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Substation earthing system design optimisation through the application of quantified risk analysis

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Substation earthing system design optimisation through the application of quantified risk analysis

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C. PEZZATO	IT

M. LEHTONEN	FI
B. ZHANG	CN
K. ODLE	US

Associated Expert

D. WOODHOUSE	AU

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Executive summary

The goal of earthing system design optimisation is to ensure adequate robustness in the design while finding a balance between cost, practicality and management of risk. The need to undertake analysis of the variability or uncertainty of parameters is a reality of the design challenge that has been clearly identified within this brochure. The use of quantified risk analysis provides an objective metric by which an engineer can demonstrate the significance of the components that make up the simplified approach or risk mitigation strategy. The engineer is then empowered to address the factors that most significantly contribute to the risk in order to optimise the design and is also provided with a non-specialist medium for communicating the decision basis with other stakeholders and clearly demonstrate how the design meets Work Health and Safety (WH&S) regulatory obligations.

Performance criteria appropriate to an installation and network may be used to generate a risk-cost-benefit analysis for individual design options. The competing design configurations may be appraised using a mixture of qualitative and quantitative measures. The risk quantification process applied in a simplified staged form is useful as an indicator of the risk levels, and also for determining the impact of uncertainty in a variable. In one instance, a 7% rise in substation Earth Potential Rise (EPR) related to a 15% rise in fibrillation probability. Risk quantification used to generate a risk-cost-benefit analysis provides a clear means for communicating with management, and it also provides an objective measure to guide designers regarding where to focus effort (i.e. in obtaining more accurate input data, or remedial measures) and how to compare design options.

Legal and regulatory perspectives are shown in Chapter 2 to underpin the need for Quantitative Risk Assessment (QRA) in demonstrating due diligence in explicitly managing risk to meet societally tolerable limits in accordance with WH&S regulations. Although there are differences in the detail within the legal frameworks in various countries the need to manage risk requires firstly that the risk to a person be quantified and then the following comparisons be made:

- After common and expected controls are implemented, is the residual risk above a level considered unacceptable or intolerable (with due consideration to societal value)?
- Are there further controls that can be applied and if there are what is the comparison between the cost of those controls and the further reduction in risk?
- Is the residual risk level, after implementing common and expected controls, at or below a level considered acceptable, tolerable or negligible?

The general considerations and examples of risk management and tolerable criteria in different countries are introduced in Chapter 3, with particular focus on the processes recognised within ISO/IEC risk management standards. While the numerical level of risk assigned to the tolerable or negligible thresholds may vary from country to country the general approach to risk assessment is common to many countries. The concept of Tolerability of Risk (TOR) and its relation to reducing risk imposed upon people to 'as low as reasonably practicable' (ALARP) is identified as a commonly applied and applicable risk management approach.

It is unfortunate that many people believe that traditional safety criteria are inherently safe. However, someone exposed to what many would consider to be a safe voltage may have a likelihood of fatality higher than 80%, and usually not lower than 10%. Given that a fatality due to indirect contact during earth fault events is a very low likelihood event, and that many variables contribute to creating a hazardous condition, the process needed to determine a tolerable voltage characteristic is not simple. Nevertheless, through the use of risk quantification it is possible to determine the range of hazard scenarios where the application of a given voltage characteristic is justified. Chapter 4 discusses the probabilistic nature of the shock event, introduces the main components of the QRA process when applied to earthing system design, as well as the processes incorporated in a number of standards, and introduces QRA processes and specific risk targets that have been incorporated within earthing design procedures in a number of contemporary national standards.

Chapter 5 summarises the fundamental yet complex and often competing design requirements facing a substation earthing system design engineer. The complexities that often exist have fostered the adoption of the quantified risk approach. Decisions which beneficially alter the hazards at one site but adversely impact other installations could not be effectively dealt with previously.

Whilst a range of earthing design processes and methods are used around the world, they all include a systematic approach to the identification and assessment of the design inputs. Chapter 6 identifies the most common of these inputs and explores in turn what variation may be expected to occur, how it might be measured or determined, and what the possible affect could be on the outputs of the design firstly in terms of magnitude of the shock hazard and secondly the risk of fatality. Parameters that have been investigated in this chapter include:

- Earth fault current magnitude and duration
- Return current distribution
- Soil electrical resistivity
- Earth fault voltage distribution
- Body current and voltage withstand criteria
- Fault frequency and person contact frequency and durations

A design process requires more than analytical accuracy to provide a design that is consistently effective in managing real risks to staff and the public. If earthing system design is to be optimised effectively it must recognise and be integrated within the overall life cycle of the environment and network in which the substation is to operate, as not all parameters are within the control of the designer. For instance, changes in the use of land adjacent to a substation can occur in the future such as encroaching residential housing with associated changes in the exposure of members of the public. Chapter 7 examines the key commissioning requirements as well as the possible threats that must be identified and mitigated in the design phase or through ongoing supervision and maintenance programmes.

Chapter 8 introduces the key elements of a generic design procedure that incorporates the use of QRA in a staged manner within the main elements of existing traditional design procedures. The shock risk quantification process may be integrated within existing design frameworks and provide designers with a defensible way to either support maintaining the present risk profile or develop a business case to justify a site-specific risk mitigation strategy. An example of how QRA may be integrated within a traditional earthing design procedure such as EN50522 is also provided.

To conclude the body of the document a number of detailed case studies reflecting substations within typical representative transmission and distribution networks are included to illustrate the use of QRA in practical cases and to show how variations in input parameters affect the residual risk imposed upon exposed people. The case studies further illustrate how the QRA process may be used when designing an individual substation or in the parametric analysis required to develop simplified design standards.

The design process that incorporates QRA empowers the design engineer to objectively address the design parameters that most significantly affect the electric shock risk to the public and utility staff, and to develop optimised risk mitigation strategies. Furthermore, such an approach enables a designer to communicate the justification behind the design and investment decisions to key stakeholders such as regulatory bodies, asset owners, business case development teams, project managers, utility staff and the public.

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Introduction

Safety for both utility staff and the public in the event of an earth fault is a responsibility and major concern for electrical utilities, government agencies, standardising bodies and asset owners. The goal of earthing system design optimisation is to ensure adequate robustness in performing the functional and safety requirements of the design at the same time as finding a balance between cost, practicality and management of risk.

Traditional design approaches were developed in times when computing capability was quite limited and often unavailable to most practitioners. This limitation forced standards setting groups to make some assumptions regarding most variables that influence earthing design. The working group has considered the intent and common applications of existing standards and concluded that for the most part their implementation is producing good outcomes. Nevertheless, the touch voltages associated with traditional safety criteria can yield fibrillation probability values more than societally tolerable fatality targets (e.g. 1 in 1 million). Therefore, traditional safety criteria can only be considered tolerably safe provided there is a low likelihood of coincidence of an earth fault occurring at the same time as a person being in an exposed position. There are clear examples where existing standards or electric shock safety criteria can be shown to lead to unnecessary expenditure, and in some cases unreasonable outcomes in terms of risk to staff or the public. The responsibility that earthing system designers, owners and operators all carry for risk to staff and the public arising from the operation of the earthing system is discussed from a legal and regulatory perspective and developed into a design process within a contemporary risk management framework.

Statistical or probabilistic studies are not new to the electric power industry. They are used widely in modelling system load flows, transient stability, lightning protection design as well as short circuit studies. The use of such studies is closely linked to the development of strategies for demonstrating due diligence in the management of risk. Given that many of the variables involved in earthing system design are probabilistic in nature, it is logical that similar statistical approaches should be applied. The variables that are examined in this document include: the power system characteristics determining the earth fault current, the earthing system configuration, the soil in which the earthing system elements are located, the exposure of people to hazardous voltage, and the physiological response of the human body to the resultant flow of current.

A Quantified Risk Analysis (QRA) and assessment process for indirect electric shock risk is described in this brochure and recommendations are made regarding the integration of QRA within the earthing design processes of existing standards. To demonstrate the application of electric shock risk quantification to realistic design problems a series of case studies have been developed examining both transmission and distribution networks. The significance of each of the design inputs is discussed within the brochure and further detailed by way of example in the case studies.

1. Notation and Abbreviations

1.1 Purpose

This section should be read with consideration of and reference to of IEC 60050 - International Electrotechnical Vocabulary, a handy version of which can be accessed at http://www.electropedia.org/. Electropedia (also known as the 'IEV Online') is the world's most comprehensive online electrical and electronic terminology database containing more than 20 000 terms and definitions.

Only terms not covered by Electropedia, or requiring further explanation, are covered in detail herein.

1.2 Electropedia Earthing Terms

The following IEC terms are important in the context of this document:

Section 195-01: Fundamental concepts

- 195-01-02 electric contact
- 195-01-04 electric shock
- 195-01-10 equipotential bonding
- 195-01-17 impedance to earth
- 195-01-18 resistance to earth
- 195-01-19 electric resistivity of soil

Section 195-02: Electrical installations and equipment

- 195-02-01 earth electrode
- 195-02-03 earthing conductor
- 195-02-05 neutral point
- 195-02-06 neutral conductor
- 195-02-26 overhead earth wire

Section 195-03: Electric shock and threshold currents

- 195-03-05 ventricular fibrillation
- 195-03-06 electrocution
- 195-03-09 let-go threshold (current)
- 195-03-10 threshold of ventricular fibrillation

Section 195-04: Operation

- 195-04-05 neutral point treatment
- 195-04-06 solidly earthed neutral system
- 195-04-07 isolated neutral system
- 195-04-08 impedance earthed neutral system
- 195-04-09 resonant earthed neutral system
- 195-04-12 line-to-earth short-circuit
- 195-04-14 earth fault
- 195-04-16 line-to-line short-circuit

Section 195-05: Voltages and currents

- 195-05-04 neutral-point displacement voltage
- 195-05-09 prospective touch voltage
- 195-05-11 (effective) touch voltage
- 195-05-12 step voltage

Section 195-06: Protective measures for electrical safety

- 195-06-03 direct contact
- 195-06-04 indirect contact

1.3 Additional Terms

Coupling factor – the amount of current returning in the shield wire or cable screen as a percentage of the fault current flowing within the phase conductor

Distribution – a reticulation that supplies the final transformers that supply LV customers

Earth Potential Rise – The maximum voltage attained with respect to remote earth during the flow of current from the earthing system through the soil surrounding it.

Split factor – the ratio of current not going into the grid as a percentage of the entire earth fault current

Sub Transmission – typically a network that fits between a transmission system and the distribution system

Transmission – typically the main reticulation conveying power between generation step up points and either sub transmission or distribution systems

1.4 Additional Notations and Abbreviations

ALARP – As Low As Reasonably Practicable

ALARA – As Low As Reasonably Achievable

DS – Distribution Substation

DTS – Distribution Transformer Substation

EHV – Extra High Voltage

HSE – Health and Safety Executive

HV – High Voltage

LV – Low Voltage

MV – Medium Voltage

NPV – Net Present Value

PPE – Personal Protective Equipment

QRA – Quantified Risk Analysis

RCB – Risk Cost Benefit

RMU – Ring Main Unit

SFAIRP – So Far As Is Reasonably Practicable

TOR – Tolerability of Risk

UHV – Ultra High Voltage

VF – Ventricular Fibrillation

WH&S – Work Health and Safety

2. Legal and Regulatory Perspectives

2.1 Context

Earthing system designers, owners and operators all carry responsibility for risk arising from the operation of the earthing system. Earthing systems in most forms serve multiple roles. Commonly they are required to manage staff and public safety, protect equipment relying on the earth circuit, and support the ongoing operation of the system by avoiding mal-operations including spurious trips [1]. It is difficult to guarantee meeting all of these requirements under all system fault conditions and reasonably foreseeable system and configuration changes and failures. Although an event may be extremely unlikely it can nevertheless occur, and therefore is foreseeable, with clear legal implications. Such failures can lead to significant economic consequences through damage to equipment or disrupted supply. However perhaps more importantly, some failures can lead to more than just economic consequences; they can lead to significant hazards to people. Electric shock by way of touch or step voltage can lead to ventricular fibrillation and death.

The hierarchy of controls (an example is shown in Figure 2.1) is a proven approach to the selection and prioritisation of controls for the treatment of risk [70].

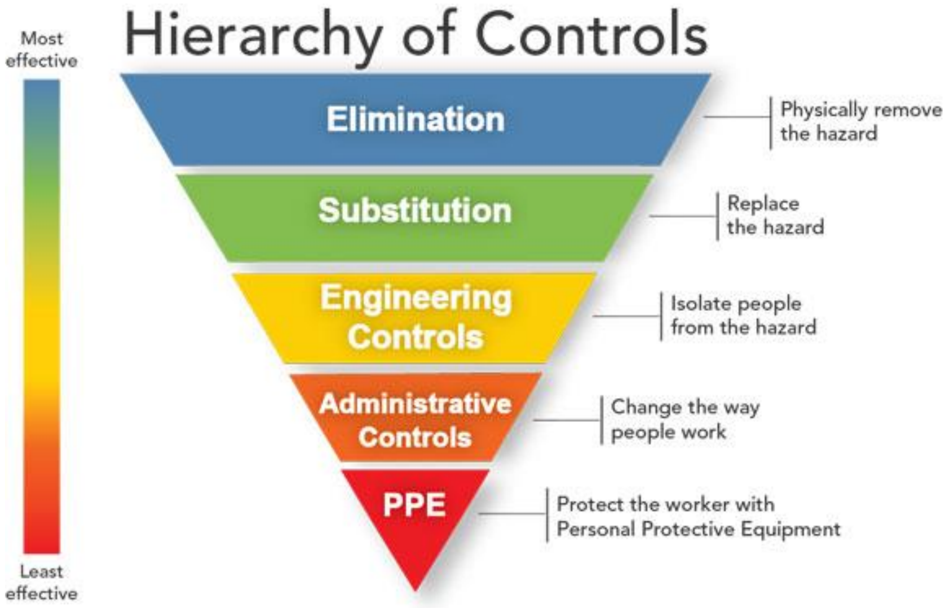


Figure 2.1: Hierarchy of Controls

In this context, the safety challenge that earthing systems must meet is more clear:

- **Elimination** - The societal value of electricity is enormous and not supplying electricity is rarely an option. Further the reduction of earthing related hazards to negligible levels is rarely possible.
- **Substitution** - There are no real substitutes for most uses of electricity.
- **Engineering Controls** - Electricity is delivered directly to where people live, making complete isolation of people from the hazard difficult.
- **Administrative Controls & PPE** - Training and PPE can be used effectively with workers but are less reliably implemented for the public.

The result of this challenge is that Engineering Controls are heavily relied on to manage risk by lowering hazards, most commonly recognised by lowering EPR and/or touch and step voltages but also by reducing the likelihood. Likelihood is commonly reduced by increasing reliability of the system and minimising fault clearing times and more recently by reducing the likelihood or duration of a person being in a hazardous contact situation.

2.2 Traditional Methods

Traditional approaches[1] to managing earthing related risk to safety relied on a combination of recognised controls or prescribed measures and the reduction of created touch and step voltages to below particular nominated levels considered or deemed safe. It is now clearly understood that these traditional criteria do not ensure survival, should someone be in the touch voltage situation coincident with the earth fault occurring and creating the touch voltage. Therefore, in most cases traditional criteria relied on such events being unlikely to produce acceptable outcomes [6][27][28].

In some countries complying with all applicable laws, codes and standards may be enough to provide the design, owner and operator legal protection, including in such cases as where a touch voltage fatality has occurred. In other countries, however, compliance with standards or common practice does not provide a legal defence and, consequentially, a legal defence must be made on some other basis. A common basis to such a defence is that the party responsible did all 'reasonable measures'. All 'reasonable measures' is not a straight forward metric, but it commonly reduces to what society, the courts and subject matter experts think ought to have been done to provide further protection. The challenge is to know at the time of producing a design what such people will think after the event.

2.3 Risk Management Methods

A common and herein recommended approach to determining the reasonableness of risk imposed on others is to firstly determine the risk level and make one or more of the following comparisons [1][4]:

a) After common and expected controls are implemented, is the residual risk above a level considered unacceptable or intolerable (with due consideration to societal value)?
b) Are there further controls that can be applied and if there are what is the comparison between the cost of those controls and the further reduction in risk?
c) Is the residual risk level, after implementing common and expected controls, at or below a level considered acceptable, tolerable or negligible?

Chapters 3 and 4 present and discuss risk assessment methodologies in general and their application to earthing design respectively. Such tools and techniques are considered valuable in the responsible allocation of finite resources to provide safety, protect equipment and support operational security. It is incumbent on each designer, asset owner or asset operator to understand their respective obligations or permissions under law and apply engineering practice, including the methods and recommendations of this document, in a way that meets the applicable laws, codes and standards for their country.

2.4 Worldwide Legal Framework Differences

It may be wondered why this Joint Working Group (JWG) cannot be more prescriptive on something as important as earthing system safety criteria? The answer lies in the fact that there are significant legal differences between countries. These differences affect what is required to provide legal protection for responsible parties.

Whilst significant differences can occur in the detail of each legal context (and each person should seek to understand their specific legal position, responsibilities and risks in their context, including their country), the major differences can be broadly categorised based on two to three legal perspectives as shown in Figure 2.2. Each specific country may have influences from more than one category.

Whilst not a rigorous legal analysis the following simple distinction between the origins of common and civil law is considered helpful. If designing for a country with origins in 'civil law' you will need a law that permits you to do what you may think you should do, and provided you then comply with that law (and a standard it makes law), you reportedly will be fully protected. If, however you are designing for a country with 'Common law' origins or tendencies you are free do what you wish as long as you don't break any laws, which will likely require more robust legal protection than simply complying with standards.

What this means for common law origin countries in particular, is that compliance with a standard or law does not in and of itself provide legal protection against action following an incident or fatality. In general, a bad outcome can

[1] The term 'traditional approaches' is used to describe common methods of the past that used voltage versus time criteria to decide what was a safe touch voltage based on discrete values for body impedance and or a safe body current.

lead to a prosecution claiming the designer, asset owner or operator was negligent. The burden will then likely lie with the defendant to demonstrate due diligence; for which in the common law case is that all reasonably practicable actions were taken to minimise the risk.

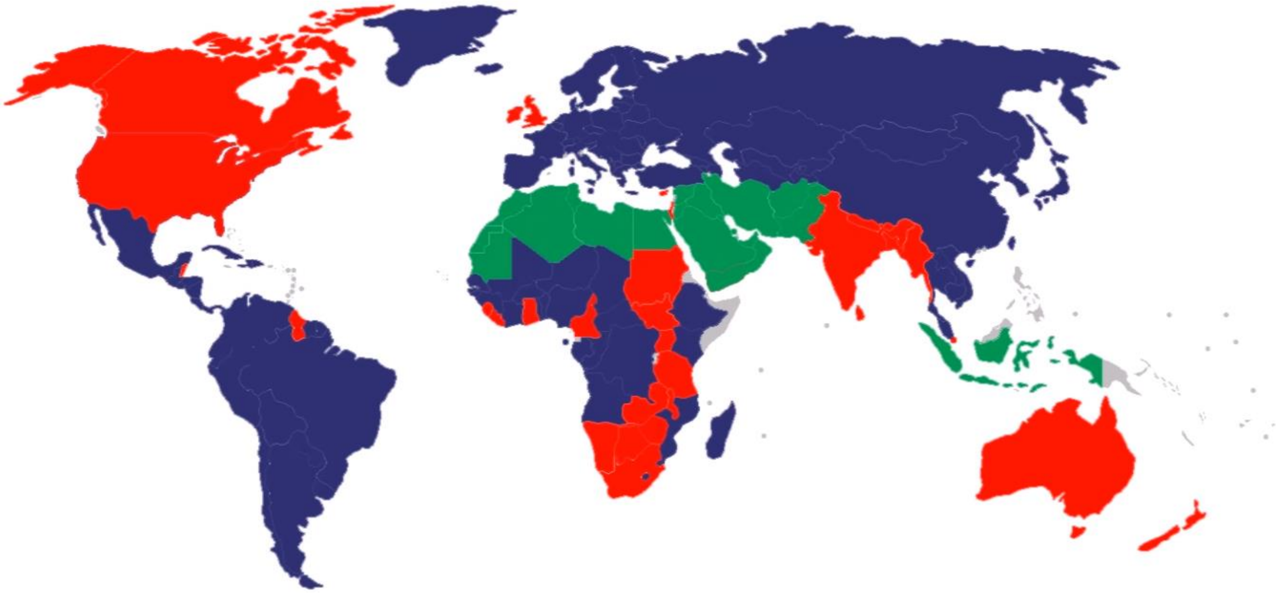


Figure 2.2: Countries with particular legal tendencies: Common (red), Civil (blue)& Religious (green) [79]

Regardless of country or task, engineers and others taking responsibility for designing, owning or operating earthing assets should remember that the technical challenge governed by the laws of nature must always be exercised within the context of the laws of man, with their contingent legal responsibilities.

3. Risk Management Framework

3.1 Introduction

This section provides general considerations and examples of risk management and tolerable criteria in different countries. An example of a general risk management framework can be described as one that leads to the identification of risk tolerance criteria described by three risk bands; an upper intolerable risk band, a lower negligible risk band and between these two, an intermediate band where risk treatment is managed on some measure of reasonableness. It is recognized that views on setting the numerical level of risk assigned to the tolerable or negligible thresholds may vary from country to country and that vocabulary describing these thresholds also varies. Nevertheless, the general approach to risk assessment is common to many countries. In some countries, the three-band classification is referred to as the 'as low as reasonably practicable' (ALARP) criteria, while in other countries the so-called "de-minimis" and "de-manifestis" risk levels are described that are in effect the two boundaries between the same three bands. The concept of Tolerability of Risk (TOR) and its relation to ALARP is then explained. Finally, a survey of numerical risk tolerance criteria and general approaches to risk adopted by national safety and regulatory bodies is provided.

3.2 General Risk Management Framework

A well-recognised risk management framework for organizations is provided in International Standard ISO 31000:2009 [2], and risk assessment techniques are introduced in ISO/IEC 31010:2009 [3]. In order to set out the risk management hierarchy and to provide consistent terminology in this document, reference is made to Figure 3.1 reproduced from [2]. From the figure, it can be seen that risk assessment forms part of the overall risk management process and itself comprises three distinct areas, namely, risk identification, risk analysis and risk evaluation.

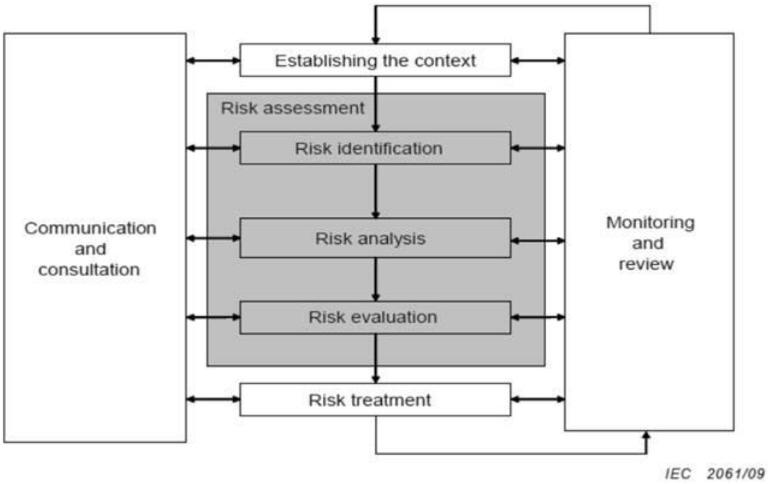


Figure 3.1: Contribution of risk assessment to the risk management process [2]

3.2.1 Risk identification

Risk identification finds the causes and source of the hazard and their impact. Risk identification methods include evidence-based methods, systematic investigation and inductive reasoning.

