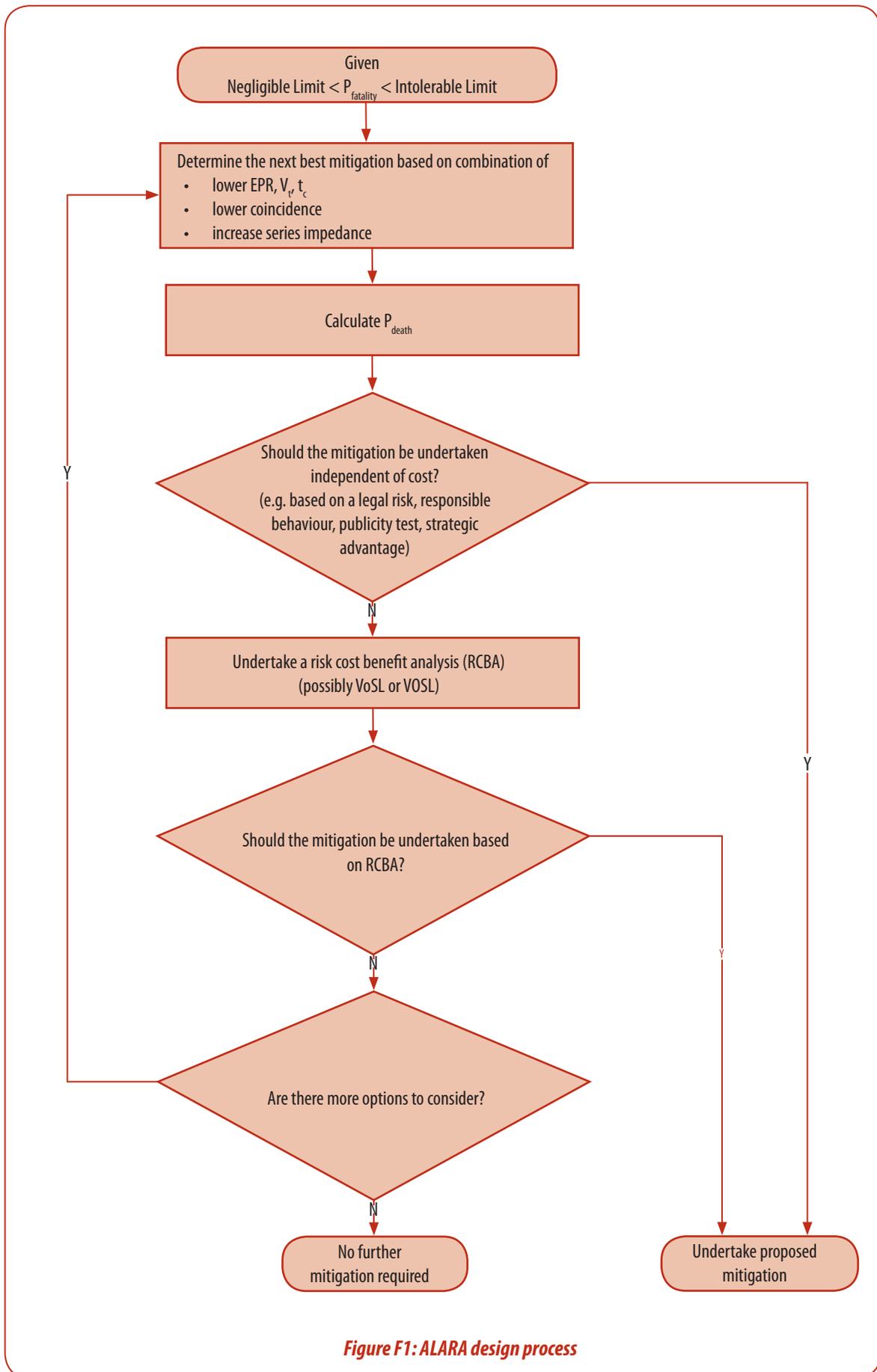
Figure F1: ALARA design process

EPR risks needs to account for the following:

» public's expectation that power systems are 'safe' provided they are not tampered with
» possibility that those at risk may be 'vulnerable' (i.e. young, old, infirm)
» 'involuntary' nature of the risk to the public
» utility's image and reputation.