3.2.2 Risk analysis

Risk analysis determines the consequences and their associated probabilities for defined hazards. The risk event consequences and probabilities are then combined to determine the level of risk. Risk analysis may be qualitative, semi-quantitative or fully quantitative. Even when full quantification is employed, it should be acknowledged that risk levels (e.g. in terms of probability of fatality) are estimates and an appropriate accuracy and precision should be used. The issue of uncertainty in quantitative risk assessment is dealt with by applying sensitivity analysis and the precautionary principle [4][36]. Within risk analysis, the following aspects in particular need to be addressed [3];

- **Controls assessment:** Existing risk control mechanisms are identified and their effectiveness evaluated.

- **Consequence analysis:** Here, the nature and impact of the event should be considered. Impacts may have high probability and low consequence or, as is the case in earthing safety, have low probability but possible high impact (fatality).
- **Likelihood analysis and probability estimation:** Three approaches are employed either separately or together.
  - ✓ Use of historical data (e.g. in the case of earthing systems safety, power system earth fault statistics, fault current level data, protection clearance times, worker or general public activity in the vicinity of touch and step hazard locations from electrical installation records.
  - ✓ Probability forecasts or estimates: where historical data may be lacking, (e.g. for a new electrical installation)
  - ✓ Expert opinion: using formal methods
- **Preliminary risk analysis:** A preliminary analysis of risk is required to rank the severity of the risk and, perhaps, to exclude other less significant risks from further analysis. Courses of action could include:
  - ✓ To treat the risk without further assessment (e.g. missing earth tapes in a substation may be identified during a substation inspection and require replacement but no further analysis is required),
  - ✓ Neglect insignificant risks, or
  - ✓ To carry out a detailed probabilistic risk analysis.
- **Uncertainty and sensitivity analysis:** There may be uncertainty in input data (e.g. fault rates) and also in models that are used to quantify the consequence of the risk event (e.g. soil resistivity estimation for EPR prediction). In such cases, it is important to carry out sensitivity analysis (as is introduced in Chapter 4.4.4 and applied within the case studies in Section 9 of this document) and determine the variation in the results and, if possible, to quantify the degree of imprecision. Where significant uncertainty remains, application of the precautionary principle is recommended [4].

3.2.3 Risk evaluation

In risk evaluation, the estimated level of risk is compared against established risk criteria to establish the severity of the risk, and whether action is required and if so the level of mitigation that is justified. Ethical, legal, financial and public perceptions are inputs to the decision-making process. Decisions about how to treat the risk may include cost benefit analysis and a common approach is to divide risks into three bands:

- An upper band: regarded as intolerable and where risk treatment is required irrespective of cost.
- A middle band, where a degree of intervention or mitigation is required but its extent of application is decided by a cost benefit analysis.
- A lower band, negligible risk band, where the risk level is considered to be small enough not to warrant any treatment measure.

The above approach is sometimes referred to as the ‘as low as reasonably practicable’ ALARP criteria system and where, in the middle band, there is a sliding scale such that risk mitigation is evaluated at the lower risk end by cost benefit analysis while at the upper risk end there is a requirement to spend until the cost of mitigation is ‘disproportionate’ to the benefit gained.

3.3 Tolerability of Risk and ALARP

The implementation of quantitative risk assessment (QRA) involves the calculation of a measure of individual risk (IR) which is benchmarked against nationally-recognized acceptable risk levels [7][39]. The risk assessment approaches developed for the control of risk at nuclear power stations [8] have often been taken as the model when QRA is applied in other areas.

The task for industry in dealing with risk to human life and loss or damage to important assets is undeniably a difficult one. Public opinion may assume or even require that there is no risk of harm from industrial installations. Experts are nowadays used to the requirement for quantifying and controlling risk although this may be a challenging task due to the uncertainty of accurately quantifying the risk. This leads to a recognition that in many circumstances there has to be an acceptance of a certain defined level of risk, or in other words, a ‘tolerable risk’. This does not mean that the risk is acceptable, however, only that the benefits outweigh the risk and that there is confidence in the measures for control of the hazard.

One of the key principles common to much health and safety legislation [9][22] is that the responsibility for protection of workers and the public lies with those who create the risks; this is usually the employer but it may also include those employed at various levels of an organization. Guidelines or standards have been produced within some countries setting out how evidence of risk and the uncertainties in describing risk are accounted for and how it is necessary to achieve a balance between the disadvantages of risk and the benefits obtained by controlling or avoiding them (e.g. UK - ‘R2P2’[7]).

The following sections describe the details of risk-related definitions, perceptions of risk and typical actual risk levels in modern society. The hierarchy of risk assessment is set out and the issues of uncertainty addressed along with the role and methodology of cost benefit analysis. The criteria for assessing risk tolerability is described and the limits between the defined risk regions quantified.

3.3.1 Definitions of risk and related terms

Risk is defined as 'the chance that something adverse will happen' or more strictly 'the probability that a specified undesirable event will occur in a specified period or as a result of a specified situation' [8]. Therefore, risk may be considered to be the combination of probability and consequence. However, the interpretation of 'risk' by a layperson may be more centred on consequence than probability and the terms 'hazard' and 'risk' may be used interchangeably in everyday language. There is a clear distinction between the two terms:

- **Hazard** being the 'potential for harm', and
- **Risk** is 'the chance that someone or something that is valued will be adversely affected in a stipulated way by the hazard'.

Duties to control risk are also qualified by expressions such as:

- **SFAIRP** - 'so far as is reasonably practicable',
- **ALARP** - 'as low as reasonably practicable', and
- **ALARA** - 'as low as reasonably achievable'.

The meaning of the word 'practicable' in this context, rather than the related word 'practical', indicates specifically that measures to control risk are 'capable of being put into practice'.

The fundamental principle regarding responsibility for creating a hazard requires that the asset owner or 'operator' must do what is reasonably practicable to reduce the risk associated with hazard unless the expense of doing so is in 'gross disproportion' to the risk [8].

3.3.2 Perceptions of and attitudes towards risk and QRA processes

It is argued that there are risks that people take willingly in order to secure certain benefits, viz. voluntary risks, and that there are also risks we are subjected to from naturally occurring events so small that they do not influence behaviour significantly [8].

For example, the risk of death from lightning in the UK is on average in the order of 1 in 10 million per annum [8], and this risk does not significantly influence behaviour although it is noted that this risk varies across different parts of the country and that, historically, there was a significantly higher death rate from lightning due to much higher numbers of rural workers [8, 10]. In other parts of the world, e.g. the US, the overall lightning fatality rate is similar to the UK, although the variation of rate across the US is much greater, for example, with Florida having 47 deaths between 2006 and 2016 and Washington zero over the same period. According to the NSLI (US), of those countries monitored, Mexico had the highest lightning related fatality rate of 1 in 2 million [11].

In the UK in 1992 [8], it was quoted that 'over 5,000 people are killed each year by traffic' and noted that while people may be cautious about using roads, it does not stop the public from using them. It is interesting that, since the publication date (1992) of [8], the number of road-related fatalities in the UK, had fallen from over 5,000 in 1992 to 1,713 by 2013 which may be due to improvements in user safety behaviour, road infrastructure and intrinsic vehicle safety [12]. Statistics of fatal injuries in the workplace in Great Britain also show a significant fall over the period 1996 to 2016, from 1.12 per 100,000 to 0.46 per 100,000 workers. The UK rate is considerably lower than the recently published EU average of 1.44 and lower than Germany (0.81), Spain (1.55) and France (2.94) [13]. The above-mentioned statistics serve as a reminder that benchmarked risk targets may need to be periodically reassessed against the backdrop of an increasingly safer environment, as worker's and public expectations of levels of involuntary risks may become correspondingly more stringent. Operators should be aware, also, that developments in information technology continue to enable a better-informed public and that it is vital to be transparent about known hazards and their control measures so as to inform the public and workers and in order to counter possible non-peer reviewed and uncritical or inaccurate information dissemination.

In the context of assessing the risk of electrocution of either an electricity worker or a member of the public under conditions of an earth fault on a power system, the risk is not voluntary and it is also important to account for this when setting appropriate benchmark levels for tolerable risk in such application. Also, although this specific hazard is not new, general public knowledge about it is probably very limited, partly because the probability of the hazard event is very small.

A clear distinction, therefore, should be made between those hazards that are voluntary and those which are outside the control or awareness of the individual although many of the latter will be caused by so-called naturally-occurring events. So, perception of risk and willingness to accept risk is affected by the apparent degree of control that an individual may have over the risk. Beyond this, perception of risk is also influenced by other subjective factors that may include ethics, trust in those creating risk, type of media coverage, the newness of the hazard. A further consideration and a more difficult one to quantify in terms of tolerability is whether a risk is categorized as of ‘individual concern’ or if it gives rise to ‘societal concern’. This latter aspect is addressed in more detail in Section 4.

The use of probabilistic targets, defining boundaries between unacceptable and negligible risk limits, is not a perfect approach by any means. It has been argued by some that a strict use of the tolerability of risk (TOR) approach to decision making has a number of shortcomings, including [49]:

- TOR cannot categorically reflect uncertainties about population variation in community values, or economic considerations.
- That ‘bright lines’ (discrete numbers rather than ranges) are inconsistent with the variability and uncertainty inherent in estimates of risk.
- That it may be misunderstood to imply that an exact boundary exists between safety and risk.

Such weaknesses or criticisms are acknowledged, but rather than discounting the TOR approach, the criticisms should be used to strengthen the approach through provision for incorporating checks and other considerations in the process. Although susceptible to misuse and misunderstanding, the concept of QRA is proposed to be more responsible, as it attempts to enumerate the real issue of the ‘level of risk’, which is at the heart of the safety policy setting problem.

3.3.3 Comparative risk levels

Statistics are available describing risks of death from voluntary and work-related activities, naturally-occurring events, fatalities from man-made disasters and transport accidents [8][23]. From such data, broad levels of risk can be described as shown in Table 3.1.

TABLE 3.1. Levels of fatal risk according to UK HSE [8]

Levels of fatal risk (average figures, approximated)	
per annum	
1 in 100	risk of death from five hours of solo rock climbing every weekend
1 in 1000	risk of death due to work in **high risk groups** within relatively risky industries such as mining
1 in 10 000	general risk of death in a traffic accident
1 in 100 000	risk of death in an accident at work in the very safest parts of industry
1 in 1 million	general risk of death in a fire or explosion from gas at home
1 in 10 million	risk of death by lightning

When using these levels for comparative purposes in assessing the relative risk of other activities, it should be borne in mind that the public has high expectations of safety concerning additional involuntary risks.

3.3.4 Risk hierarchy and uncertainty

As introduced in Section 2, it is worth noting that the top of the hierarchy of risk control is the consideration of measures to avoid the hazard completely and to make the system inherently safe. Lower down the hierarchy are measures to reduce risks when it is deemed not possible to avoid the specific risk.

It is recognized that quantitative risk assessment (QRA) is a useful tool in regulating risk and while many obvious and visible hazards can be tackled straightforwardly, other hazards are not so visible and difficult to quantify accurately because of the complexity of the system and/or uncertainty of data. The safety voltage hazard at electrical installations under earth fault conditions falls into this category. As for any power system modelling task it is important to consider the level of uncertainty in the risk calculation. When calculating the individual risk of fatality of a person subjected to a touch voltage under an earth fault condition, the assessment is:

- Complex – for example assessing the probability distribution function or range of touch voltages depending upon range of fault cases, and
- Subject to uncertainty of data in some of the key parameters such as the presence probability and activity statistics of workers at electrical installations.

Where such knowledge uncertainty exists, the precautionary principle should be applied and conservative assumptions made. The precautionary principle, concerns hazards subject to high scientific uncertainty, and rules out lack of scientific certainty as a reason for not taking preventive action. It was formulated originally in the context of environmental protection [–36], but, it is now applied more widely, particularly if serious harm may occur even if the likelihood is small [7]. The precautionary principle helps to mitigate against complacency about low risk events where the 'absence of evidence of risk' is sometimes taken as 'evidence of absence of risk'.

3.3.5 Criteria for assessing tolerability

The criteria that determine which category of severity a risk falls into is fundamental to the whole risk assessment and management process. Following the quantification of the level of risk associated with the given exposure scenario the most common criteria for assessing risk is the framework known as the tolerability of risk (TOR)[7]. Such a framework defines levels of risk in terms of that which is: unacceptable, tolerable and broadly acceptable [7]. These regions accord with the broad classifications outlined in ISO31010 [3]. It is noted that 'tolerable' does not mean 'acceptable' and that there is no activity that carries 'zero risk' [7].

The TOR framework is described by conceptual models such as that used by the UK HSE [7] shown in Figures 3.2. The figure shows a triangle representing increasing levels of risk for a particular hazardous activity. The figure shows the 'ALARP' region within which risks may be considered as tolerable and where cost benefit analysis (CBA) may be employed to assess the merits of safety improvements. As mentioned in the introduction, these regions are sometimes alternatively described by the use of the de-manifestis and de-minimis risk levels [15]. The 'de-minimis risk' is taken as a natural background risk established by events such as lightning, earthquakes or hurricanes while the 'de-manifestis risk' is taken as the threshold value of the non-acceptable risk of death. The correspondence of the de-minimis and de-manifestis risk level to ALARP is shown in Figure 3.2, while Figure 3.3 shows an example TOR framework recommended within the UK National Grid H&S standard [16]

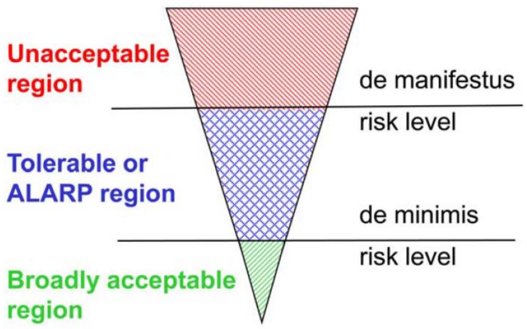


Figure 3.2. 'De manifestus' and 'de minimis levels' and ALARP [15]

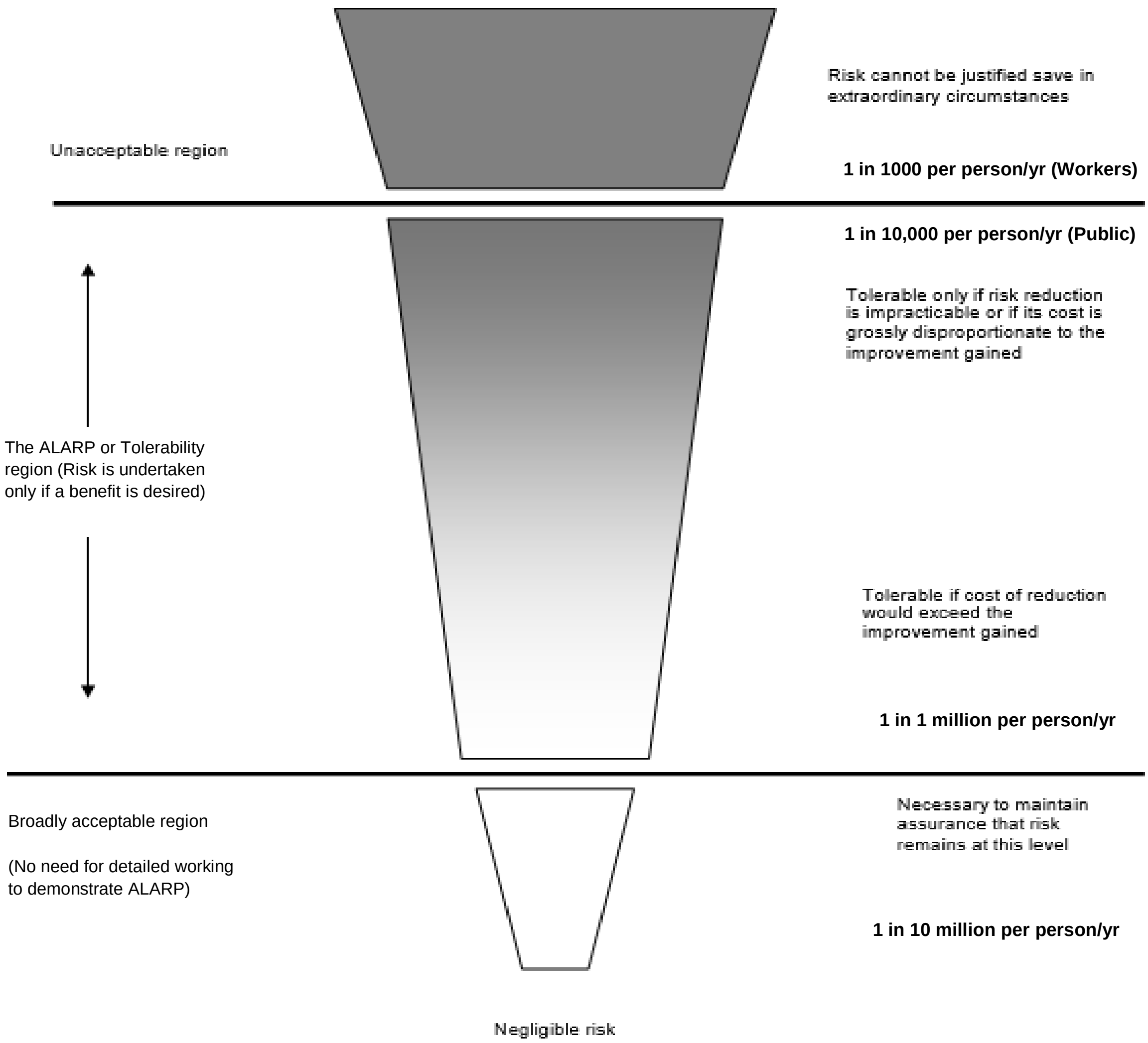


Figure 3.3. UK National Grid H&S Standard NS-MP1 [16]

With reference to the TOR framework shown in Figure 3.2 and 3.3, the broadening of the triangle represents increasing risk and the dark zone at the top of the triangle illustrates the unacceptable region and any activity falling here is considered unacceptable irrespective of its perceived benefits. At the other end of the triangle, risks in this region are considered broadly acceptable and, generally, either insignificant or well-controlled. The boundaries between each zone are described in more details as follows:

- Boundary between ‘tolerable’ and ‘unacceptable’ regions for hazards that potentially cause fatality

This boundary is considered to be difficult to define. However, as an example the UK HSE [8] suggests a level of one in a thousand per annum for general workers averaged over a working life. For members of the public, who have the risk imposed on them, the risk limit is set a magnitude lower at one in ten thousand. It is considered that most industries in the UK achieve risk levels much lower than this range and often societal concerns play a more important role in determining whether risks at these levels are deemed acceptable or not.

- Boundary between ‘broadly acceptable’ and ‘tolerable’ regions for hazards that potentially cause fatality

The UK HSE defines a risk of individual death of one in a million per annum for both workers and the public to be a very low level of risk and this figure should be used as the boundary between the ‘broadly acceptable’ and ‘tolerable’ regions. It is noted that in the UK, the background level of risk of fatality is one in a hundred per year averaged over a lifetime and a one in a million per year risk is considered extremely small compared to this background level. It is interesting, also, that the HSE uses the example of general risk of fatality from electricity (one in a million per annum) and cites the many individual and societal benefits and lives saved as a result of its use. In other words, risk of such electrocution is a tolerated risk because the benefits it brings are seen to outweigh the risks.

- Tolerable or ALARP region

The ALARP region lies between the two aforementioned regions. Here, it is considered that people may tolerate the risks to secure benefits; however, it is also expected that the risks be properly assessed, suitably controlled and kept ‘as low as reasonably practicable’. The example shown in Figure 3.3 provides some more detail about sub-regions within the ALARP region. With reference to this figure, just below the threshold of the unacceptable region, asset owners would be expected to invest to reduce risk up to the point where such expenditure is grossly disproportionate to the risk reduction achieved. As one moves downwards within the ALARP region of the figure, the less it is considered worth investing to reduce risk until the point is reached where it may not be worth investing at all.

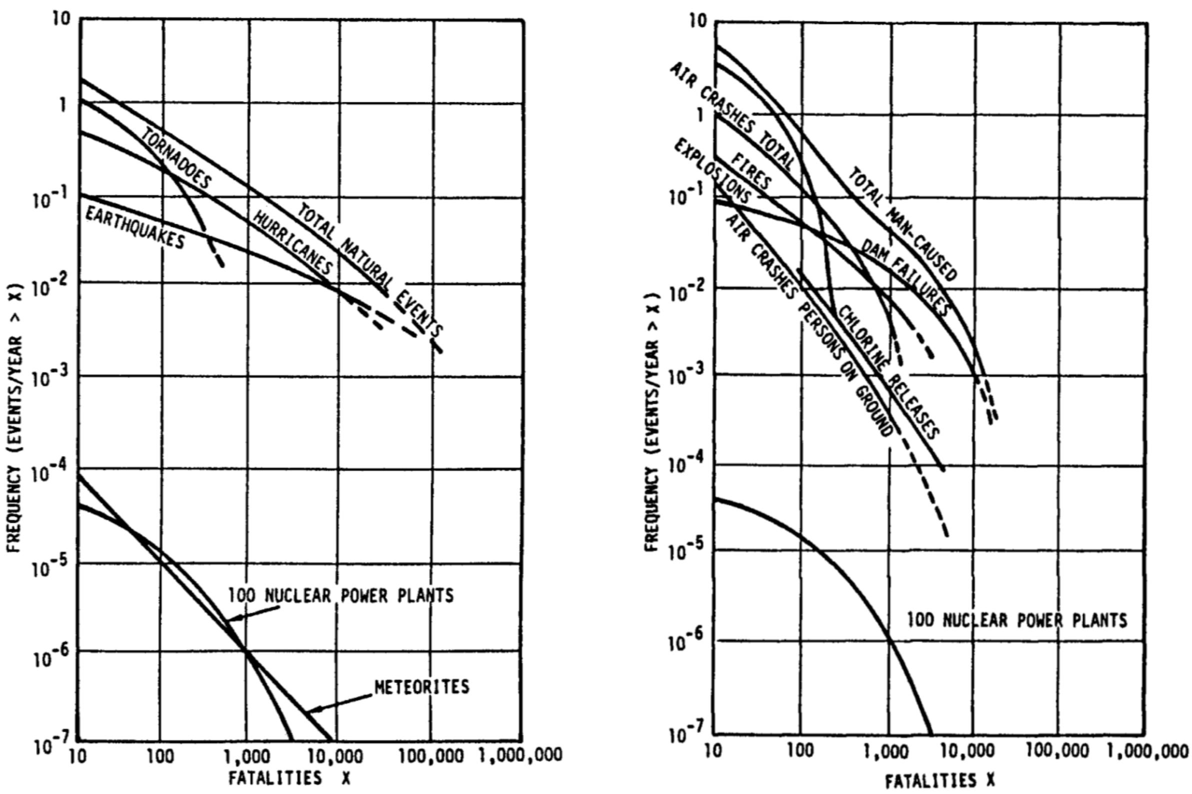
This framework, therefore, may apply to any hazard and the quantitative levels of individual risk that define the boundaries of these three regions depends on the hazard in question and the practicability of solutions to reduce it. A survey of the boundary values used by different countries is presented in Section 3.4.

3.3.6 Sensitive scenarios and risks of multiple fatalities

Certain hazard scenarios are considered by society as being more sensitive than others. Examples include the death of a child or a hazard that could induce cancer. Assessing the impact of societal concern regarding such sensitive scenarios is a difficult task when setting risk levels, particularly determining when they should override the limits set out in Section 3.3.5. Currently, there are no generally accepted values that bias risk tolerance for particular hazards or towards susceptible sub-groups of the population.

However, most risk assessment guidelines include specific criterion governing societal concerns when the hazard involves multiple fatalities [17][20][42]. In this context, the ‘societal risk’ concerns the relationship between tolerable risk and the number of people suffering from the realization of the hazard. Although a number of TOR frameworks are used across various industries, the most common framework is based on the use of so-called F-N curves, where F is the frequency at which the hazard may kill N or more people. Figure 3.4 shows an example of actual F-N characteristics relating to a range of hazard scenarios based upon actual events. Both individual and societal risk should be assessed as part of the normal QRA process. Societal risk is most commonly found to be the most critical condition when considering the impact of a large industrial plant such as a chemical plant with liquid toxic substances or a flammable gas plant with populations in close proximity.

The results of a study [19] of the societal risk associated with a number of natural (e.g. earthquakes) and man-made (e.g. dam failure) hazards are shown in Figure 3.4.



a) Natural event fatality frequency b) Man-made event fatality frequency

Figure 3.4 Actual F-N characteristics [19]

Figure 3.5 illustrates a range of F-N TOR criteria used in various countries [20].

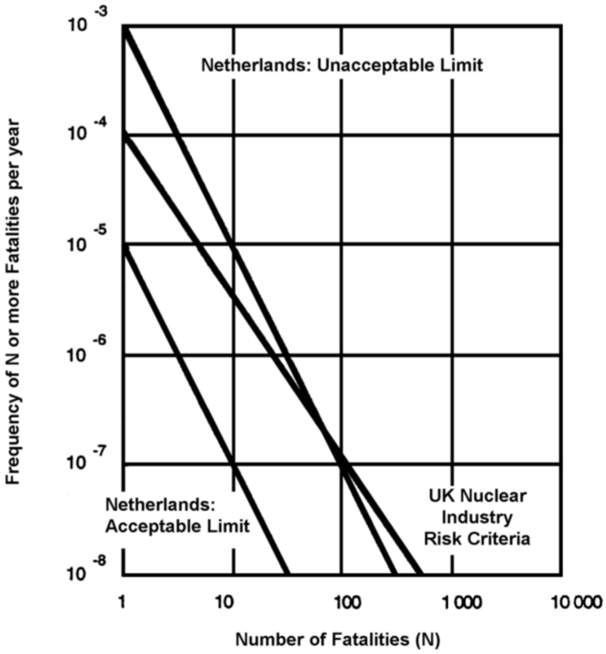


Figure 3.5 Societal risk F-N TOR criteria

An example is given in Figure 3.6 [17] showing the F-N criterion curve that is based on the UK HSE recommended benchmark 'intolerable point' of 50 deaths if the frequency is more than one in five thousand and where the curve is extrapolated with a gradient of '-1' (i.e. a slope of -45 degrees). In the assessment of tolerability of possible multiple fatalities, actual F-N estimated curves would be compared against this criterion curve.

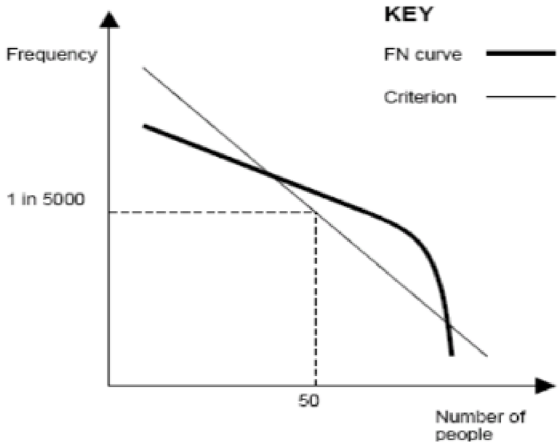


Figure 3.6. Example of an FN curve and the 'R2P2' criterion point (1 in 5000 and 50) [17]

Section 4.5.2 Illustrates where the F-N approach is applied to earthing system design [1][17] with benchmark levels of tolerable risk aligned with hazardous industry TOR criteria for that country.

3.3.7 Risk cost benefit analysis

When assessing risk reduction actions as part of a QRA, a cost benefit analysis may be useful to compare the merits of different options or to justify the implementation of a specific option. The estimate of costs associated with investing to improve safety is straightforward, however, when the measure may prevent a fatality it is necessary to place a value on this.

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.

To reduce the risk, precautions or risk mitigation shall be applied so far as is reasonably practicable (SFAIRP) or as low as reasonably practicable (ALARP), which is where the cost is not grossly disproportionate to the benefit gained.

The design should be evaluated to ensure all reasonable precautions, whose costs are not grossly disproportionate to the benefits, have been included. Assessment of risk mitigation is an iterative process to reduce the earthing design risk so far as is reasonably practicable (SFAIRP) or as low as reasonably practicable (ALARP).

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 [1][11][12][13][14].

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 (e.g. value of life) while the cost is the cost of a successful mitigation strategy. Particularly, 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 [21][24] show that values varying between approximately $2 million and $20 million have been used in various countries.

The UK HSE proposes a monetary ‘value for preventing a fatality’ (VPF) but stresses that this does not represent a value that society may place on a human life or a court’s compensation for such loss but rather a cost associated with, inter alia, prevention of death, grief and suffering. The magnitude of the VPF that the UK HSE uses is based on the UK Department of Transport’s document on the valuation of road accidents in Great Britain [14]. This document describes how the valuation of fatal casualties is based on an individual’s willingness to pay (WTP) approach. The casualty costs include (i) lost output – the measure of loss of working productive capacity, (ii) medical and ambulance costs, and (iii) human costs – reflecting the non-resource element of costs such as pain and distress etc. The 2012 benchmark value of preventing a road casualty was £1.7M [14] and this figure, index-linked, is currently adopted by the HSE when conducting a cost benefit analysis (CBA). However, the HSE notes that since the VPF is based on the WTP approach, the figure may depend on the particular hazard in question. For example, HSE uses a figure twice that of the ‘road traffic’ figure when considering risks of cancer.

3.3.8 TOR framework boundary examples

The TOR framework boundaries for a number of countries for a range of hazard types are summarised in Table 3.2. Care should be taken before using any TOR criteria as the assumptions associated with the input parameters vary for each hazard scenario. For instance, it is common practice to allocate 'safety margins' to uncertain and/or critical parameters in an effort to be conservative.

Table 3.2: Survey of legislation related to health and safety, risk responsibility and tolerable risk limits

Country	Tolerable individual annual risk of death from one activity or exposure	Tolerable societal annual risk of death from one activity or exposure[1]	Notes
Australia	10^{-6} to 10^{-4}	$F < 10^{-6} \times (N / 10)^{-1.5}$	[1][61].
Canada	Basic safety limit =10^{-4} Basic safety objective =10^{-6}	FN curve slope = -1 Intolerable intercept with N=1, 10^{-3} Negligible intercept with N=1, 10^{-6}.	[97]
Hong Kong	Intolerable risk = 10^{-5}	FN curve slope = -1 Intolerable intercept with N=1, 10^{-1} Negligible intercept with N=1, 10^{-4}. Limit on N=1000	[96]
India	10^{-5}, 10^{-6}	FN curve slope = -1 Intolerable intercept with N=1, 10^{-3} Negligible intercept with N=1, 10^{-6}.	[96]
Netherlands	10^{-6} to 10^{-8}	$f < 10^{-3} \times N^{-2}$ */year for N ≥ 10* FN curve slope = -2 Intolerable intercept with N=1, 10^{-3} Negligible intercept with N=1, 10^{-5}.	Limits approved by parliament [94].
UK	10^{-6} to 10^{-4}	FN curve slope = -1 Intolerable intercept with N=1, 10^{-1} Negligible intercept with N=1, 10^{-4}. (Existing plants)	UK applies the ALARP principle [R2P2] [4][9].
USA	1.4×10^{-8}	FN curve slope = -1 Intolerable intercept with N=1, 10^{-3} Negligible intercept with N=1, 10^{-6}	'De-minimis' approach adopted where risk investment for risks less than quoted do not require investment. [95]

Note 1: F - annual frequency, N - number of deaths

3.4 Summary

The public debate on quantified tolerable risks from industrial plants and electrical installation is considerably advanced in many countries. Similar approaches are emerging in the setting of limits or ranges for acceptable risks.

As an essential anchor point for the setting of 'de minimis risks', natural background risks such as lightning, earthquakes or hurricanes are often taken. The 'de minimis thresholds' for the probability of an individual's death tend to range between 1: 100,000 (10^{-5}) to 1: 100,000,000 (10^{-8}) per individual per year. The threshold of unacceptable annual 'de-manifestis' death risk appears to lie mainly in the range of 1: 10,000 (10^{-4}) to 1: 1,000,000 (10^{-6}). In some countries, also a limit value for the societal (collective) risk is indicated.

Any decision to determine a tolerable risk must take into account both technical expertise, as well as social values.

4. Application of Quantified Risk Assessment to Earthing Systems

4.1 Introduction

What constitutes a 'safe' earthing system has been defined in a number of different ways in different countries. In some countries, the earthing system is considered adequate if the impedance is below a set value (e.g. 1Ω), while other countries define safe step and touch voltage as a function of time. The second approach is more realistic as to uses physiological constraints when determining criteria for safety. However, it is becoming increasingly obvious that a further step is required to either justify continued use of traditional 'safety voltages' or assess the risk associated with an individual site or class of assets.

Risk quantification and assessment provides such a tool and may be used to generate a risk-cost-benefit analysis providing a clear means for communicating to management, and also providing an objective measure to either justify existing approaches or guide designers regarding where to focus effort (i.e. in obtaining more accurate input data, or remedial measures) and how to compare design options.

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

- Identify hazard scenarios where more traditional approaches are non-conservative and where more stringent criteria may be justified (i.e. allowed touch voltages be lowered) 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.

Given that a fatality due to indirect contact during earth fault events is a very low likelihood event, and that any individual hazard scenario has a large number of variables impacting upon the actual risk profile, it is not possible to base any estimation of what voltage versus time characteristic should be 'tolerable' on the earthing experience of every individual. However, through the use of risk quantification it is possible to determine the range of hazard scenarios where the application of a given voltage characteristic, including those in IEC 61936 [28] 'C2' or IEEE80 [27] Dalziel characteristic [37], is justified.

The latter part of the preceding Chapter 3 provided an overview of risk management processes. This chapter provides the background to the application of QRA to power system earthing risk management. It discusses the probabilistic nature of the shock event, introduces the main components of the QRA process when applied to earthing system design, as well as the processes incorporated in a number of standards, and introduces specific risk targets that have been incorporated within earthing design procedures in national standards.

4.2 Historical Perspective

National and international standards for the design of earthing systems for substations have traditionally been based on methods that combine a defined set of supposedly conservative (deterministic) conditions to yield a target safety voltage threshold. This process has resulted in a variety of different voltage versus time characteristics. Examination of the risk profiles of many substations has shown that in some circumstances the traditional approach has led to excessive mitigation costs and in others allowed the public to be exposed to too great a risk [6][27][28].

There are many probabilistic influences involved in assessing safety, with regard to the fault current magnitude and duration, as well as the probability of the fault occurrence, and the presence probability of a human being (this is further discussed in Chapter 6). This has led some countries to introduce a new approach to earthing system design based on the explicit application of probabilistic methods.

The following points identify cases where indirect shock risk has been quantified, either for use in developing tolerable safety standards (i.e. touch voltage vs protection clearing time withstand curves), or to assess the risk associated with a specific or class of hazard scenario (i.e. voltage source and contact exposure mechanism):

- Australia 1960's: Risk to telecommunications staff was quantified using probabilistic studies in the 1960's [38], in order to determine the maximum impressed voltages to allow on telecommunications circuits. The resultant tolerable safety standards (i.e. 430V, 1000V and 1500V) were less stringent than the International Telecommunications Union (ITU) standards (i.e. 430V and 650V) [40].

- Finland in 1970's: Finland adopted a set of earthing voltage requirements as part of the Electrical Safety Code [41], based upon a probabilistic analysis of the contributing factors. Although the Finnish study was designed specifically for their system configuration and physical constraints (soil resistivity between 1000 and 10000 Ωm, and being snowbound during winter months), the following extract is generally applicable.

  'When applying probabilistic calculations to the safety studies of the electric power system or its part, one has to accept the fact that no absolute safety exists in reality. For example, the problem of the earthing voltage has to be solved by accepting a certain accident probability that on different earths can be very low. The result based on probability calculation can, of course, then be expressed deterministically as a categorical requirement. This is often the most suitable way in practice, however, the determination of the requirement as well as the interpretation of its context presumes a probabilistic way of thinking and evaluation'.[41]

- IEC479 (1974) [18]: This document published physiological details of human fibrillation current withstand expressed in probabilistic terms. The introduction to the document included specific direction to include consideration of actual risks before using the current withstand data to develop voltage withstand criteria in practise.

  'There are, however, other aspects to be taken into account, such as probability of faults, probability of contact with live or faulty parts, experience gained, technical feasibilities and economics. These parameters have to be considered carefully when fixing safety requirements, ... for electrical installations.'

- Australia in 1980's [43][44][54]: In the 1980's the power industry undertook probabilistic studies to determine tolerable design criteria for distribution and transmission structures. This work generated tolerable prospective touch voltages of up to 8kV (for clearing times less than 0.2 secs) associated with transmission structures based upon an annual fibrillation fatality risk increase limit of 1: 1,000,000 (10^{-6}).

- Germany VDE 0141 [33]: The 1976 edition allowed for networks 110kV or higher to consider a design current of 70% of the maximum fault current. This allowance was based upon the low likelihood of the coincidence of maximum fault current and a person being in the worst case contact location.

- IEEE papers in 1980's: Following the Finnish approach the risk associated with the flow of earth fault currents was calculated for specific assets assessed (e.g. metro system) in a number of North American IEEE papers [32]. Also, a number of the papers at an international symposium in Toronto on electrical shock safety in 1985 [45] concluded that a need existed for the development of probabilistically based safety criteria.

- IEEE80 [27]: IEEE80 clearly acknowledges that a hazardous electric shock incident will only occur given the coincidence of a number of variable conditions, and then makes the general observation that the '*relative infrequency of hazardous incidents is due to the low probability of the coincidence of those necessary conditions*'. The design safety criteria recommended in IEEE80 is based upon the work of Dalziel [37], who based his work upon the same physiological data as the IEC working group led by Biegelmeier, and generated a current versus time characteristic that was claimed to provide safety against ventricular fibrillation for 99.5% of all persons.

- IEC 61936 (2002) [28]: The international HV installation standard IEC61936 uses selected physiological data from IEC60479 [18] for body impedance (50%), body current withstand (5%), and heart current factor (LH to feet) to generate a permissible prospective touch voltage curve. As was the case for IEEE80, IEC61936 does not overtly incorporate a probabilistic process, however, it does include the following statement: '*It must also be recognized that fault occurrence, fault current magnitude, fault duration and presence of human beings are probabilistic in nature'*.

- UK in 2000's: The UK has adopted an alternative design process in a national annex to the Cenelec earthing standard BS EN50522 [46]. The flowchart has been augmented to allow designers to undertake a quantified risk analysis if normal touch voltage criteria are found to be inadequate (i.e. too stringent, or unable to take special conditions such as sporting events consideration). Examples are included based upon the work undertaken at the Cardiff University [29][47] that incorporates IEC60479 physiological data with system performance information and uses Monte Carlo analysis to determine risk profiles associated with transmission system assets.

- New Zealand 2000's: The power utility industry within New Zealand produced an earthing guide covering 'Risk Based Earthing System Design' in 2003 [73] and released the 'Guide to Power System Earthing Practice' [80] in 2009 containing application of QRA to a range of case studies.
- Australia/New Zealand in 2000's: Under the auspices of the Energy Networks Association a team developed a risk quantification process, based upon the work undertaken in the 1990's, and embedded the process within an industry guideline, ENA EG-0 [1]. In addition, a software tool was developed to provide users with the ability to assess risk of fatality for a given hazard scenario. The tool entitled Argon [48] was developed within the power utility Ausgrid and made available for free download on the ENA website. An alternate tool based on the same methods and source data has been made available at the request of the Study Committee B3 Chairman to ensure the ongoing availability of a tool to provide a point of reference. The web based tool is called Argonium and can be found at [100]. The ENA working group undertook risk workshops and developed a number of sample criteria based upon a conservative assessment of commonly expected conditions. The initial work focussed upon power utility substations, as well as distribution and transmission assets. Subsequently several Australian and New Zealand standards working groups have used the techniques described in ENA EG-0 to redevelop a number of safety standards covering: distribution and transmission assets AS/NZS 7000 [50], metallic pipelines AS/NZS 4853 [51], and finally AS2067 (2016) [52] (companion to IEC 61936). The latter standard covers all HV plant and includes typical criteria covering a wide range of applications including mining and industrial hazard scenarios.

It is recognized that the earthing system is a safety critical system, as it is required to operate in times of potential crisis to manage the flow of earth fault and lightning current. It is the task of the design engineer to protect the safety and well-being of staff and the public. The engineering ethical code places great importance on the engineer's responsibility to incorporate safety as an integral component of the design, installation, commissioning and operational phases of any project. While it is clear that no such thing as absolute safety exists, it is an engineer's responsibility to make systems as safe as reasonably possible. The following statement from the document entitled 'US Presidential/Congressional Commission on Risk Assessment and Risk Management - 'Framework for Environmental Health Risk Management'' [39] published in 1997 clearly defines the regulatory requirement for managing involuntary risk:

> *'Where an individual person may be exposed to involuntary risk (beyond their control) due to exposure to a hazardous condition then the appropriate regulatory requirement placed upon the body generating the risk was the need to manage the imposed risk increase.'*

It is well understood that all engineering decisions are inherently risk based as are all safety standards. In particular all earthing design is risk based by virtue of the fact that many of the significant parameters (power system, human interaction, and enveloping environment) are necessarily statistical in nature. The foregoing brief case descriptions highlight the publications that acknowledge the statistical nature of the shock risk associated with indirect contact during earth fault events. As shown, a number of recent earthing safety standards are making the risk based nature of the decisions overt rather than hidden, and have incorporated the ability to undertake a quantified risk analysis within the earthing design process. Such an approach is supported by the following quote from a Cigre publication illustrates [53].

> '*While a worse-case deterministic assessment may show high values of potential gradients near faulted towers, a more realistic probabilistic assessment often shows that the likelihood of an event is very small and conventional earthing designs adequate.*'

The traditional approach was driven by the need to give to practitioners a practical, easily accessible method to design or assess against which required simple thresholds. However, the foregoing discussion shows that there was a clear acknowledgement that earthing system design has relied upon the probabilistic nature of events and the susceptibility of people to shock in an implicit rather than an explicit manner. Legal requirements are increasingly and more clearly directing power system asset owners to the fact that they have a duty of care to demonstrate due diligence in managing the risk of potentially hazardous voltages to staff and the public [1][89].

Practitioners experience in managing the risk associated with the release of fault energy and consequent fault voltages shows that not only is a probabilistic view needed, but also that a holistic system wide view is often required. This is due to the nature of current flow from the source to the point of fault and returning throughout the network via metallic paths and the soil creating hazard voltages at points throughout the network. To achieve such a view, collaboration may be required across areas of responsibility or between utilities, not only to understand the nature of the risk, but also to determine the most socially responsible and economical means to control the hazard and mitigate the risk to staff and the public. A traditional process that does not differentiate between the various risk sources and exposure scenarios is unable to meet these requirements [88].

Therefore, practical experience and modern business constraints are both requiring that design be based upon a process that can model realistic operating conditions rather than relying upon supposedly conservative traditional design processes.

4.3 Probabilistic Nature of Shock Event

The necessary conditions that must coincide before a person will enter fibrillation through the mechanism of indirect shock during an earth fault related event are probabilistic in nature. They include:

a) Relatively high fault current to earth in relation to the area of earth system and its resistance to remote earth.

b) Soil resistivity and distribution of earth currents such that high potential gradients may occur at points at the earth's surface.

c) Presence of an individual at such a point, time, and position that the body is bridging two points of high potential difference.

d) Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under circumstances a) through c).

e) Duration of the fault and body contact, and hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity.' [27]

Both the IEEE [27] and IEC [28] guidelines recognize the probabilistic nature of shock events due to indirect contact during earth fault conditions. Chapter 6 discusses the probabilistic nature of each of these factors. The following section summarises how earthing system design may incorporate the probabilistic factors in an explicit manner.

4.4 Risk Quantification Methods

This section gives an overview of the key elements of QRA as applied to earthing system design, and outlines the elements of a typical design process. A recommended detailed design process is provided in Chapter 8.

4.4.1 Probability of fatality

The probability of fatality due to indirect contact with a fault voltage may be expressed simply for independent events as shown in Equation 4.1[38]. It recognizes that in order for a person to receive a fatal shock they must be situated at a point of contact at the same time as they experience heart current of sufficient magnitude and duration to enter fibrillation.

$$P_{fatality} = P_{fibrillation} \times P_{coincidence} \quad \text{(Eqn 4.1)}$$

Where

$P_{fibrillation} = f(V_{applied}, R_{series}$, contact configuration, fault duration)

$P_{coincidence}$ = f(fault frequency, fault duration, contact frequency, contact duration)

4.4.2 Probability of fibrillation

The value $P_{fibrillation}$ is the probability that the heart will enter ventricular fibrillation. It is a Probability Distribution Function (PDF) driven by the magnitude and duration of current flowing through the heart. It is usually calculated by convolving the applied voltage PDF with the withstand voltage PDF, numerically by Monte Carlo simulation [29][47]. The probability that a human enters fibrillation for a particular applied voltage is a function of the following two variables:

- **Shock circuit resistances**: these include body resistance, footwear, gloves, and materials that increase the foot to earth contact resistance such as crushed aggregate or asphalt.
- **Body current withstand criteria**: The amount of current that the heart can withstand for a particular time without entering fibrillation is a distribution intended to reflect the range of susceptibilities across the human population. By applying an interpolation of published IEC safety curves, a more accurate assessment of individual risk of fibrillation is developed in the form of probability surfaces as a function of applied voltage, fault clearance time, and current path.

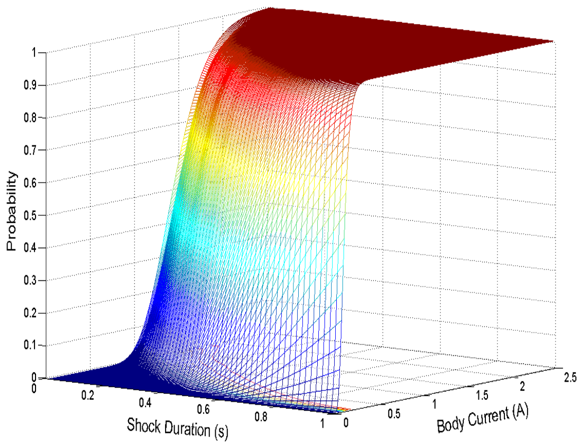


Figure 4.1 Probabilistic body current fibrillation withstand characteristic example [29]

Figure 4.1 shows a cumulative probability surface of ventricular fibrillation as a function of body current and shock duration [29] based upon the data provided in IEC60479. In some traditional approaches a single value, such as 1kΩ, has been assumed to be representative of the human population's body impedance when establishing hazard limits (e.g. IEEE80). IEC60479 describes in detail how the impedance of the human body varies across the population, including its voltage dependence due to the skin impedance varying and breaking down at voltages higher than 200V, and the impact of moisture on the skin. Further detail is provided in Section 6.5.

Most allowable voltage curves in common use have a probability of fibrillation that is not a constant and are dependent upon distribution of clearing times [57][81], due to not using the full PDF response for both body current withstand and body resistance. Allowable voltage curves (with respect to clearing time) that have a specific and constant probability of fibrillation with respect to clearing time provide designers with a robust characteristic that may be consistently applied independent of clearing time. This approach has been adopted within the Australian context [1].

The voltage across the human body (applied voltage) that drives current through the body and thereby completing a shock circuit in an earthed situation, is determined by the impedance of the body, the impedances of the other elements in the shock circuit and the voltage driving the fault circuit.

The applied voltage is a function of the following variables:

- Earth fault current magnitude and duration: refer to Section 6.1.
- Return current distributions: refer to Section 6.2
- Soil resistivity: refer to Section 6.3
- Earthing system configurations: refer to Section 6.4
- Path through the body (e.g. hand to hand or hand to feet): refer to Section 6.5

Each of these factors are clearly not singular but variable, and therefore when represented by a single value care must be taken in the selection of the representative value.