Consideration should also be given to what is the most appropriate way to apply the VoSL to the RCBA. Following are two such approaches the first analysis is based on the cost of a fatality, while the second considers the per person cost of lowering the risk of fatality.

For the purpose of the examples within this Guide, a VoSL value of $10 million has been used. It would be considered prudent for an individual utility to develop their own value of saved life (for example, based on relative risk profile and professional advice) and discount cash rate.

F.3   Example 1—Cost of fatality (individual exposure)

For example, if the equivalent probability P_e has been calculated as 10^{-5}, then the risk level is in the ALARA or Intermediate region. This means that either the risk be reduced to the 'tolerable' level, or that a risk cost benefit analysis should be done to determine if it is cost effective to implement risk treatment measures.

This equivalent probability means that value determined has been deemed equivalent to one individual fatality per 100 000 years (= P_e^{-1}) and since the VoSL is $10 000 000, over a period of 100 000 years the liability per year is:

$$L = \frac{VoSL}{P_e^{-1}} = VoSL \times P_e$$

$$= \$10\,000\,000 \times 1 \times 10^{-5} = \$100 \text{ per year}$$

F1

Where

L   =   Asset owners liability per year (dollars).

The present value of risk treatment can be calculated using the remaining lifespan of the asset, the liability per year and the expected rate of interest on an alternative investment (discount rate). The present value (**PV**) figure calculated is considered a positive return as the investment into the elimination of hazards will result in a reduction of the liability equal to the **PV**.

$$PV = L \sum_{i=1}^{Y} \frac{1}{(1+D)^i} = \frac{L}{D} \left[1 - \left(\frac{1}{1+D} \right)^Y \right]$$

F2

Where

PV   =   Present value (dollars)
L   =   Asset owner's liability per year (dollars)
D   =   Discount rate (fractional rate of interest)
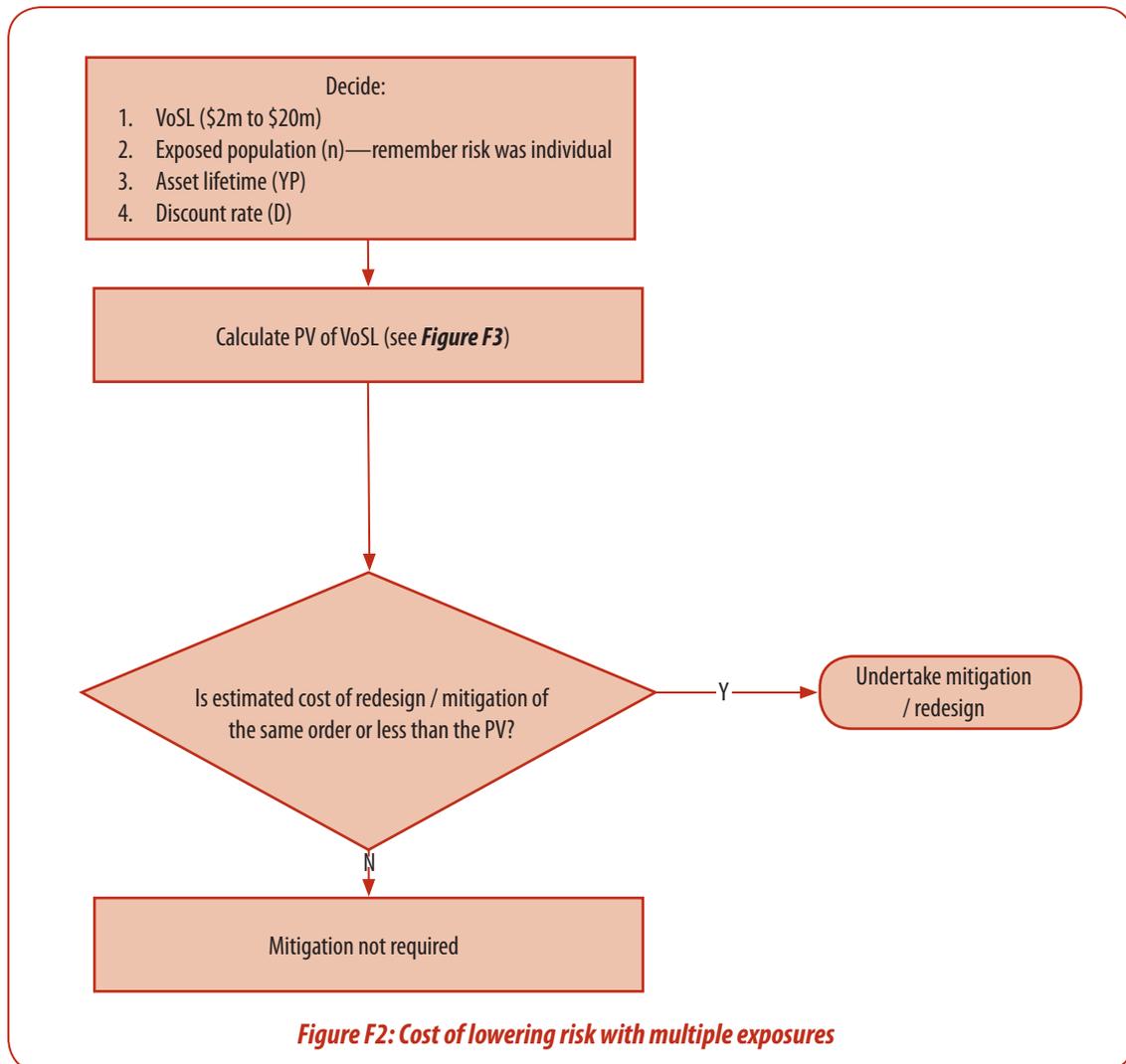Y   =   Number of years which the asset will remain potentially hazardous (years).

If a discount rate of 0.04 (four percent) is used then the present value of the reduction in liability can be calculated as approximately $2148 for a remaining asset lifetime of 50 years. A discount rate of four percent is used in this context as a conservative representation of the interest on the opportunity cost investment. The choice of discount rate has a significant affect on the PV calculated and should be chosen carefully [9]. The discount rate varies over time and depends on the individual utility's cost of capital and can vary from three to 10 percent.

The PV is used to provide a guide as to the appropriate level of expenditure that should be used when determining whether risk treatment is a cost effective option. The PV is compared to risk treatment costs to ensure that costs are not grossly disproportionate to the reduction in liability.

In this case, comparing this figure to the costs of risk treatment (say $5000), it appears that the implementation of treatment is not cost effective. However, as this P_e equates to an 'intermediate risk', the cost is clearly not 'grossly disproportionate' and so risk treatment should be fitted.

F.4 Example 2—Cost of fatality (multiple exposures)

An alternative approach is to calculate the cost of mitigation for a given asset based on the number of exposed people (n) (over one year period) (see **Figure F2**).

Decide:
1. VoSL ($2m to $20m)
2. Exposed population (n)—remember risk was individual
3. Asset lifetime (YP)
4. Discount rate (D)

Calculate PV of VoSL (see **Figure F3**)

Is estimated cost of redesign / mitigation of the same order or less than the PV?

Y → Undertake mitigation / redesign

N

Mitigation not required

Figure F2: Cost of lowering risk with multiple exposures

$$PV = \frac{P_{fatality}\ n\ VoSL}{D} \left[1 - \left(\frac{1}{1+D} \right)^{Y} \right]$$

F3

For $P_e = nP_{fatality}$ where 'n' exposed people behave independantly of each other.

In certain situations the implementation of a risk treatment option may not entirely eliminate the probability of fatality, but merely reduce the probability to a lower value. A risk cost benefit analysis may be applied using the amount by which the probability has been reduced to determine whether the risk treatment option is worthwhile.

It should also be borne in mind that, even for 'low risk' situations where RCBA indicates risk treatment is not required, a continuous monitoring and review process is still to be carried out to ensure that the overall risk level remains within the 'low risk' region. In the case of high cost projects it may be argued that a relatively low cost risk treatment is always to be incorporated (based upon the precautionary approach).

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