For example, when selecting a fault current value for MV faults fed from a substation, one approach has been to add a fault resistance of 1Ω to the source impedance at the bus feeding the fault. Such an approach is clearly very conservative. However, it may be appropriate, if the cost to society is not high and that the risk to members of the society living adjacent to such a substation is not unreasonable. Conservative assumptions may be used provided the impact on all affected people is consistently managed. For example, it is inconsistent to use conservative design criteria when determining mesh conductor spacing within a substation simply because it is easy to manage, and ignore the impact of voltage hazards on people living nearby the substation. The use of QRA recognises the statistical nature of these parameters and enables a consistent, justifiable design rationale.

4.4.3 Probability of coincidence

The value $P_{coincidence}$ is the probability that a person will be present and in contact with an item at the same time that the electrical potential of the item is affected by the flow of earth fault current. The contact characteristics are an integral component contributing to the real risk to an exposed person. However, non-electrical inputs such as demographics of human movement are often seen as being difficult to quantify. Nevertheless, the exposure probability whilst often awkward to deal with plays a very significant role in differentiating site risk profiles in real life.

Coincidence probability formulae for both individual and multiple fault/contact event scenarios are required in order to assess individual and societal (multiple fatality) risk exposures [1].

It is common for some people to be uncomfortable with the task of estimating the frequency and duration of contact in exposed locations. While the use of extremely conservative (or worst case) values is psychologically appealing to many, it is rarely appropriate and not validated by shock statistics. The determination of typical frequency and duration characteristics for a given exposure scenario may be undertaken in a number of ways. The following points provide some initial guidance regarding the determination fault/contact coincidence probability:

- When examining earth fault statistics it is worth considering that a certain percentage of fault events will give rise to an insignificant EPR, either by virtue of flowing directly through metallic paths (e.g. cable sheaths) or having line and fault resistance to sufficiently limit the current (e.g. line falling on the ground).
- The risk analysis should consider the hazard exposure of a representative individual and the possibility of a multiple fatality (termed Societal Risk) event occurring.
- When considering public exposure, it is usually sufficient to focus on the effect of an individual asset (e.g. impact of neutral voltage rise or soil voltage rise due to adjacent power installation).
- When considering utility staff exposure, the annual risk may be considered to consist of the cumulative exposure whilst undertaking work at a number of sites over the course of a year. It is considered reasonable to use typical exposure rates spread across a working year. Some work involves changing the permanent earthing configuration (e.g. workers within a substation replacing outdoor switchgear with grid conductors and crushed aggregate displaced), or consistently being positioned in a certain location (e.g. substation perimeter fence repair and replacement). It is not considered realistic for the permanent earthing configuration to be able to limit touch voltages when partially disturbed. Therefore, safety for such work processes is usually managed through the use of site or process specific safety measures (including the use of Personal Protective Equipment), or installation of local equipotential gradient control (e.g. at operating points within switchyards).

Section 6.6 provides a detailed description of the methods for calculating individual and societal (i.e. multiple fatality) fault/contact coincidence probability, as well as examining the sensitivity of the risk of fatality to variations in the contributing factors within the coincidence probability.

4.4.4 QRA process summary

Chapter 3 provided an introduction to risk analysis and assessment processes. This section describes the key elements involved in determining the risk of fatality due to indirect shock using a process that incorporates quantified risk analysis. While the process does not greatly differ from existing design processes, the various components of the QRA process provide a designer with a greater understanding of the real threat to life, and the ability to better focus mitigation strategies where they can be most effective in reducing the shock risk.

4.4.4.1 QRA process components

An overview of the various components of the quantified risk analysis and assessment process that may be incorporated within an earthing system design process are shown in Table 4.1 and briefly described in the following points.

Table 4.1 Quantified risk analysis process components

1	Power system configuration definition
2	Human exposure definition
3	Earth potential rise determination
4	Cumulative fatality probability determination
5	Sensitivity and criticality analysis
6	Risk mitigation assessment and justification

Component 1: Power system configuration definition

The information required to define the power system configuration includes:

- earth fault current delivery and return systems for each voltage level,
- fault frequency statistics (preferably within a station, as well on lines feeding or fed from the substation),
- earthing system configuration (including details of overhead earth (shield) wires and cable sheaths),
- configuration of surrounding metal installations (e.g. pipes, railways or conductive fences)
- soil resistivity, and
- protection system response characteristics (predicted or statistical).

Component 2: Human exposure definition

Observation points at which the risk profile will be determined are to be identified. These points are the locations at which staff or public are in contact with metalwork (both within a substation, and on any metalwork or utility service outside the station) or walking in areas of high voltage gradient (area immediately surrounding a station) and able to receive an electric shock during earth fault occurrences. Each point is characterized by:

- contact location,
- contact voltage (%EPR),
- contact configuration (e.g. hand to feet),
- series impedance (e.g. footwear),
- contact frequency and duration.

Component 3: Earth Potential Rise (EPR) determination

Voltage characteristic to which the person(s) will be exposed (magnitude and frequency) based upon the driving EPR generated in response to the range of earth fault events which create an EPR at the substation. The EPR may be defined by a probability density function or as a series of discrete values, each with a particular duration and likelihood probability [56][60].

Component 4: Cumulative fatality probability determination

The risk to which a person is exposed comprises the accumulation of risk associated with each contact scenario over the course of a year. The annual cumulative fatality probability for all expected fault events, for the exposure scenario being considered, may be calculated in a number of ways.

- A simple method that enables each parameter and step of the process to be easily observed, is as follows: for each fault instance, determine the associated fatality probability for the exposure scenario under consideration, and then summate each fatality probability to determine the total annual fatality probability for all expected fault events for the given exposure [58][59].
- Alternatively, the analysis may be undertaken using probabilistic distributions for each parameter and Monte Carlo analysis used to derive the final probability of fatality characteristic [29].

Component 5: Sensitivity and criticality analysis

Assess the sensitivity of output (fatality risk) to changes in the input, and uncertainty in defining critical parameters. Chapter 6 provides guidance regarding the uncertainty and criticality of the various factors contributing to the shock risk for an exposed person.

Component 6: Risk mitigation assessment and justification

Assessment of the risk profile using risk-cost-benefit analysis to justify mitigation where required (see Section 8.2).

4.4.4.2 Analysis Scope

Regarding the scope of the risk analysis, earthing related hazards are often the result of complex interactions of electrical power systems (both power sources and earthing systems), metallic plant (e.g. conveyors, pipelines, fences), and the earth in which they reside. The interactions are triggered by power system events associated with local power plant (e.g. earth fault on a tower or substation, earth fault current flowing along phase conductors to a remote fault location, or lightning strikes to exposed plant (e.g. conveyors transfer stations), electrical power lines or overhead shield wires). Although the triggering event may be local, the nature of the power system operation is such that the investigations need to look at the overall power system involved, as any earth fault current flow must return to its source(s) and may create hazardous voltages at locations remote from the point of fault. Therefore, the 'system wide' nature of the flow of possibly hazardous fault energy needs to be understood if the real hazard locations are to be identified and the most efficient, cost effective risk mitigation strategy implemented.

4.4.4.3 Implementing an iterative or staged design process

As for a traditional earthing design, it is normal practise to begin with simplified conservative assumptions and a standard design configuration that meets functional requirements. Often touch voltage/time curves are applied based upon 'first pass' conservative assumptions. If the design does not comply or the situation does not meet the boundary conditions applicable to the design curve, then a QRA may be applied [88][89].

The QRA provides a designer with the ability to more effectively assess the impact of all significant parameters, fine-tune additional mitigation measures and justify expenditure to reduce risk in areas that do not meet TOR requirements.

Within a QRA process it is usual to begin with conservative assumptions, and gradually fine-tune input parameters if the risk is found to be intolerable and mitigation costs excessive. As for any traditional design process care must be taken to appropriately consider future conditions.

4.4.5 Recent examples of quantified risk assessment applied to earthing system design

Quantified or probabilistic risk analysis and assessment has been explicitly incorporated within earthing system design processes in both technical publications and standards documents since the early 1960's, as outlined in Section 4.2. Appendix A provides an overview of the steps involved in quantifying earthing related risk, as presented in more recent technical publications and applied within design processes incorporated within standards documents.

4.5 Earthing System Design Safety Targets

As for the management of risks in general, when setting risk criteria for people exposed to voltage hazards due to the flow of earth fault current, the underlying principle is that people should not involuntarily be subject to a risk that is significant in relation to the background risk associated with what could be realistically expected to be 'normal movements'[2]. The tolerance of society to an imposed risk is also dependent upon the number and ages of the individuals exposed to the risk. The occurrence of a hazard (risk event) that 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 is usually undertaken both in terms of risk to the

[2] To assist the practitioner, 'normal behaviour' has been used in [1] to describe the reasonable behaviour of the average person, who is potentially exposed to the hazard. In calculating coincidence risk, the use of worst case or extreme behaviour is misleading.

segment of the society exposed to the risk and the risk to a 'typical' or 'representative' 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.
- **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 is most likely to be a determining factor in the tolerability of the risk associated with a hazard for areas where many people congregate.

Following the risk management principles outlined in Chapter 3, the setting of safety or risk tolerance guidelines for both risk exposure classes is described in the following sections. It is expected that an asset owner would implement commonly accepted risk mitigation measures as a base design consistent with the hierarchy of risk control. The impact of the resultant design is then analysed to assess the risk level to which staff and public would be exposed. 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, intermediate (or ALARP), or tolerable (or negligible)).

4.5.1 Individual risk

The TOR framework as commonly applied to assessing individual risk profiles relating to earthing related risk in the UK [7], Australia [1][52] and NZ [73][80] is described in Table 4.2.

Table 4.2 Individual risk assessment guidelines

Probability of Single Fatality (per annum)	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 ALARP region	Must minimise occurrence unless risk reduction is impractical, and costs are grossly disproportionate to the safety gained.
$\leq 10^{-6}$	Low or Tolerable risk	Risk generally tolerable, however, risk treatment may be applied if the cost is low and/or a normally expected practice.

4.5.2 Societal concerns and risks of multiple fatalities

Societal risk concerns the relationship between tolerable risk and the number of people dying from the realization of the hazard (during a single event). The criterion is based on the use of F-N curves, where F is the frequency at which the hazard may kill N or more people. Two examples of how the societal risk may be assessed is described as follows:

4.5.2.1 UK Application

The UK HSE recommended criterion for societal concerns when the hazard involves multiple fatalities [17] is based on the 'intolerable point' of 50 deaths, if the probability is more than one in five thousand and where the curve is extrapolated with a gradient of '-1'. In the assessment of tolerability of possible multiple fatalities, actual F-N estimated curves would be compared against this criterion curve.

4.5.2.2 Australian Application

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 [20][52]. The societal F-N risk limits are presented in Figure 4.2 that includes an example risk profile.

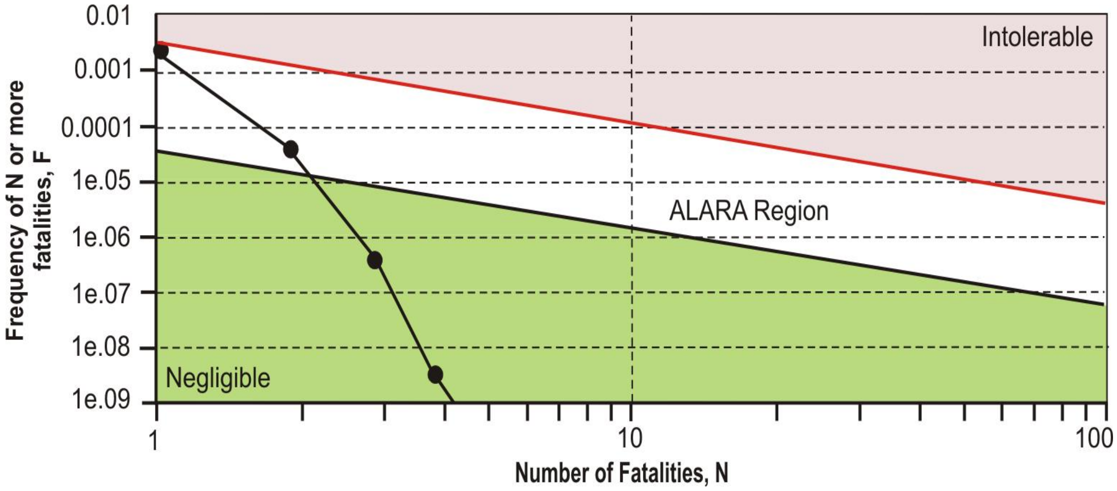


Figure 4.2 Societal risk assessment guidelines [1]

Application guidelines include the following [1]:

- Societal risk limits are independent of population size.
- Societal risk relates to any person(s) being affected, based on a typical or average expected exposure.
- Population is based on the number of people who could reasonably be expected to be in an exposed position at one time.
- Three exposure classes warranting separate analysis have been identified:
  - ✓ Uniform exposure - time independent, where people's movements are largely independent),
  - ✓ Gathered exposure - time dependent – where people's 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, theme parks, schools or cattle sale yards. People's exposure may be characterised as being of higher contact frequency, but over a limited time span, and
  - ✓ Generalised exposure (time dependent): In this scenario, the rate at which people make contact and fault events occur are both non-uniformly distributed, allowing for seasonal fault conditions as well as time of day/week exposure profile.

Experience in applying QRA to earthing related risk in Australia over a 15-year period has shown that while individual risk exposure has been found to be the factor governing the design requirements for managing earthing related risk in the vast majority of cases, societal risk is significant in instances such as those list under 'gathered' exposures. In these cases, a high number of people can be in an exposed position at one time warranting more stringent design targets [1][52].

Chapter 8 examines existing design processes and provides a generic earthing design process that incorporates risk quantification. Each step of the design process is discussed with focus upon the findings of the risk assessment analysis in Chapter 6.

4.6 Examples of Earthing System QRA

Following are simple examples of earthing related hazards being assessed using a risk-based approach. The intention of this section is to demonstrate at a high level the approach.

4.6.1 Individual risk calculation example

A jogger goes for a run every day of the week. Not far from home the jogger opens and closes a gate to access the forest trail. He opens and closes the same gate on his return. His total contact time with the gate is 10 seconds. The gate in question is in a metal fence located near a 275kV switching station. When a fault occurs at the switching station an Earth Potential Rise occurs and voltage gradients are created in the surrounding soil. These voltage gradients lead to a touch voltage at the jogger's gate.

The fault rate creating a significant touch voltage at the gate is conservatively estimated at once every 10 years and the primary clearing time is 100msec.

For a switching station not yet built the touch voltage the jogger will be exposed to can only be determined by estimation through calculation or computer modelling. For an existing switch station the touch voltage can be directly measured. In this example the touch voltage was measured to be 650V.

The measured touch voltage is compliant with the IEC 61936 target safety criteria used in the switching station design. For the 0.1s clearing time the applicable criteria is 669V.

This TB outlies a QRA method for determining the increased probability of fatality of the jogger per annum by calculating and then multiplying the probability of fibrillation and the probability of coincidence (that being the probability of a fault occurring coincident with the jogger being in the touch voltage situation).

For this example the probability of fibrillation, as discussed in Section 6.5, is calculated to be 0.05 [1][48], which equates to a 1 in 20 chance of fibrillation. The coincidence probability can be calculated as described in Section 6.6 and in this example is 1.17×10^{-5}. The increased probability of fatality is therefore 5.83×10^{-7}, which is below the commonly used negligible risk threshold of 10^{-6}. Consequently, no further risk treatment is necessary.

4.6.2 Societal risk calculation example

A new aquatic play centre is being designed to be built and opened before next summer. The many pumps, heaters, lights and other loads require a high voltage substation at the park. The electrical designer has presented a common earthed design between the MV and LV, and in this example the MV is not earth fault limited. The earthing system design has used IEC 61936 target safety criteria, which provides an allowable of 226V.

The highest touch voltage in the park is 200V, however, this touch voltage or very similar appears in a number of locations including the entry gate at each of the water slides and at 20 metres of hand rail where people queue for the rides. For this example the probability of fibrillation for a bare footed person is calculated to be 0.063 [1][48], which equates to a 1 in 16 chance of fibrillation.

To assess the individual risk, we follow the same procedure as Section 4.6.1. For 5 visits per year with 200 contacts of 3s duration per visit the probability of coincidence is 1.11×10^{-5}. When combined with the fibrillation probability of 0.063 the fatality probability is calculated to be 7.0×10^{-7}, which is again below the commonly applied negligible level of 10^{-6}.

To assess if the societal risk is also negligible we need to consider the exposure of all those present at the aquatic play centre. Patrons either come to the am or pm session which last 4 hours each. The average person has 100 contacts of 3s duration during their visit. As the centre is open half the year there are around 360 sessions per year. This data requires an assessment of the societal risk based on the non-uniform distribution of contacts and for this example the societal risk results are presented in Figure 4.3 following. As the result is above the commonly applied tolerable risk threshold further risk treatment is necessary before opening the facility.

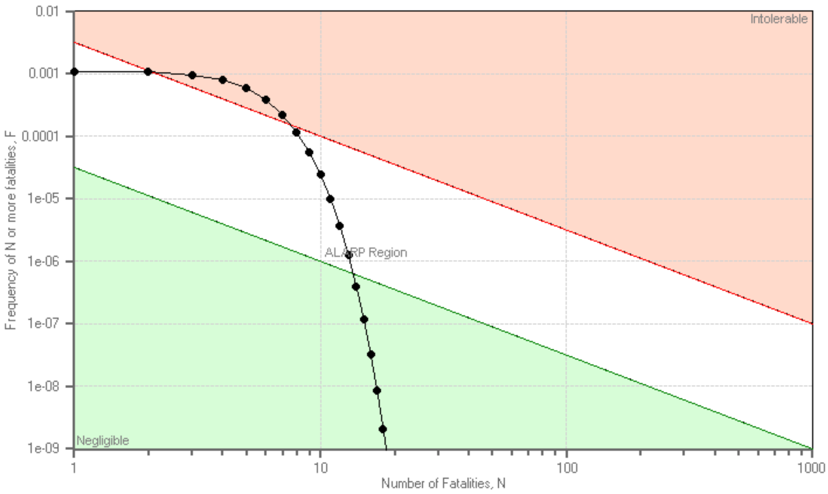


Figure 4.3 Societal risk example using [48]

5. Safety Earthing Philosophy

The key intent of an earthing system is to provide a return path for stray or erroneous currents within an AC power system. These currents are present within power systems, generated by load imbalances, inductive transfers (including electric and magnetic field effects at power and harmonic frequencies) and faults involving earth.

Earth faults usually represent the most hazardous circumstance for an earthing system, where step and touch voltages are produced between conductive structures associated with the substation earthing system, the surrounding soil and other conductive structures not directly associated with the earthing system under fault. Determining where these hazardous voltages appear and ensuring their magnitude is limited to acceptable levels is a key goal for a substation earthing system design.

5.1 Fundamental Design Requirements

The fundamental design requirements may be considered to fall into three key categories:

1. Provide safety for people (public & staff)
2. Protect equipment
3. Support operational security

These are discussed in more detail in the following sections.

The provision of a substation earthing design, beyond the philosophy outlined herein, should also meet the following specific objectives:

- Define tolerable touch and step voltage based on current paths through the body, resistivity of the body, duration of current flow, likelihood of faults and predicted contact rates and durations of the potentially exposed person.
- Assure that the function is available over the lifetime of the installation.
- Analyse earth potential rise based on actual current flow across impedance to ground. Fault locations both inside and outside a substation or ring main unit may need to be considered.
- Consider local touch and step voltage conditions as well as transferred potential. The requirements have to be met for people inside and outside the perimeter of an electrical installation as well as for transferred potential in remote locations and for reverse potential transfer into the substation area
- Provide a current path which is capable to carry maximum current over maximum time without mechanical damage (mechanical impact on the conductor, mechanical impact from current forces, temperature rise, corrosion, n-1). In order not to violate temperature limits of the conductor repeated current flows in a short sequence has to be considered.
- Define acceptable maximum earth potential rise with respect to the withstand capability of equipment. If earth potential rise is less than the withstand level of the equipment the requirements for this aspect are met.
- Worst case assumptions generally lead to a safe side solution but such designs may be unnecessarily onerous with respect to costs.

The typical design procedure includes:

- Data acquisition
- Design with respect to thermal and mechanical requirements
- Design to keep touch and step voltages requirements
- Verification of design based on calculations or measurements

Such designs can now be optimised through the application of quantified risk analysis which, in particular, allows different situations of varying exposure and hazard magnitudes to be compared using a single common measure.

Further guidance on earthing design including the risk based design is provided in Chapter 6.

5.1.1 Safety for people

All earthing system design approaches seek to limit the risk of a person being killed by exposure to a touch or step voltage. Traditional criteria for what is considered safe were justified principally by a history of acceptable outcome.

The approach to substation earthing systems outlined in this document differs from previously accepted philosophies for one of the following reasons:

- The hazards associated with an earthing system, specifically touch voltages, are quantifiable in terms of risk posed in the form of a probability of fatality. Whilst the means and precision of this approach may be academically contested for some time, the means to relatively compare hazardous situations of different circumstances has consistently proven its worth since its adoption, wherever it is adopted.
- The hazards produced by an earth fault can be produced throughout the associated earthing system. Different approaches to earthing system design which have been adopted worldwide to simplify decision making processes in this regard are not universal cure. Inappropriate application can still lead to unacceptable outcomes. Understanding how earthing works at a network level is the only proven means to achieving compliance in design and throughout the lifetime of an earthing system.
- No design is flawless. Earthing systems are safety systems and therefore need to be commissioned. Testing of earthing systems to prove compliance completes the requirements of a quantified risk approach.

5.1.2 Equipment protection

Another goal for substation earthing system design is to ensure that equipment is protected from the impact of currents flowing to earth during normal operations as well as during fault conditions. The resistive nature of current flowing in soil results in voltages being created on the soil around buried earthing system elements which are injecting current into the soil. These voltages in the soil are a fraction of the voltage on the buried elements which can be referred to as the earth potential rise, or EPR.

Instruments or plant connected to different parts of an earthing system or locations at different potential will be exposed to part of the earthing system EPR. EPR is the voltage created on an earthing system when current passes through it, either on its way to the neutral source, or in the case of most substations, returning to the neutral source through the earthing system from the soil. If equipment is exposed in this manner, either:

- the voltage is imposed across insulation, in which case the voltage exceeding the insulation level will result in damage, or
- the voltage is imposed across electrical/electronic components, in which case the sensitivity of the device will determine its fate, similar to the exposure of a person.

Most equipment is exposed to earthing related hazards across some component of its insulation, which is a much higher level than people can withstand, so people are normally the critical consideration. Equipment loss is normally treated as an economic loss, however, some circumstances where equipment loss leads directly to life threatening hazards should correspondingly be treated as a threat to life.

5.1.3 Operational security

The unnecessary loss of supply due to earth related events is also normally treated as an economic loss, but in rare circumstances it can also lead to life threatening hazards (such as loss of back-up power in a hospital). It is not uncommon for equipment damage to lead to the loss of supply but the loss of supply should be restricted to the affected circuit or circuits. Earthing systems should be designed to deal with events involving earth without causing unnecessary loss of supply by maloperation such as EPR or induction from a fault causing protection operation on other circuits.

5.2 Neutral Treatments

It has long been recognised that the magnitude and duration of earth faults have significant impact on the hazards posed by step and touch voltages. Worldwide, numerous approaches have been used to influence the nature of earth faults, primarily through different neutral treatments. The treatments range in variety from the use of solidly earthed neutrals, to complex impedance matching treatments which minimise the earth current under most fault conditions.

The choice of neutral treatment in most countries relates primarily to historical philosophies and the nature of network construction and operation [64][65][74]. Common methods of neutral treatment include:

- Isolated neutral

- Resonant earthing (Peterson coil) – maintain supply (for limited time e.g. 2 hours), or clear supply (within seconds), or use a combination of methods to ease identification of fault location (additional neutral earthing to pass current for a short period to detect fault location or clear the fault)
- Resonant earthing with additional residual current compensation
- Low impedance neutral grounding with resistors or reactors (including solid grounding)
- High impedance neutral grounding
- Earthing of faulted phase in substation (to give relief to fault location)
- Earthing of unfaulted phase to convert to double earth fault and cause fast disconnection

5.3 Reticulation Philosophies

The delivery and safe provision of power around the world has produced numerous different approaches to network construction and its associated earthing systems. These include:

- Single wire earth return
- 2 phase systems
- 3 phase systems balanced and unbalanced
- 3 phase systems with additional neutral conductor (multi grounded neutral)
- earth reticulation (shield wires, earth wires, optical earth wire (OPGW), under slung earth wires, counterpoise conductors)

All these approaches have significant impact on earthing design limitations and opportunities.

5.4 Interconnection Versus Segregation

One decision within earthing system design which is considered and debated worldwide is whether to combine or separate earthing systems associated with different system voltages common to a substation. This decision can also be impacted by the presence of lightning protection and telecommunications systems which may also decide to use separate or combined earthing as an option. Furthermore, metal pipe systems or railway tracks passing nearby or entering a substation have to be considered as they can defeat segregation.

Within distribution supply networks it is typical to see combinations of separated and common earthing designs used at distribution substations supplied from the same major substation (see Section 9.2). How earthing system policy decisions such as these impact the performance of major installations is a complex problem, particularly where positive outcomes for one site may prove negative for another.

It is complexities such as these which fostered the adoption of the quantified risk approach. Decisions which beneficially alter the hazards at one site but adversely impact other installations could not be effectively dealt with previously.

6. Probabilistic Analysis of Key Design Parameters

Whilst a range of earthing design processes and methods are used around the world, they all include a systematic approach to the identification and assessment of the design inputs. This section identifies the most common of these inputs and explores in turn what variation may be expected to occur, how it might be measured or determined, and what the possible affect could be on the outputs of the design firstly in terms of magnitude of the shock hazard and secondly the risk of fatality.

Variability can come in many forms, for example soil electrical resistivity can have variability because of measurement error, geographical differences between measured areas and the target site, seasonal changes leading to freeze/thaw, changes in rain fall affecting upper layers, seasonal fluctuations leading to big changes in the water table, or even ground dewatering via bore hole pumps. Some are variations that can be measured or otherwise estimated, others are actually the variation due to inaccuracy and/or errors.

Traditional methods tend to include a single or small range of numbers for each input. The methods presented in this brochure allow ranges to be used for inputs, leading to a better representation of the expected outcomes. In each of the following sections we have described the key considerations and approach to be able to assess the effect of the variability and also to present the range of common affect.

The following parameters are investigated in this chapter:

1. Earth fault current magnitude and duration
2. Return current distribution
3. Soil electrical resistivity
4. Earth fault voltage distribution
5. Body Current and Voltage Withstand Criteria
6. Fault Frequency and Person Contact Frequency and Durations

6.1 Earth Fault Current Magnitude and Duration

6.1.1 Introduction

For high voltage (HV) power systems, faults due to insulation breakdown are inevitable. Typical causes of faults include insulation breakdown (e.g. due to contamination of external insulation, insulation material degradation, lightning strikes, system overvoltages, asset aging), downed conductor (e.g. due to equipment failure, support structure movement, vandalism) and system or operator error related mal-operations as well. Technologies have advanced in many areas to reduce the likelihood of power system faults but unfortunately, faults can never be disregarded.

The most direct and perceptible consequence of faults is the dramatically elevated magnitudes of current, comparing to those under normal operations. The high currents will in turn lead to voltages being impressed upon metalwork and soil in the vicinity of the fault location, or induced in parallel metalwork (e.g. pipelines), as well as creating significant heat and mechanical forces in the current conducting parts of the system. For these reasons, power system fault analyses are crucial in determining the magnitude of electrical shock risk under earth fault conditions, the adequacy of equipment, as well as guiding protection relay configurations and settings.

Earth fault current may flow directly from a single phase to earth, between two phases and earth (i.e. L-L-G) either locally or as a cross country fault. A cross country fault typically occurs when an initial single phase earth fault causes the unfaulted phases to increase in voltage. Consequently, the overvoltage condition stresses insulation at other locations and can cause an insulation breakdown on a separate phase at another location. Networks with isolated or compensated neutral earthing are most susceptible to cross country faults, which are often of significant magnitude.

When determining the risk profile of a given power system asset it is important to determine the magnitude of earth fault current flowing for any fault case that will give rise to an earth potential rise (EPR) at the asset. Thus, for a substation it is important to assess current magnitude and distribution for an earth fault both on the primary side of the station as well as faults within the secondary network fed via the substation under investigation. This section of the brochure focuses on the established theories and practices in carrying out fault calculations and Section 6.2 will specifically address the part of analysis relevant to current distribution in earthing systems.

6.1.2 Fault calculation methods

In order to understand the performance of an earthing system both the magnitude and distribution of the fault current in the various parts of the power system must be known. In the past symmetrical components were used requiring a number of simplifying assumptions, however, modern software tools use fundamental electromagnetic equations to solve the effect of all couplings.

Earth fault magnitude may be calculated using techniques provided in IEC 60909 [67] and IEEE 399 [68] standards (refer to Knight [66] for comparison analysis). Both methods usually calculate maximum currents, and both have some simplifications, although the answers are tolerably close in the majority of cases. In some circumstances, a designer may need to consider actual local conditions such as fault resistance. Some of the assumptions that are often made when doing fault current studies may not be appropriate to earth fault safety analysis. These include:

- No change is allowed in the type of short circuit, e.g. a line-to-earth short circuit remains line-to-earth during the time of short circuit
- No change in the network for the duration of the short circuit
- Arc resistances and any other fault loop impedances (including earth grid impedance) are ignored
- All line capacitances and shunt admittances and non-rotating loads, except those of zero-sequence system, are neglected

However, for earthing studies it is important to consider impedances at the point of fault as well as any changes in magnitude due to circuit isolation due to protection operation or changes in earth fault type (e.g. L-G evolving into a L-L-G fault)

When calculating the value of earth fault current at a location the initial offset is considered. It is normal practise not to consider the current peak value but to take into consideration the rms value of the initial short circuit fault current. See Figure 6.1.1 following.

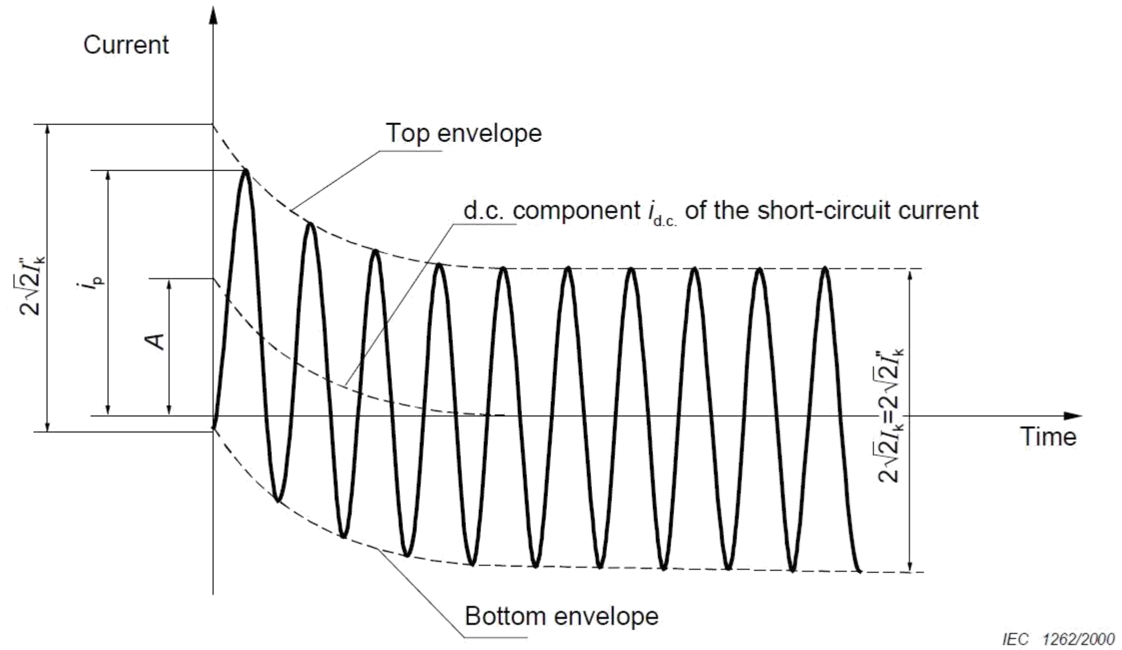


Figure 6.1.1 A schematic diagram of short-circuit current of a far-from-generator short circuit with constant AC component (IEC 60909-0:2001 [67])

In Figure 6.1.1 key characteristics of short-circuit currents are illustrated using a far-from-generator short circuit example, where:

I_k'' = initial symmetrical short-circuit current,

i_p = peak short-circuit current,

I_k = steady-state short-circuit current,

$i_{d.c.}$ = DC component of short-circuit current, and

A = initial value of the DC component $i_{d.c.}$.

The document focuses on the calculation of the initial symmetrical short-circuit current (I'_k).

The work by Dalziel and others was based on rms symmetrical current in determining the tolerable body current [27]. Thus, a calculation is needed to convert the actual asymmetrical fault current to the rms symmetrical fault current upon which the shock equations are based. IEEE 80 [27] recommends that the following 'decrement' or correction factor be used to scale the fault current to derive an equivalent 'energy' when determining a value of EPR for human safety hazard assessment. Equation 6.1.1allows for the D.C. offset but makes no allowance for reduction of the A.C. value due to machine characteristics.

Df = Symmetrical decrement or correction factor

$$= \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2.t_f}{T_a}}\right)} \qquad \text{Equation 6.1.1}$$

where

Ta ≈ Equivalent system sub-transient time constant

= X/(ωR) (secs)

tf = Fault duration (secs)

ω = Angular rotation – 2πf

f = Frequency (Hz)]

X&R = System transient impedance components.

This equation conservatively assumes:

- maximum D.C. offset,
- that sub-transient impedances only contribute, and
- that the ac component of the fault current does not decay.

Table 6.1.1 provides decrement factor results for 50Hz earth fault conditions and a range of X/R ratios:

Table 6.1.1: Decrement factor D_f for various X/R ratios at 50Hz [27]

Fault Duration	**Decrement Factor D_f**			
t_f (secs)	$X/R = 10$	$X/R = 20$	$X/R = 30$	$X/R = 40$
0.10	1.148	1.269	1.355	1.417
0.20	1.077	1.148	1.213	1.269
0.30	1.052	1.101	1.148	1.192
0.40	1.039	1.077	1.113	1.148
0.50	1.031	1.062	1.091	1.120
0.75	1.021	1.042	1.062	1.082
1.00	1.016	1.031	1.047	1.062

The fault current has an initial asymmetry or D.C. offset determined by the initial point on wave. Higher fault currents near generation or rotating machines may have a reducing rms value due to the machine characteristics. It is normal to ignore the reduction in the initial rms value for earthing design. When the fault duration is less than 0.5 seconds, and particularly with high X/R system impedance ratios, the rms value of current used in determining EPR safety criteria and telecommunications coordination should be increased.

From Table 5.5 it can be seen that for very fast clearing times (≤ 0.1 secs) a factor of 40% is calculated with X/R = 40. For clearing times of 100 milliseconds or less the phase at which the fault is initiated has a significant impact on the decrement factor. The decrement factor for these clearing times can significantly increase as the transient dominates the earth fault current. It is recommended that either a transient study be completed in these instances to determine the decrement factor or the decrement factor be adjusted to compensate for the transient dominance by a factor of up to 50% [86].

6.1.3 Fault scenarios

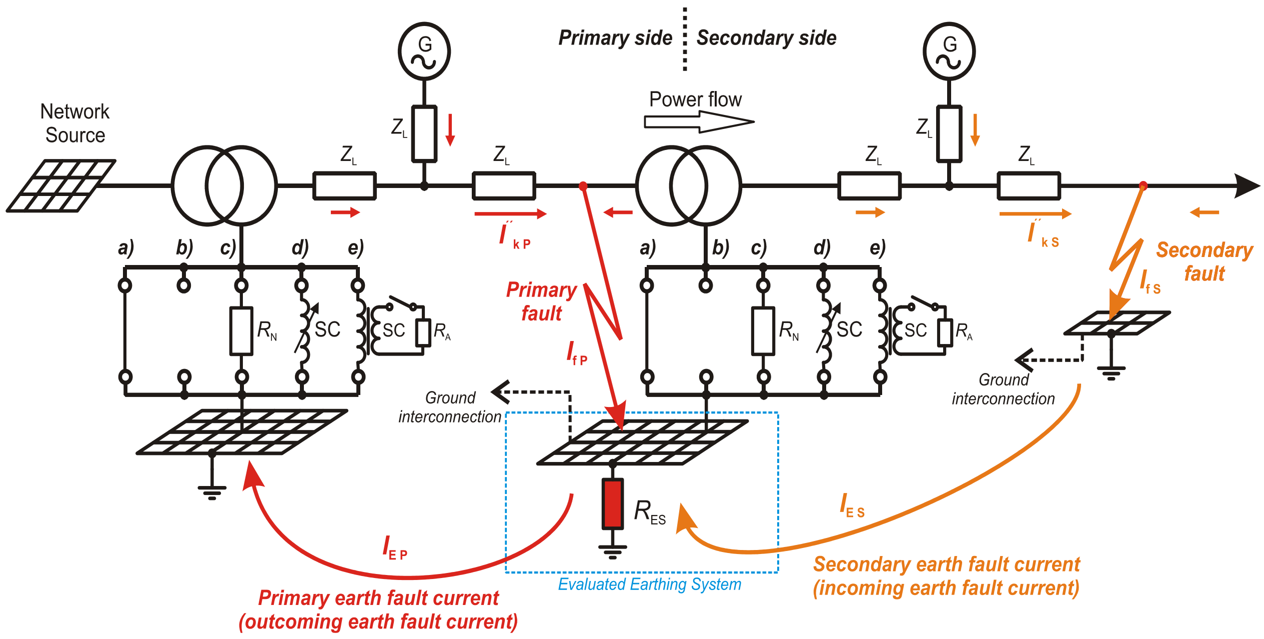


Figure 6.1.2 Typical fault scenarios for consideration

Primary fault at a HV substation – with low station resistance the current magnitude is dependent upon source impedance(s), connected lines, and generation capacity. Often use ‘future maximum’ system conditions.

Secondary faults fed from a HV substation – the EPR at the source station is dependent upon: transformer zero sequence impedance, line impedance (including earth wire/cable sheath influence), and resistance at the point of fault. Cross-country faults occur on compensated systems when the increase in voltage on unfaulted phases during an earth fault leads to a breakdown in insulation on the initially unfaulted phase. The magnitude of a cross country fault current can be very large as it is not limited by the system compensation.

6.1.4 Probability characteristics of fault current amplitude

It is worth pointing out that almost all existing earthing standards choose to err on the conservative side, which means the maximum values of earth fault currents are used for safety assessments. However, the magnitudes of short-circuit currents depend on various parameters including fault locations, network configurations, instantaneous value of voltage at the moment of fault ignition, generators in operation, number of transformers grounded and load/demand states of the network. Whilst the above is true for both transmission and distribution earth faults there are significant differences in the relative importance of the various factors.

Figure 6.1.3 was generated to illustrate the distributions of earth return current values, for primary earth faults at two (2) different transmission substations, on the basis of the transmission network load condition [82]. Evidently, earth return current does depend on the network load condition to a degree, however, such variation may not yield a significant EPR variation.

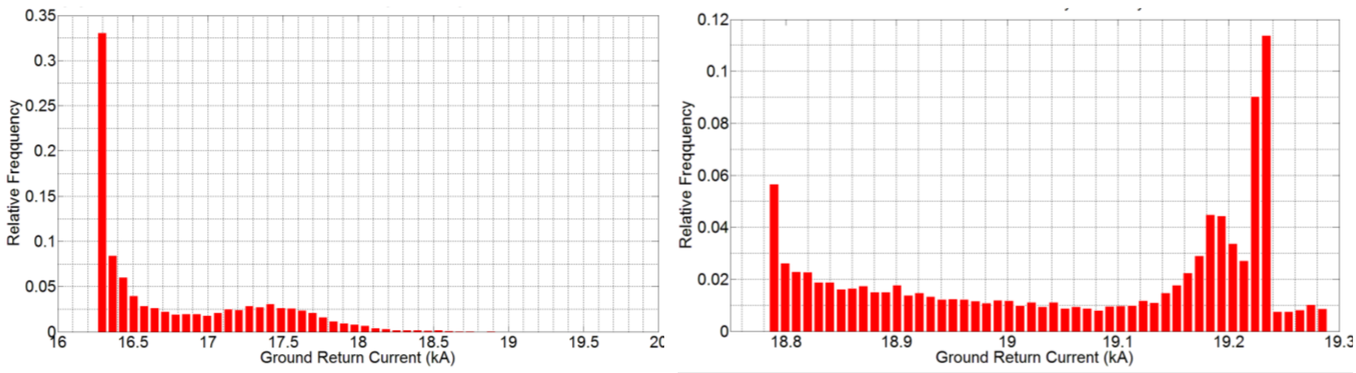


Figure 6.1.3 Distribution of earth return current values based on UK transmission network load condition [82]

Example: Figure 6.1.4 illustrates the range of earth fault current magnitudes measured at a 33/11kV substation, and correlated by calculation, for an MV system [60]. It may be seen that 90% of the cases show currents that are less than 20% of a typical design earth fault current. The ‘1Ω bus fault’ design earth fault current is the earth fault current that is calculated by applying a 1Ω fault resistance to the secondary bus of a substation.

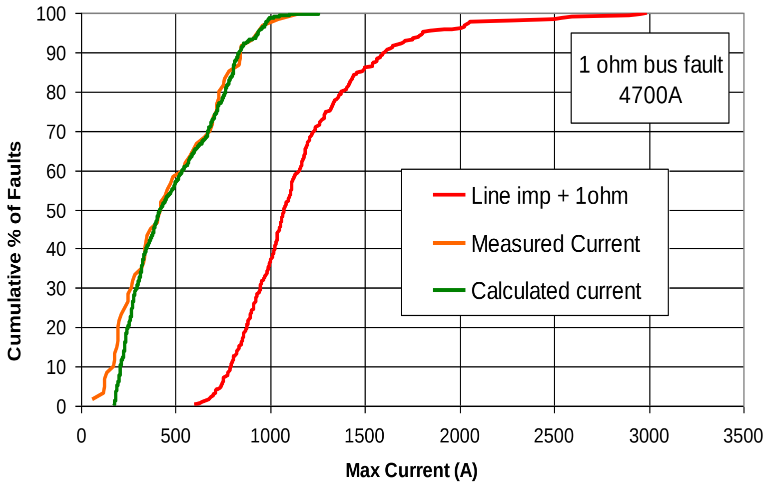


Figure 6.1.4 MV system earth fault magnitude [60]

Another overly conservative design earth fault current that is sometimes included in design specifications is that of the busbar fault rating. It would be extremely rare for the actual maximum possible earth fault current to ever reach such a current value, and the primary protection scheme will clear high current earth fault events much faster than the fault duration often specified.

6.1.5 Probability characteristics of fault clearance duration

Modern power systems employ sophisticated protection systems to detect and isolate faults. Power systems rely greatly on the reliable operation of protection systems, for instance to manage the stability of power system, the extent of damages to both faulted and healthy plant, loss of supply, as well as personnel safety. Transmission network fault clearing times are usually of very short duration (<0.2secs) while distribution networks often have a greater range of clearing times.

Example 1: Figure 6.1.5 and 6.1.6 show the range and proportion of earth fault clearing times recorded for the Portuguese HV and MV networks respectively.

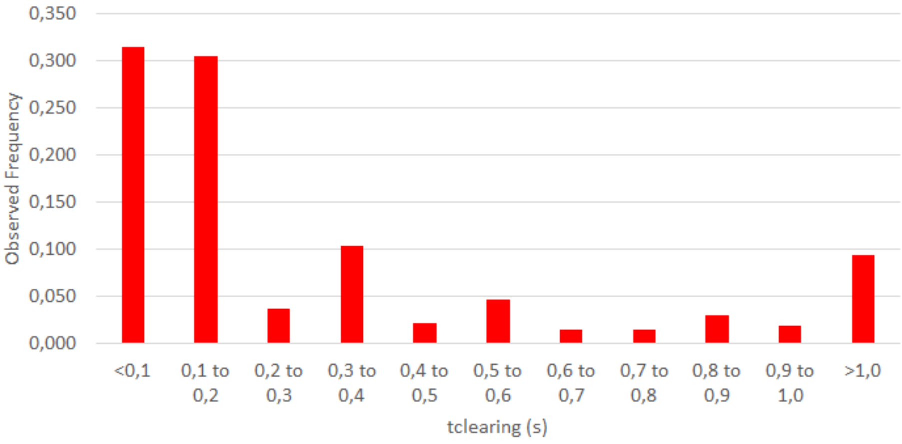


Figure 6.1.5 HV Earth fault clearing time data from the Portugese network[3]

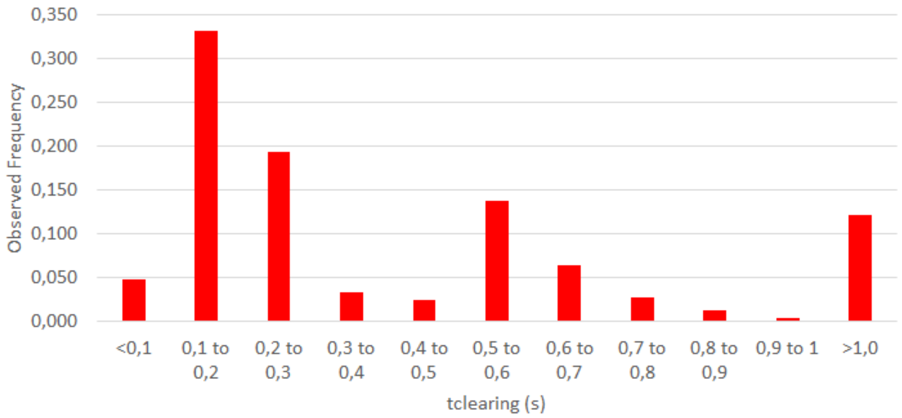


Figure 6.1.6 MV Earth fault clearing time data from the Portuguese network[3]

Example 2: Figure 6.1.7 shows a distribution of recorded fault clearance times for both the 400 and 275kV systems in the UK over a 10-year period. The figure indicates that the spread of fault duration is quite small and that the target values have been achieved in over 90% of cases.

[3] Data provided by EDP Distribuição

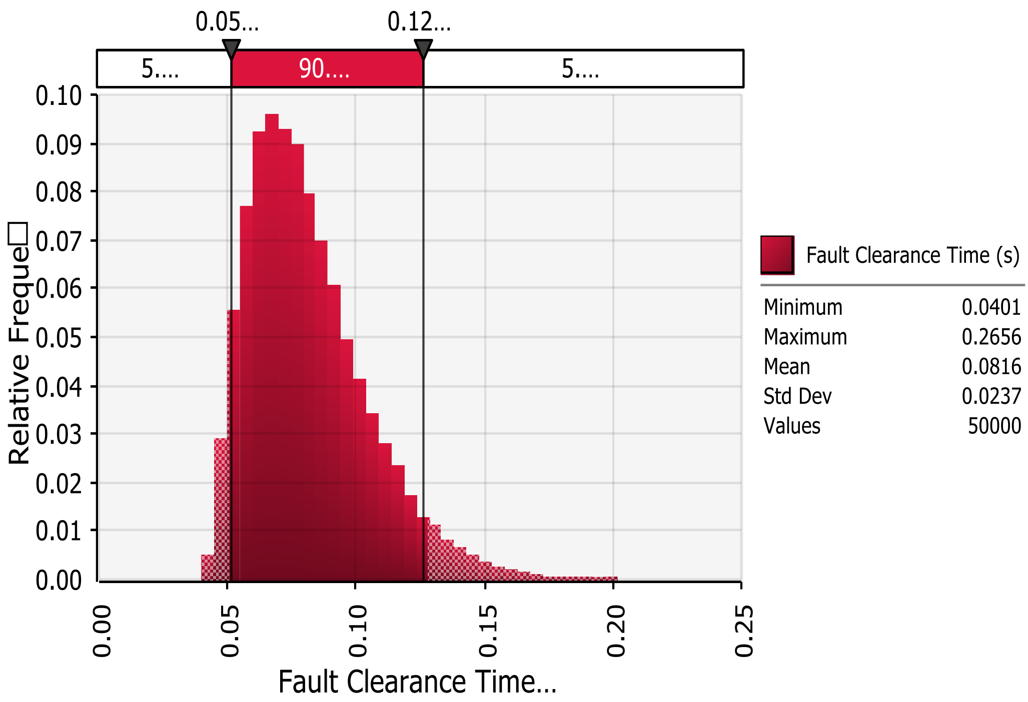


Figure 6.1.7 Distribution of recorded fault clearance times on a transmission network over a 10-year period[4]

The duration of an electric shock affects both the consequence, in terms of probability of fibrillation, and the likelihood, in terms of the probability of coincidence. Therefore, the distribution of fault clearance times should be accounted for carefully when the overall safety from earthing related hazards is assessed.

6.1.6 Impact on risk

Fault current that flows to earth results in an EPR on metalwork and soil within an affected region. This voltage rise may create step, touch and transfer voltage hazards at locations where utility staff or the public could receive an electric shock. Section 6.4 further discusses the impact of soil voltage and associated hazards. The impact of fault current magnitude and duration upon the risk to which a person might be exposed is shown in the following examples taken from the case studies in Section 9.

6.1.6.1 Transmission Substation Risk Response

Taking the 400kV fault scenario from Section 9.1 as an example (see Figure 6.1.8), a factor of 2 change in the fault current (and hence EPR) led to changes in risk of fatality of some 9 orders of magnitude (for the mesh touch voltage contact scenario investigated).

[4] Data provided by UK National Grid

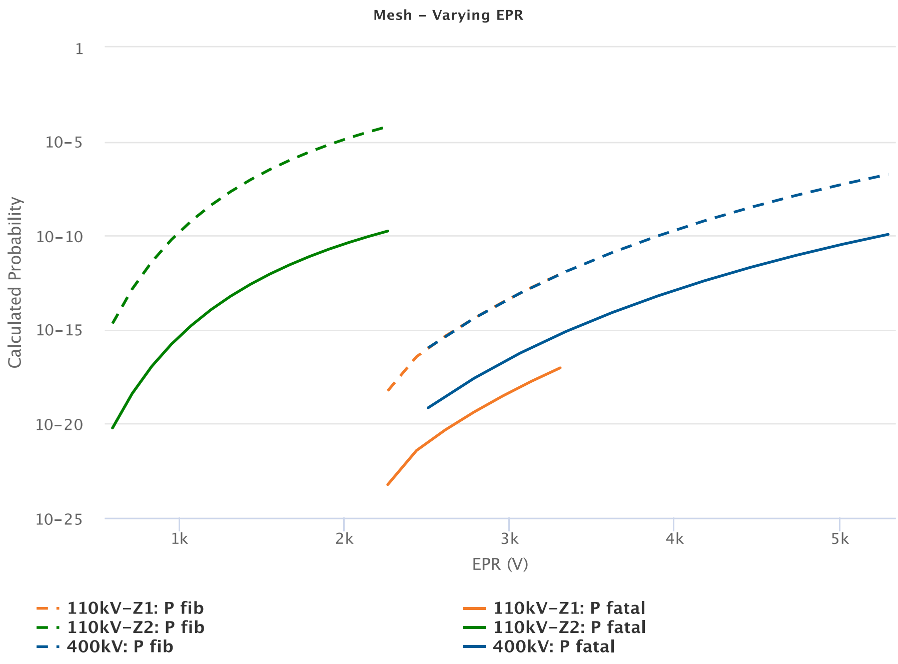


Figure 6.1.8 EPR variation impact on calculated risk

6.1.6.2 Distribution Substation Risk Response

For the specific system configuration examined in the distribution case study in Chapter 9.2 the variation in probability of fatality as earth fault current magnitude and duration vary is shown in Figures 6.1.9 and 6.1.10 respectively, for a range of neutral point earthing configurations.

The following graph shows that the risk of fatality reduces significantly with reduction in earth fault current magnitude but increases asymptotically with increases in current.

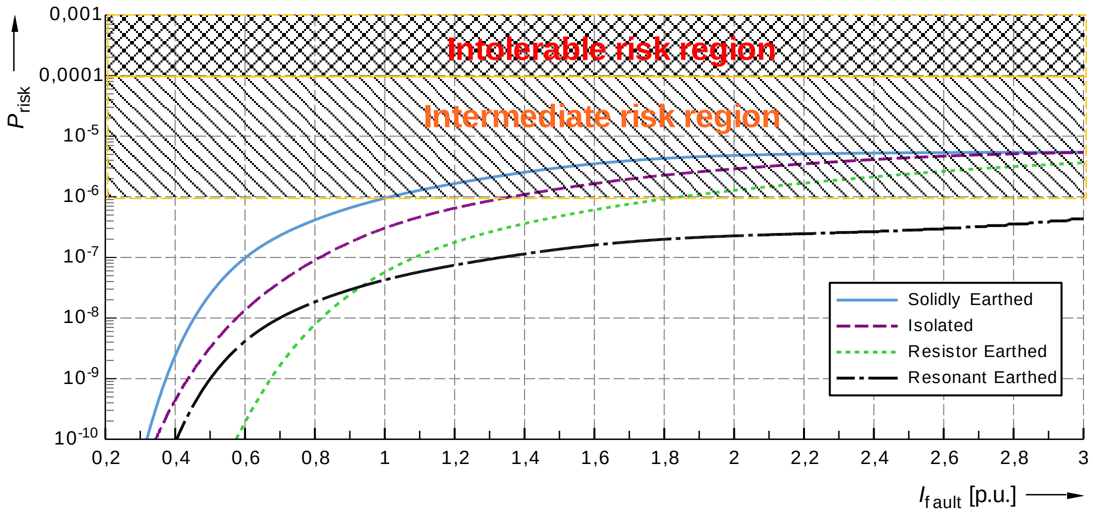


Figure 6.1.9 Probability of fatality response to variations in earth fault current magnitude

The following graph shows that the risk of fatality again reduces significantly with reduction in earth fault current duration and increases asymptotically with increases in duration beyond the base value.

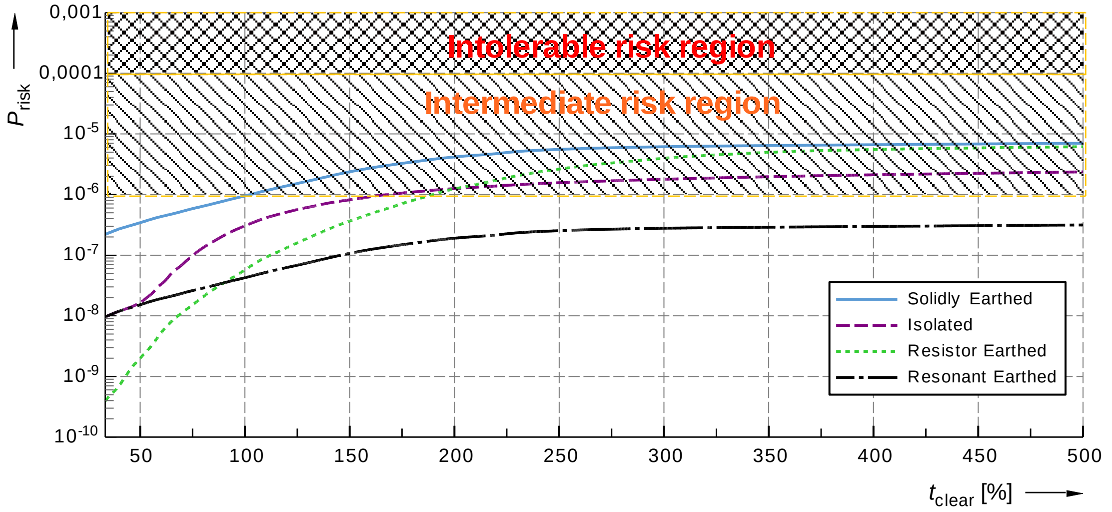


Figure 6.1.10 Probability of fatality response to variations in earth fault current duration

The foregoing examples relate to the particular system configuration assumptions and calculation methods used in the case studies.

6.2 Return Current Distributions

6.2.1 Introduction

From an earthing perspective, only the portion of fault current that returns to the remote source(s) via the buried earthing components and the soil (rather than the total fault current) is responsible for the earth potential rise (EPR). This portion of current is termed 'current to earth' (I_E) in EN 50522 and other standards also entitle it as earth current or earth return current.

Building on the previous section on fault current calculation, this section focuses on earth return current I_E , calculation methods and probabilistic features.

6.2.2 Earth return current distribution determination

EN50522 [6] suggests the parameters of various components of the power system used in determining the division and distribution of fault current, which implies a simplified method of calculating I_E . In Figure 6.2.1, $3I_0$ is the three times zero sequence current of the line, I_N is the current via neutral earthing of the transformer, I_F is the earth fault current, I_{RS} is the current to earth via the earthing installations local to the fault, and Z_∞ is the chain impedance (earth wire and tower footing ladder network) of the infinite overhead line.

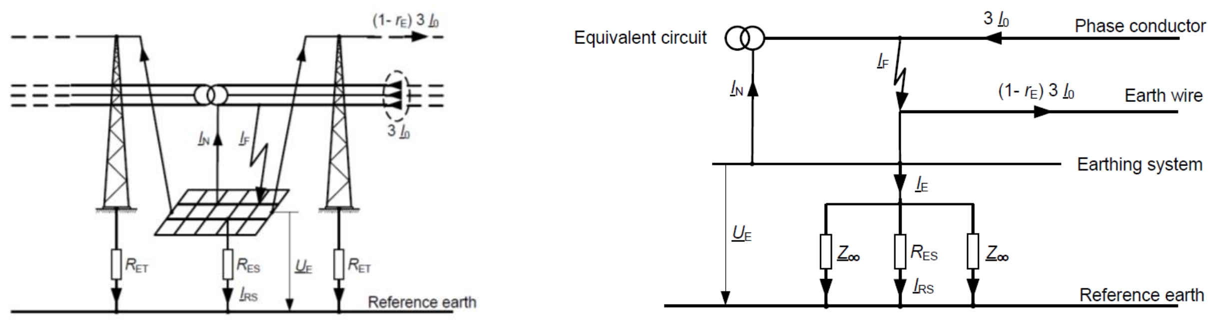


Figure 6.2.1 Currents, voltages and resistances for an earth fault [6]

It is obvious that the earth potential rise (in volts) should be calculated as the product of I_{RS} and R_{ES}, i.e. the resistance of the local earthing system to remote earth. This approach inherits the shortcoming of low accuracy when dealing with earthing systems of large dimensions because of the mutual coupling between the substation earth mat and other conductive items (including the first couple of OHL towers). Since it is not practical to represent this phenomenon with a lumped parameter circuit model, determining the grid current is either estimated using specialised earthing analytical software or measured using modern testing methods. In Figure 6.2.1, r_E is namely the reduction factor of the overhead line [6]. As for conductive mutual coupling, determination of current distribution in overhead earth wires and cable sheaths is commonly achieved by estimation using specialised earthing analytical software or measurement using modern testing methods [30][33][34][35].

Many fault current calculation packages do not model in detail the coupling into metallic return paths such as cable sheaths and overhead line shield wires. The use of typical values of coupling or shielding factors may be used, but is susceptible to errors due to ignoring soil resistivity variations and the direct conductive effect of nearby low earthing impedance sites. IEC 60909-3:2009 [67] provides not only the above theoretical explanation but also worked examples, ranging from simplistic 'infinite' long OHL scenarios to more complex cases comprising of three single-core cables, which are also covered in far greater details elsewhere [71].

6.2.3 Probability characteristics of the Local Earth Current

When following typical conventional earthing system procedures (e.g. IEEE-80 guide [27]) the earth return current values for earthing design were often taken as 'the largest value of grid current will result in the most hazardous condition', which implies that values of earth return current are not fixed and may exhibit probabilistic characteristics. A QRA investigation will usually assume source impedances based upon maximum generating capacity but will examine variations in current dissipated in the local earthing system and resultant EPR magnitude due to the range of possible fault locations (i.e. not just a 'worst case' fault consideration).

The two sections covering earth fault current effects reinforce the fact that the risk profile is strongly dependent upon the fault current magnitude flowing through the local earthing system. The impact has been demonstrated by direct measurement [60] and calculation [92]. Moreover, a 'first pass worst case' calculation may significantly overestimate the risk profile of an asset.

6.3 Soil Electrical Resistivity

6.3.1 Introduction

This section describes the key considerations regarding soil electrical resistivity with respect to earthing systems and their design and performance.

A challenging part of soil electrical resistivity analysis is that there are many factors which influence electrical resistivity that are not within the control of the designer. These factors can influence electrical soil resistivity by orders of magnitude in some cases. Earthing systems are installed in all different types of soil and geological contexts. It is well known that the performance of the earth grid from an earth potential rise, touch and step voltage perspective can be significantly influenced by local variations in soil resistivity along with seasonal variations in temperature, moisture, salinity and other variations. Thus, an understanding of the electrical characteristics of the soil where the earth grid will be installed is an important part in producing an earthing design.

6.3.2 Key sources of information

Several key sources of information can be drawn upon to understand the soil electrical resistivity. Electrical resistivity testing surveys such as the Wenner and Schlumberger methods can provide a one-dimensional cross section of the soil for any single sounding. Acquiring multiple arrays in multiple directions extending sufficient distance can provide a geological context of the electrical resistivity. Anisotropy in the soil can be detected with proper testing techniques to detect whether the soil contains any significant vertical or horizontal variations.

Best practices in acquiring sufficient soil electrical resistivity data can be complimented with reviewing soil borehole logs to evaluate surface variations of shallow layers, geological maps of the area for macro variations in geological structures (thus electrical resistivity variations) among other sources.

6.3.3. Common key and quantifiable parameters

The electrical property of soil resistivity is a fundamental parameter used in the evaluation of the performance of an earthing system. Current methods in use range from assuming some particular soil resistivity value, measuring and interpreting soil resistivity using Wenner, Schlumberger or similar method, to interpreting complex three dimensional geotechnical surveys.

Almost all the methods in common use simplify the measurements or assumptions when examining electrodes by assuming either homogeneous or horizontal multi-layer soil models. The influence of the physical geology of the site, and the surrounding geology and metallic facilities or interconnected earthing will also influence the risk profile of the site.

The following table shows certain key parameters which influence the general electrical performance of the soil and further provides a summary of their effect.

Table 6.3.1: Key parameters influencing soil resistivity [27]

Parameter	Key Effect	Typical Variability
Soil Components	Affects most of the below factors	Large variation although not usually across small areas
Moisture Content	Affects electrical resistivity through electrolyte performance	Large increase in resistivity below 15% moisture content but this commonly only occurs in surface layers
Salt Content	Affects electrical resistivity through electrolyte performance	Large increase in resistivity below 15% moisture content but this commonly only occurs in surface layers
Temperature	Affects electrical resistivity through diffusion velocity performance	Freezing of soil increases electrical resistivity by orders of magnitude of the surface layers. Drying out of soil can increase electrical resistivity of the surface layers,
Water table	Affects electrical resistivity through electrolyte performance	Changes in tides, seasonal water table changes or changes in surrounding water table due industrial processes can significantly influence the results.

Since the grid and electrodes which make up an earthing system can be buried very near the surface, the variability of the key parameters can significantly affect the performance of the grounding system as the seasons change. Both freeze-thaw and rainy-drought conditions can significantly affect the electrical resistivity of the surface layers over the course of a season and from one year to the next. Industrial processes such as water table storage or mining nearby can significantly affect the performance of the earthing system.

6.3.4 Influence of buried structures

The performance of an earth grid also depends on the footprint of the site and the proximity to other buried metallic structures. These structures include fences, pipelines, distribution neutrals, transmission tower grounds, industrial pipes, cathodic protection systems, residential water pipes are just a few examples and can significantly affect the performance of the earthing system. The physical encroachment of buried metallic structures does not directly affect the soil electrical resistivity. However, the presence of these systems whether directly connected, electromagnetically induced or conductively coupled through the soil can significantly influence the ability to acquire electrical resistivity survey data for a site. Furthermore, the presence of these structures affects the performance of the site by providing alternative paths for current to return to the source. As the current takes alternative paths, electrical earthing hazards can be present under fault or steady state conditions.

If testing is performed near buried metallic structures including buried earth grids, significant errors will be introduced in the readings. For sites where an existing earth grid is being evaluated, the proximity effects cannot be avoided. In some cases, it is possible to estimate and correct for the influence of the buried structures influencing the test readings. However, often in situations such as dense urban environments, simple test methods cannot provide test data free of the influence of buried metallic structures. Thus, not only are advanced testing techniques required to acquire meaningful test data, interpretation of results requires significant expertise and engineering judgement. The development appropriate electrical resistivity models for use in earthing design and evaluations involves evaluating reasonable boundary conditions based on consideration of all available information.

6.3.5 Influence on design process

From a design and evaluation perspective, an understanding of the soil electrical resistivity of the area where the earthing grid is to be located or is already installed is a key input in evaluating the performance of the earthing grid under earth fault conditions. The performance of the earthing grid from a safety perspective will be directly influenced by the soil conditions at the site. However, there are multiple physical variables to consider in the design process which will influence the soil electrical performance. The following figure shows a high-level summary of the key inputs to consider from a design perspective when evaluating the soil whose individual variations will result in changes in the grid performance.

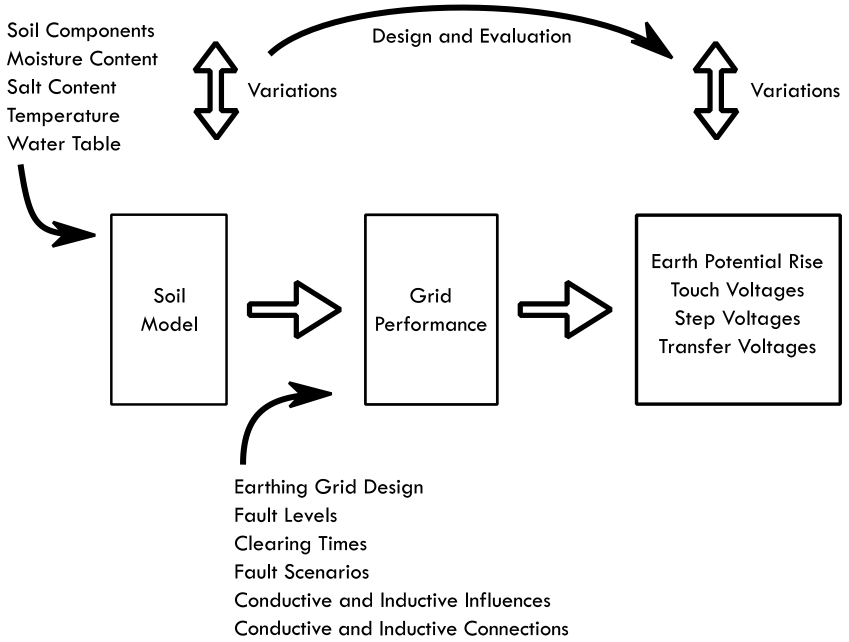


Figure 6.3.1: Overview of key inputs relating to soil parameters

Variations in the key inputs to the evaluation and interpretation of the soil resistivity will follow through to variations in the outcome of the computation of risk profiles for the site.

Even when a sufficient understanding of soil electrical resistivity of the site is developed with the above considerations, further variations in the soil electrical resistivity are imposed due to seasonal environmental variations. These are the parameters not in the control of the designer which require significant engineering judgment in interpreting their effects on the overall risk profile and producing appropriately robust designs.

For example, drying out of the soil can drive out moisture from the top layers which can change the surface resistivity by orders of magnitude in either direction. Freezing of the surface layers of soil can increase the surface resistivity by orders of magnitude up to the frost depth. Mining sites can use the soil to store water for processes which can significantly vary water tables in proximity to the electrical supply substation earth grids. Seasonal variations in the water table occur over the life of the earthing grid which can affect surface and mid-range layers of the soil electrical resistivity. These and other factors outside the control of the earthing engineer need to be accounted for in the evaluation of the site and result in a range of parameters to be considered for the quantified risk analysis.

6.3.6 Influence on risk

Even the best understanding of the electrical resistivity of the area is subject to one or more of these external factors which cause variations in the either the surface layers, mid layers or even deep layers. It follows that responsible evaluation and design of the earth grid, from a safety perspective, requires consideration of the external factors influencing soil electrical resistivity, seasonally and over time. Identifying the parameters that are significant over the lifetime of the asset is not a trivial task. However, the experienced earthing engineer can develop representative boundary conditions to ensure the risk profile for the entire site, over the life of the asset, is managed.

Current best practice draws from multiple information sources to enable a comprehensive evaluation of the soil electrical resistivity to be made where the earthing systems will be or is already installed. Key to the design and evaluation is consideration of all the seasonal variations in the soil parameters. The earthing engineer is responsible for developing sufficient boundary conditions in an earthing design to manage the variations in electrical resistivity. These boundary conditions follow through to the risk profiles for the site discussed in this brochure.

Three case studies follow which examine the impact of soil resistivity on shock risk profiles:

Case 1: Isolated grid in homogenous soil resistivity

Case 2: Distribution system with interconnected multi-grounded neutral network

Case 3: Soil resistivity testing

6.3.6.1 Case 1: Isolated Grid in Homogeneous Soil

In the first case, the earthing system analysis required is straight forward as there are no earthing paths other than the soil in which the isolated grid is located. A simple grid is buried at 0.5m with perimeter electrodes driven to 10m deep in 50Ωm homogeneous soil. For a given earth fault level, the EPR and maximum touch voltage can be determined reasonably well by empirical or analytical techniques. In this instance the base case has an earth fault level (EFL) of 1kA, giving an EPR of 1kV and a maximum touch voltage of 55% of EPR. The clearing time for a 1kA earth fault is 0.35seconds.

The key variations for consideration in this case are soil resistivity (assumed to be homogeneous), EFL and clearing time. Whilst EFL and clearing time are more rigorously covered in Section 6.1and 6.2 they are included in Case 1 for comparison to the effect of resistivity variation. The following table presents the effect of variations in soil resistivity, earth fault level and protection clearing time on risk of fibrillation. To determine the actual fatality risk the risk of fibrillation must be multiplied by the risk of coincidence, which is contact case specific and unaffected directly by changes in the soil resistivity.

Table 6.3.2: Individual fibrillation probability dependence on soil resistivity, EPR and protection clearing time.

Variable	Value	Significant Effect	Risk ($\boldsymbol{P_{fib}}$)
Electrical Resistivity	25Ωm	EPR	5.07E-08
Electrical Resistivity	50Ωm	EPR	1.08E-06
Electrical Resistivity	100Ωm	EPR	6.66E-06
EFL	800A	EPR	3.28E-07
EFL	1000A	EPR	1.08E-06
EFL	1200A	EPR	2.91E-06
tc	0.1s	Allowable	3.62E-07
tc	0.2s	Allowable	1.08E-06
tc	0.4s	Allowable	4.33E-06

The impact of changes in homogenous soil resistivity, earth fault level and fault clearing time on the risk of fibrillation for a small ‘standalone’ earthgrid may be summarised as follows:

Homogeneous resistivity: As the soil resistivity doubles the EPR and hence touch voltage that the person experiences will also double. However, the risk of fibrillation increases by well more than double (ie 20 to 5 times) with a doubling of soil resistivity (between 25Ωm and 100Ωm). The percentage increase gradually reduces with increasing soil resistivity, because as the soil resistivity increases so too does the foot to ground contact resistance, which in turn limits the current through the body, and therefore the risk of fibrillation.

Earth fault level: As for soil resistivity, the EPR and hence touch voltage will increase linearly with increases in earth fault level. However, as the soil resistivity is constant the foot to ground contact resistance is a constant within the shock circuit. The risk of fibrillation increases by more than 25% (i.e. between 9.2 and 8.5 times) with a 25% increase in earth fault current (ie between 800A and 1200A), although the percentage increase more gradually reduces with increasing soil resistivity.

Fault clearing time: As the fault clearing time doubles in two steps (i.e. between 0.1secs and 0.4 secs) the risk of fibrillation more than doubles, increasing at a rate of between 2 and 3 times the rate of increase in the fault clearing time.

This simple scenario illustrates the point that while a change in EPR indicates an increase in hazard level, it is not a good indicator of change in fibrillation risk, and that the error is non-conservative.

6.3.6.2 Case 2: Distribution Case Study

There are two key factors impacting most substation earthing systems, the electrical characteristics of the soil where the earthing grid is installed and the impact of any additional electrical interconnections. In cases where the physical size of the earthing grid is small compared to a larger interconnected earthing system (in the case of the ‘Global Earthing Systems’ or ‘Multi-Grounded Neutral’ systems), the direct external connections may dominate the performance of the earthing systems. In other cases, the presence of these systems can lead engineers to believe the associated risks under earth faults are low, however, these interconnected systems may not perform as expected. The following figure shows the cases where the risk profile of an interconnected system becomes intolerable according to the societal risk presented in section 4.5.2.2.

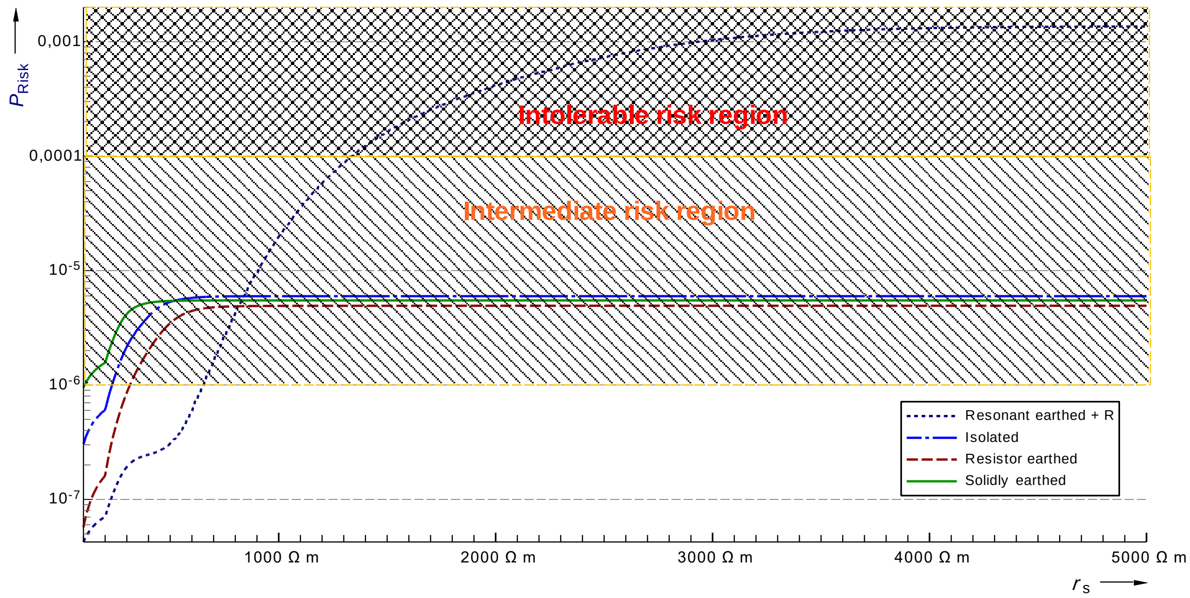


Figure 6.3.2: Individual probability of fatality dependence on soil resistivity for all neutral point connection configurations

The figure above shows the individual risk for various earthing configurations of the distribution case study shown in Section 9.2. As electrical resistivity of the soil increases, the risk quickly moves into the intermediate risk region. The case of the resonant earthed system with a switched resistor moves into the intolerable region as the resistivity increases above 1400Ω-m. Section 9.2 provides further background to this case study.

6.3.6.3 Case 3: Soil resistivity Testing

While soil resistivity has a large impact on the performance of an earthing system, acquiring accurate soil resistivity test data can be difficult in some instances, such as where extending far enough with the test probes is not possible due to surrounding infrastructure or inhospitable terrain. This example investigates the consequences of failing to extend test probes far enough while measuring soil resistivity. Both a simplified substation and a complex realistic site were investigated to show the relevant cases where the risks imposed on the public were significant.

Two main earth grids are considered. This simplified grid of a 50m x 60m earthing grid with 10m grid spacings is simulated 0.5m below grade. The second earth grid is the same substation earth grid and encroaching fence used in Section 6.4.3. The following figure shows a representative sketch for the detailed model and the proximity of the adjacent fence.

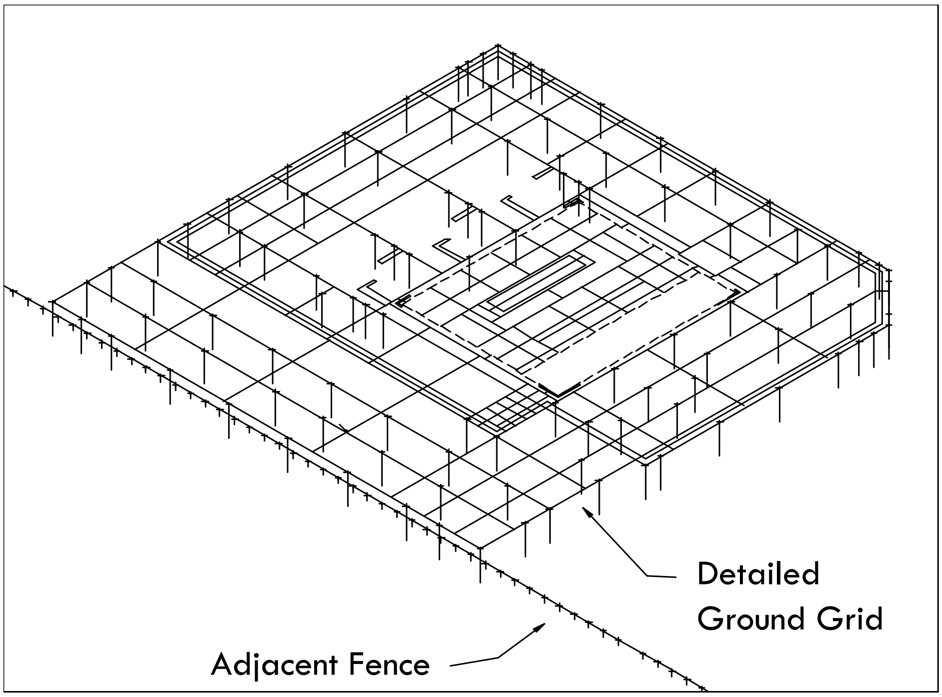


Figure 6.3.3: Detailed model of station grid with adjacent fence

A perfect two-layer soil model of 10Ω-m over 1000Ω-m layering and a top layer thickness of 30m has been used in the analysis. Simulation software was used to simulate a Wenner profile test with the perfect two-layer soil model to develop representative apparent resistivity soil measurements. Inversion software was used to compute expected soil models, and the overall earth potential rise, maximum touch voltage values were evaluated based on the soil models. Finally, the probability of fibrillation was computed for each maximum test probe spacing scenario and plotted for analysis.

The following figure shows the resulting two-layer soil models for the simulation of each Wenner measurement. The simulations were evaluated for spacings up to the maximum spacings of 10m, 30m, 100m, 300m and 500m. The following figure shows a graphical summary of the computed two-layer soil models.

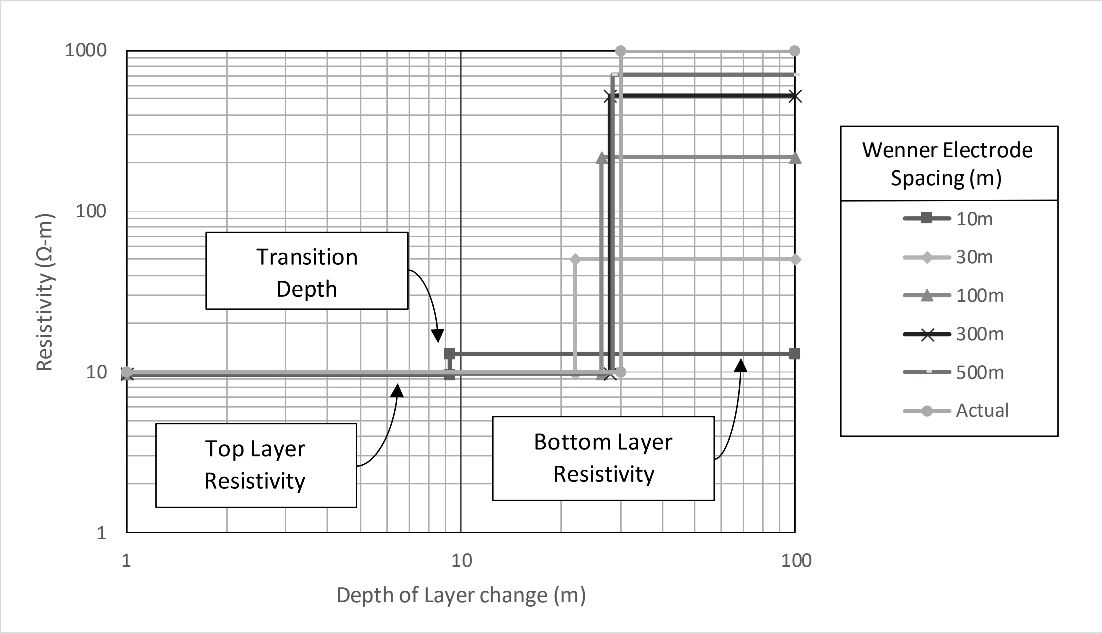


Figure 6.3.4: Computed soil models dependence on maximum probe spacing

The figure above shows the magnitude of the electrical resistivity for the top and bottom layers versus the location of the depth changes along the horizontal axis. For example, the Wenner test readings for case where 30m separation was achieved, detection of the layer change was acceptable at 22m, but the magnitude of the electrical resistivity of the bottom layer was not detected at 1000Ωm (it was only detected to be 50Ωm).

Each earth grid was simulated for the interpreted soil layers and the resulting probability of fatality for a person standing on crushed aggregate within the substation earthgrid area was computed for the following fault levels 10.5kA, 20kA, 40kA.

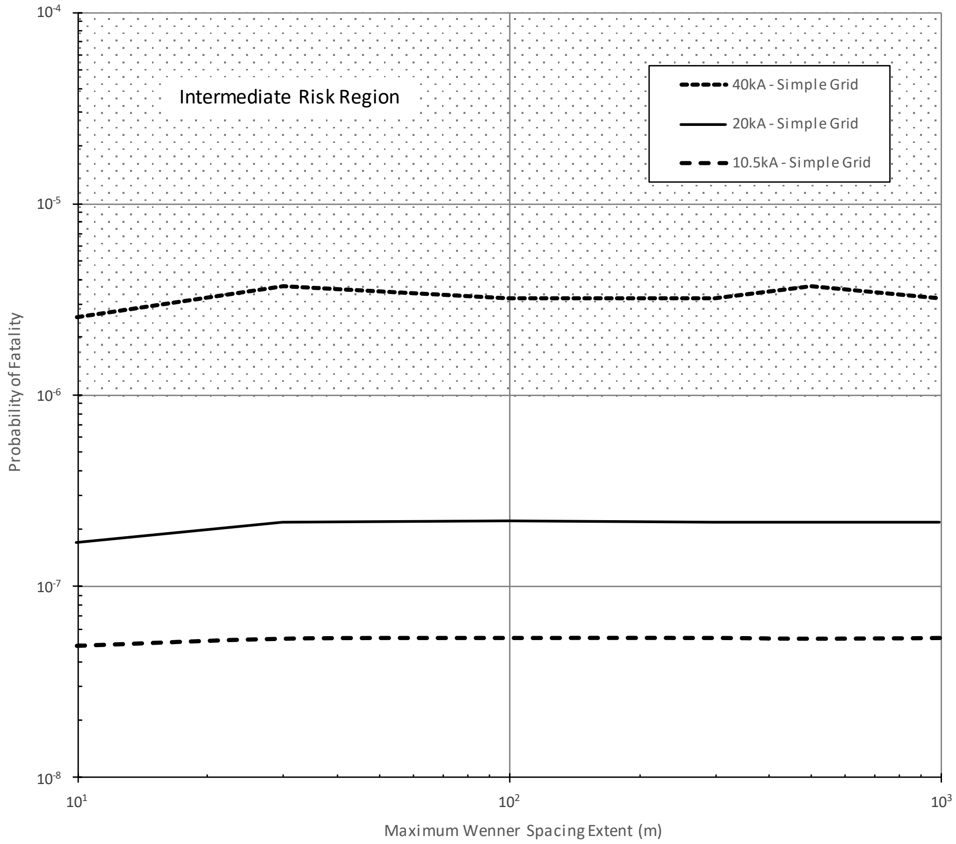


Figure 6.3.5: Computed probability of fatality for a touch scenario within a simple earth grid

The figure above shows that for this case the evaluation of probability of fibrillation was not highly dependent on the Wenner spacing over the simulated spacings. This was a result of evaluating touch voltage values inside the substation earth grid with a 100mm thick layer of 3000Ωm insulating gravel. This scenario contrasts significantly to the following case where the touch voltage hazards are assessed for a person touching the adjacent fence where insulating gravel was not present.

The following figure shows the probability of fatality for the following fault levels 5kA, 12kA, and 20kA for the more complex earthing system shown in Figure 6.3.3.

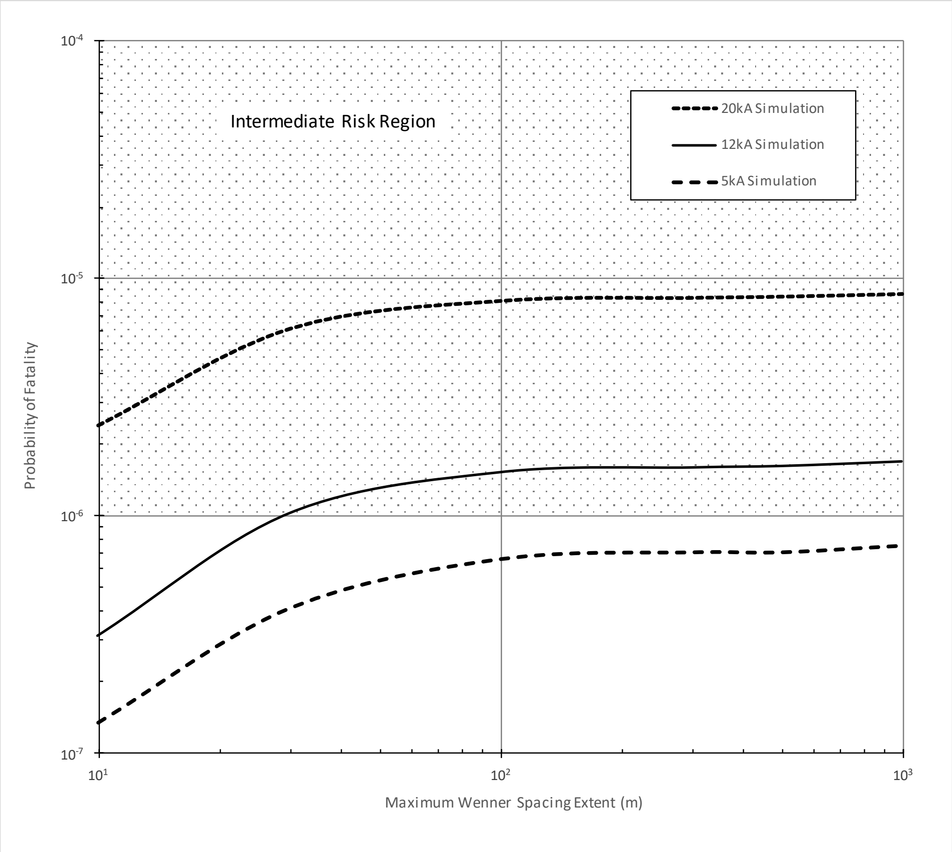


Figure 6.3.6: Computed probability of fatality if touching a fence near a complex earth grid

The figure above shows three scenarios where depending on the fault level, the extent of the Wenner spacing and the resulting probability of fibrillation was independent (5kA), dependent on the extent and material (12kA), and completely within the intermediate risk area (20kA) and independent of the Wenner spacing.

Evaluating the probability of fatality within a substation as shown in the first example was primarily dependent on the overall fault level and EPR and less dependent on the accuracy of the soil resistivity data due to the presence of crushed aggregate. Whereas evaluating the probability of fatality on the fence outside the substation shows significant dependence on fault level, EPR and spacing.

These two examples show the extensive level of engineering judgement and prudence required in acquiring soil resistivity test data. There are no simple rules-of-thumb as to what extent is required to accurately evaluate and develop representative soil models for use in earthing analysis.

6.4 Earth Fault Voltage Distribution

6.4.1 Introduction

The previous section describing the fundamentals of electrical soil resistivity did not specifically discuss voltage distribution. As earth fault current enters earthing conductors it subsequently enters the resistive medium. The current is distributed as a current density taking all available paths according the laws of physics returning to the source(s). The ability of the earth to conduct the current efficiently and reliably is the primary reason for burying earthing conductors. The fundamental task of the earth to conduct the current back to the source(s) results in voltage distributions in the resistive medium. Typically, the design criteria used in substation earthing designs consider the voltage distributed at the surface in the proximity to the earth grid.

Voltage Distribution: Estimating and predicting the voltage distribution is important in the design process. However, due to the significant variations in the electrical soil resistivity, voltage distribution varies with the electrical resistivity. Furthermore, buried metallic structures common within and surrounding electrical substations all become additional paths for currents to dissipate. Buried metallic structures such as foundation reinforcing bars, screw piles, water and gas pipelines, fences can dissipate earth fault current or pick up earth fault current and transfer voltage hazards to remote locations. Analytical methods are usually less reliable at predicting the performance of the voltage distribution created by these additional paths compared to measurements of the performance using an accurate test methodology.

Touch and Step Voltage: Despite the complicating factors in predicting the performance of an earthing system, the voltage distribution at the surface near any metallic structures within or near the substation gives rise to voltage differences for any persons or animals subjected to the voltage differences. Most established earthing standards address what are known as touch and step voltage exposure. A touch voltage is described as the voltage difference applied across one hand to two feet. The touch voltage scenario is typically described as the difference between the voltage of the metallic earthed objects within a substation and the voltage of the surface one metre from the object that can be touched. A step voltage is described as the voltage difference applied across two feet separated by one metre in any direction where the voltage gradients are present. Since there is some finite body impedance in either scenario, current will flow through the body. Specific details of the complex physiology of the human body within the entire contact circuit is discussed in Section 6.5 following.

Voltage Distribution and Hazards: An earth fault current entering an earthing system provides current density in the soil which leads to voltage gradients at the surface of the earth. The resulting voltage differences provide exposure of the public to a hazard if a person or multiple people are touching metallic structures or are standing or walking near the surface gradients.

The voltage distribution along any interconnected earthing conductors such as a system neutral or shield wire will have the effect of distributing the current outside the main earth grid conductors. Thus, hazards can be directly transferred out of the system extending kilometres from the substation.

Metallic structures in proximity to earth grid conductors but not connected to the earth grid can result in a touch and step voltage hazards due transferring a lower voltage in proximity to the voltage gradients generated by the earthing system.

It is important to have methods available to estimate the voltage distribution within and in proximity to earthing systems. Predicting the voltage distribution is key from a design perspective in providing an earthing system design which minimizes the risk of touch and step voltage hazards. Despite all the variations due to the soil resistivity and buried structures, engineering methods have been developed which can be applied to provide a reasonable assessment of risk to the public. Testing and verification of the performance of the earthing system can then be used to verify the risk.

6.4.2 Historical methods for estimating voltage distribution

Predicting and estimating the voltage distribution for an earthing system has developed over many years from empirical techniques, to numerical methods and to measurement methods. The development and progression of the techniques used to predict voltage distribution have become more complex as better understanding of the performance of earthing systems is studied and measured. The factors that drive the development of more advanced techniques are described in the following sections.

6.4.2.1 ANALYTICAL TECHNIQUES

The development of simple analytical techniques early in the earthing system design was based on the theoretical performance of simple geometries using uniform soil resistivity models. This gave rise to analytical solutions to predict voltage distribution for simple horizontal and vertical earth conductors. Simplified equations for predicting circular plates are still used to provide estimates of earth grid impedance today. The simplified equations can provide estimated voltage profiles for determining how far out voltage gradients might be influencing buried structures near earthing systems.

Analytical techniques can be used to determine mutual conductive effects between single electrodes and thus be useful in estimating proximity effects in both testing and other buried structures.

6.4.2.2 Empirical Techniques

As physical earth grid configurations are obviously not a simple geometric shape, empirical techniques were developed which enhanced the analytical solutions. The estimation of voltage distribution accounting for more complex geometries is still available in published standards such as the IEEE80 [27]. Consideration for multiple horizontal and vertical electrodes are included along with the influence of up to two horizontal layers of soil in these methods.

6.4.2.3 Numerical Methods

Numerical methods were developed over many years which expand the ability of predict the performance of an earthing system. The following methods are commonly used in software developed for predicting voltage distribution:

- Image methods for single, two-layer and multiple layer horizontal soils: predict grid resistance, solve conductive coupling between conductors, predict voltage distribution
- Moment Methods: provide conductive, mutual conductive, mutual inductive, mutual capacitive
- PEEC method: provide conductive, mutual conductive, mutual inductive, mutual capacitive

Commercially available software tools have been developed using these techniques. It is recommended that the method or methods being used by a software tool be understood along with the limitations and boundary conditions associated with the software. Some software tools may appear to be using numerical methods but may actually implement analytical and/or empirical methods. As with all numerical tools, there are limitations which can lead to over or under assessment of hazards. All the complexities of physical earthing systems cannot be captured in software, but they are still useful in evaluating boundary conditions.

Care should be taken to undertake suitable verification of results provided by any of the above methods. It is common for software tools to be incorrectly used. Potential problems include incorrect default settings, inaccurate soil electrical resistivity data or fitted models, errors in other inputs, errors in the actual model (such as near connection but not actual connection between conductors), and incorrect selection of the options within the software tool for a particular calculation (for example choosing the correct potential or choosing appropriate segmentation). All methods can produce significant errors if inaccurate soil electrical resistivity data is used.

6.4.2.4 Measurement Methods

Methods have been developed to directly measure the voltage gradients within or in proximity to an earthing system. Once an earthing system is established, accurate measurements of the voltage distribution, touch voltage and step voltage hazards are often the only way to assess a site, due to the unknowns. The current best practices involve the use of current injection methods. When a test current is injected over a power line phase conductor or conductors (or some other representative circuit) and into the earthing system, the current distribution and voltage response can be directly measured. Touch, step and transfer voltages can be measured in a scaled version of the real fault current provided the measurement equipment can measure accurately despite the noise and potential error caused by the power frequency, harmonics and DC voltages and current both in the vicinity or impressed on the earthing system.

Measurement techniques are often the only practical way to evaluate exposure to voltage differences in complex, interconnected earthing systems where analytical, empirical and numerical methods cannot account for all the complexities and variations.

Whilst most commonly used for commissioning and ongoing supervision of earthing systems, measurement methods can produce results that are accurate inputs to design processes where there are existing earthing systems. The common example is expansions to or redevelopment of existing stations, however testing power systems or other conductive assets nearby a new station can also be useful.

The direct measurement techniques close the loop on the analytical, empirical and numerical predictions in the design phase.

6.4.3 Voltage distribution and effects on QRA

The following provides a summary of key elements which can provide a material consequence to QRA

- **Design Errors** – Inaccurate calculation can over or underestimate the required earthing system size.
- **Installation Errors** – Conductors may not be installed at the design depth, and structures intended to be isolated such as a security fence may become inadvertently connected.

- **Unknown Buried Structures** – Unknown buried metallic structures such as pipelines could influence voltage gradient distribution
- **Nearby encroachment** – Surrounding housing, distribution networks, fences and pipelines can significantly influence voltage gradient distribution causing hazards to be present where not originally considered.

If during the assessment or design phase, consideration of for the encroaching infrastructure is made, the risk of touch and step voltage hazards can be quantified using the methods presented in this document.

6.4.4 Case studies

Two examples are examined in this section, one with a separated perimeter security fence which is inadvertently interconnected to the high voltage equipment earthing system and a second with an encroaching external fence.

6.4.4.1 Separated Fencing

The following two figures show how expected voltage gradient values change significantly in the example where a substation security fence which was intended to be isolated from the main HV earth grid was inadvertently connected during construction.

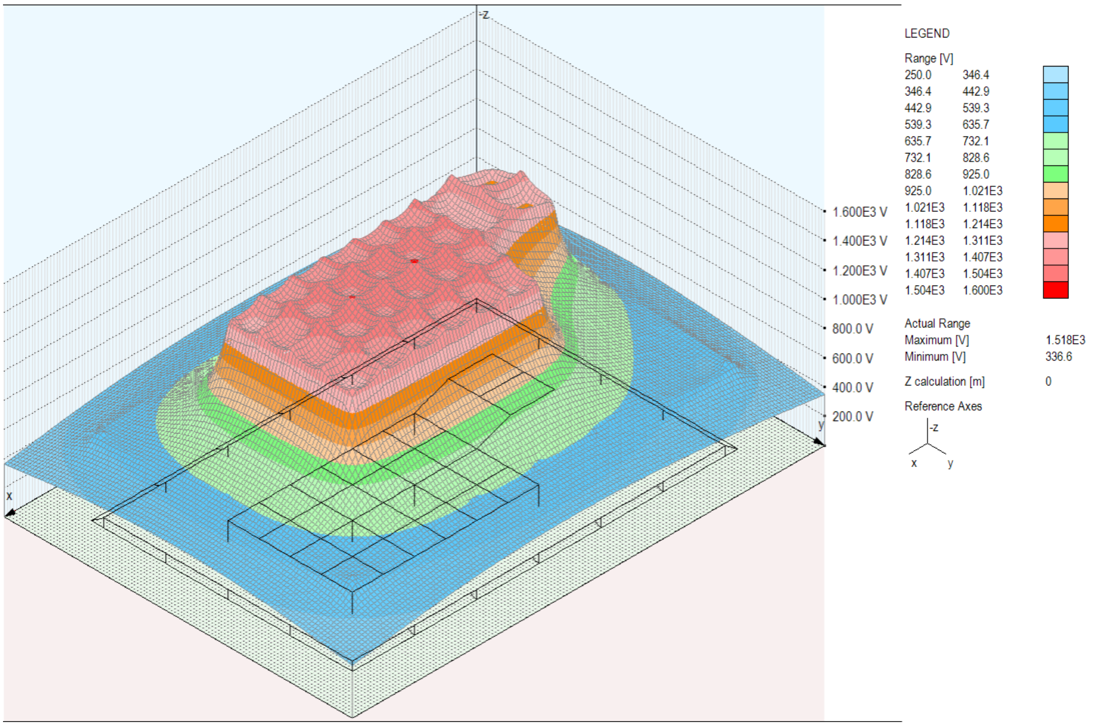


Figure 6.4.1: Isolated fence surface voltage distribution

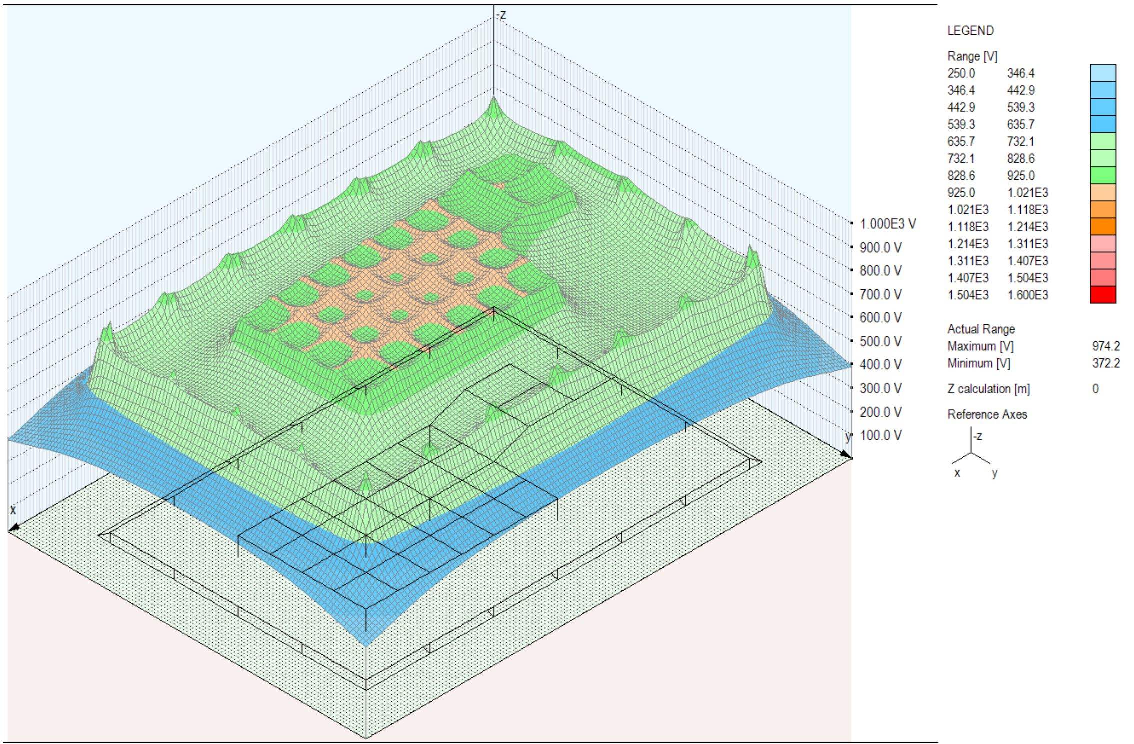


Figure 6.4.2: Interconnected fence surface voltage distribution

The figures above show how completely different the surface gradient voltage distribution can be when the fence was inadvertently connected. In the second scenario, hazards could now be present on the fence despite the lower overall EPR due to the energy transfer and addition current density near the fence.

6.4.4.2 Encroaching Fences

Scenarios where metallic infrastructure encroach to the area of a high voltage substation earth grid, surface voltage gradient distribution can significantly change. The following figure shows the expected surface voltage gradient distribution of a typical substation. The subsequent figure shows a detailed computation of the surface voltage gradient of a fence installed three metres from the substation earth grid.

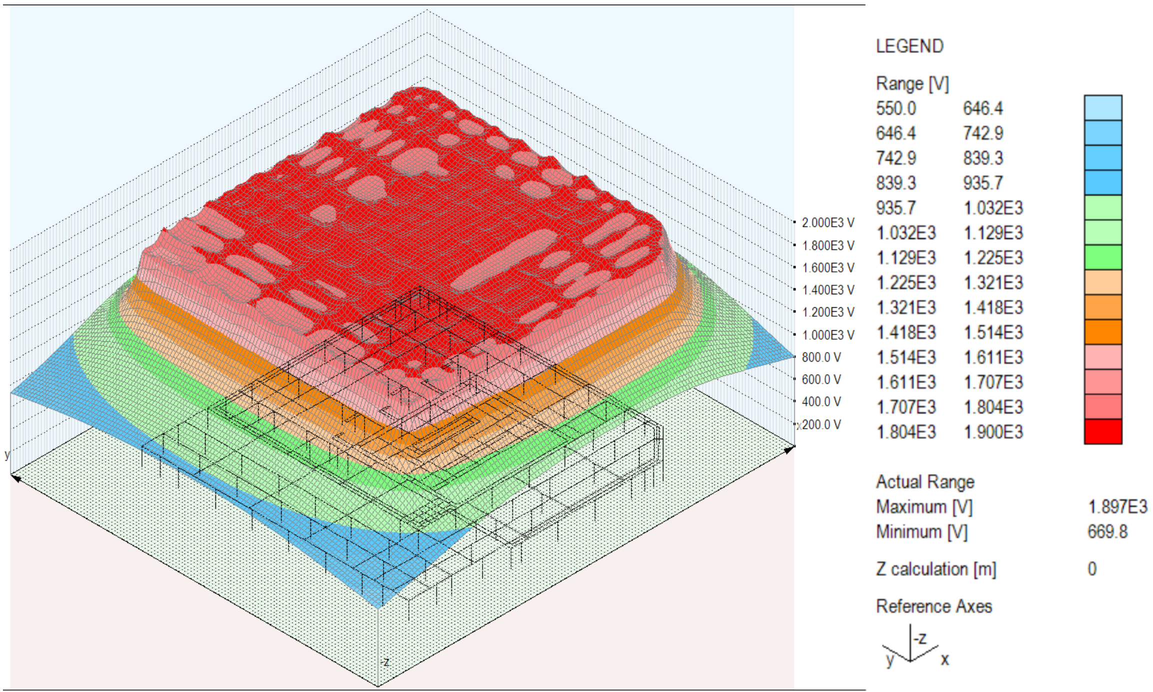


Figure 6.4.3: Surface voltage gradient of a typical substation

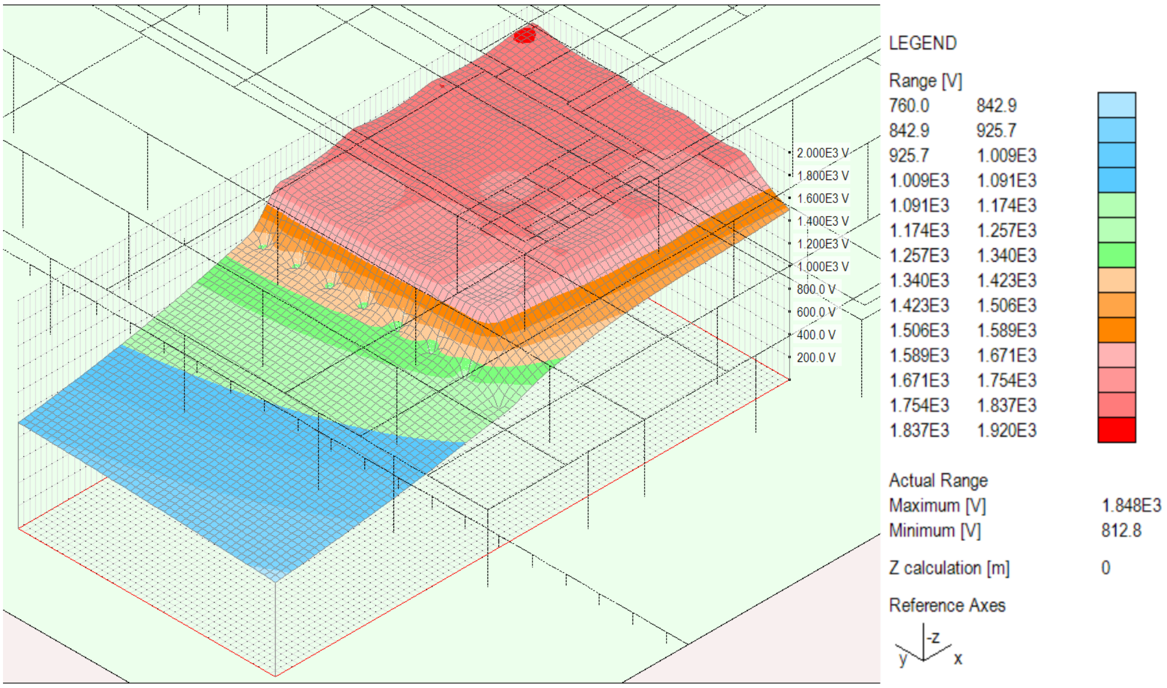


Figure 6.4.4: Detailed computation of surface voltage gradient with a fence (SW corner)

In the first instance with no encroaching fenceline, the touch voltage to the outside of the security fence is in the order of 300 volts. The voltages induced on the adjacent fence are significant in this scenario and would induce both touch and step voltage hazards not present if the fence were not installed so close to the earth grid. In this scenario, touch voltage hazards can be present on the adjacent fence both near and all along the fence due to transfer hazards. In the example above, induced conductive voltage transfer to the fence varied from 750V to 1,033V while the EPR of the energized earth grid was about 1,900V. The voltage coupled through the soil to the fence could be transferred to locations away from the substation presenting high touch voltages (say 600volts) where people could be present. For the case where the touch voltage increases from 300 volts to 600 volts the fibrillation probability increases from 0.05 to 0.25 (ie a 5 fold increase). Further, if the likelihood of contact and fault frequency are taken into consideration for a range of locations it is possible to calculate the expected risk of fatality and thereby more effectively manage the risk profile of the site.

6.4.5 Conclusions pertaining to risk analysis

This section demonstrates that predicting voltage gradients is important during the design phase in order to determine expected touch voltages to allow calculation of the risk of fatality at locations where people may be present. Predicting the performance of voltage gradients and their impact on fibrillation probability can be used to compare the effectiveness of mitigation options for a site and can be used to manage risk of fatality. Although analysis of current distribution and voltage gradients are critical components of the design process, commissioning the system by measurements is the most effective way to assess the actual risks imposed on utility staff and the public. Once commissioning measurements are performed, consideration of seasonal soil variations can be evaluated using appropriate engineering methods which might include the use of numerical methods.

6.5 Body Current and Voltage Withstand Criteria

The starting point for the derivation of the safety criteria is the fundamental research into the effect of electric current upon the human body. The passage of an electric current through the body produces many effects, which vary not only in intensity but also in kind. Thresholds have been defined for perception, let-go and ventricular fibrillation (VF). Although asphyxia and cardiac arrest do cause a number of fatalities, ventricular fibrillation (VF) is considered to be the main cause of death by electrical shock.

The definition of *fibrillation probability* is the probability that an individual exposed to a particular *voltage hazard* will suffer cardiac arrest due to ventricular fibrillation, where a *voltage hazard* is a fixed voltage applied across the human body for a finite duration.

6.5.1 Effects of current on human beings

The accepted research characterising body impedance and fibrillation current thresholds is detailed in IEC 60479 [18]. These parameters are presented in a probabilistic manner as 'values which are not exceeded' by some percentage of the population. The implication, which also fits intuition, is that human parameters cannot be adequately characterised by a single value but must be described as probabilistic distributions with a range of values presented across the human population. Individuals randomly selected from the population are likely to have different characteristics.

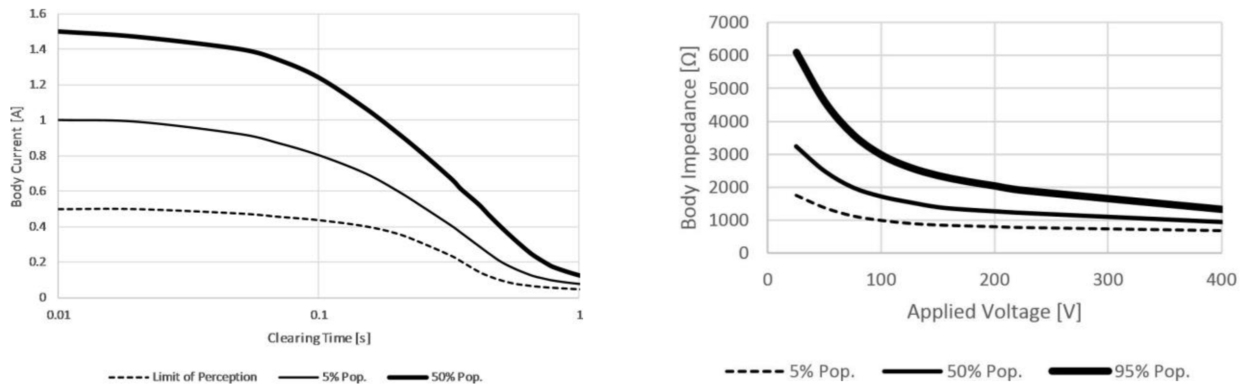


Figure 6.5.1: IEC60479 population curves for body current withstand and body impedance.

Significant investigation of the electrical characteristics of the human populace, primarily by Prof. Gottfried Biegelmeier, led to the publication of [18] including population fibrillation data which are graphed in Figure 6.5.1a. In Figure 6.5.1b the population body impedance data is shown, which demonstrates the dependence of body impedance on the voltage applied to the body, is graphed.

6.5.2 Path factors

How electric current affects a person is dependent on the path that current takes through the body. The path impacts the overall resistance that the body contributes to the shock path and the exposed individual's sensitivity to the current flow, as the path changes the portion of the body current passing through the heart.

The resistance of the body is dependent on the path that the current takes through the body and is described by the resistive path factor, or RPF.

The sensitivity of the heart is dependent on the percentage of the shock current that passes through the heart, which in turn is dependent on the path that the current takes. The relationship between path and heart current is described by a Heart Current Factor, or HCF. The values of HCF noted in [18] are reproduced in Table 6.5.1.

Table 6.5.1: Heart Current Factors (IEC61479)

Current Path	Heart Current Factor
Left hand to left foot, right foot, or feet; both hands to both feet	1.0
Left hand to right hand	0.4
Right hand to left foot, right foot, or both feet	0.8
Back to right hand	0.3
Back to left hand	0.7
Chest to right hand	1.3
Chest to left hand	1.5
Seat to left hand, right hand, or both hands	0.7
Left foot to right foot	0.04

6.5.3 Series resistances

As established in Section 6.5.1 increasing the current through a body increases an individual's susceptibility to fibrillation. Restricting the level of current that an individual may be exposed to can effectively be achieved by increasing the resistance in series within the exposed individual's shock path. Common means of increasing series resistance include: personal protective equipment, such as footwear and gloves, and an insulative surface layer, such as crushed rock or asphalt.

- GLOVES - Electrically rated gloves are widely accepted as a barrier to receiving electrical shocks. Where work is to be carried out with the circuit 'live' (i.e. some LV work) the use of gloves is necessary and almost guaranteed to be followed. However, given the relative rarity of a shock being received by an operator from protectively earthed operations, it is considered imprudent to include a factor for glove impedance in the analysis. It has been observed that even where written instructions or policy documents stipulate the wearing of gloves for operation of switchgear, operators often do not wear gloves, or only wear leather gloves. It is also not practical to assume that maintenance staff working in or on electrical apparatus, or weeding around a substation, will wear gloves. As the assumption that gloves will be worn is not considered sufficiently robust, no allowance for glove impedance is usually included in any analysis.
- FOOTWEAR - Footwear provides additional series impedance for all utility staff working in or near substations, and also for the majority of the public walking near a substation. However, children playing in a backyard or a person turning on a garden tap may not be so likely to be wearing footwear. Therefore, when undertaking a risk assessment, a three stage approach has been proposed:
  - ✓ Conservatively assume no footwear.
  - ✓ Assume footwear only for utility workers.
  - ✓ Assume footwear for utility staff and some of the public, allowing for variations in impedance and flash over voltage.
- CRUSHED ROCK - As distinct from gloves and footwear, surface layers such as crushed rock, asphalt and concrete may be considered to be part of an installation. Therefore, the additional impedance offered is usually included in the applied touch voltage characteristic (i.e. reduced touch voltage).

  While surface layers are quite valuable in reducing the shock risk, they need to be managed carefully. It is important to assess the condition of the crushed rock if the substation requires the presence of an effective insulating layer for the safety of personnel. To assess the effectiveness of the layer there are two main factors: the depth of clean rock (need a minimum of 25mm) and the size of the rock particles (need a minimum of 15mm diameter particles). Thin layers of rock are easily displaced or compromised by weed growth, and the presence of soil throughout the rock layer makes the layer of rock useless. Like gloves, crushed rock is not an appropriate safety barrier external to the supervised area of a substation. A more practical material for areas beyond the substation fence is asphalt.

- ASPHALT - Unlike crushed rock, asphalt may be installed to a well controlled thickness and be expected to remain in service without fear of disruption due to thieves, compaction, soil or leaf ingress. The effectiveness of asphalt may be compromised over time due to plant growth and soil deposition. Asphalt may be made up of a wide variety of materials: aggregate (crushed stone gravel or slag), binders (mineral based, petrochemical, bitumen), and possibly modified binders or additives (e.g. cement, polymer, scrap rubber, elastomer, cellulose fibre, or even wool). Breakdown voltage results vary widely from 1.6 to 12kV (for breakdown to 100mA with electrodes on dampened surfaces), see [75]which also provides a range of impedance characteristics for a range of asphalt samples recovered after 2 to 30 years service.

6.5.4 The shock circuit

A typical earthing related shock circuit is illustrated in Figure 6.5.2. The voltage across the individual exposed to the hazard, V_t, is referred to as the *touch voltage*. It is clear from this circuit that the individual's body impedance alters V_t. The source voltage for the circuit, expressed as V_{pt}, is referred to as the *prospective touch voltage* [79].

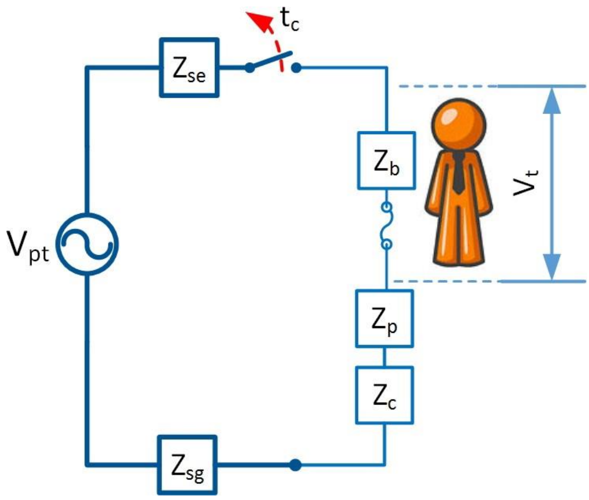


Figure 6.5.2: Equivalent touch voltage circuit

It is assumed that there exists a protective element that will detect the fault and break the circuit after some finite period, referred to as the *clearing time* (t_c).

The human body is represented by the combination of a voltage dependent resistor Z_b and a fuse that blows at the fibrillation current threshold. Allowance is made for additional impedances in the circuit including the contact impedance with the ground Z_c and a protective series impedance Z_p which represents items such as shoes, gloves or surface layers, that may be non-linear. For example, shoes are expected to have both an impedance and a breakdown voltage. Note: in this TB the term *voltage hazard* is used to refer generically to the left half of this circuit, that is the combination of a prospective touch voltage and clearing time.

The impedance Z_{se} is the source impedance of the electrical network. The impedance Z_{sg} is the source impedance of the earth return network. The total source impedance could be said to be represented by Z_s=Z_{se}+Z_{sg}. While the earth return source impedance is implied as being entirely through the ground, it may consist of many parallel paths, including buried metallic structures such as pipes and other earthed infrastructure.

The circuit described in Figure 6.5.2 explains the large range of possibilities in earthing related voltage hazards. While the term *touch voltage* has been used to describe the hazard, the same circuit is applicable to any current path through the body, adjustable by using the heart current factor and body path resistance factor concepts outlined in IEC60479 [18]. The other impedances and the equivalent circuit must be adjusted to suit. For example, in a step voltage situation the legs are in series in the circuit whereas in a touch voltage they are in parallel.

The response of the touch voltage circuit is summarised by Equation 6.5.1.

$$Vt = \frac{Zb}{Zse + Zp + Zc + Zsg + Zb} Vpt = \frac{Zb}{Zs + Zb} Vpt\,; \quad \text{Where } Zs = Zse + Zp + Zc + Zsq$$

Equation 6.5.1

6.5.5 Fibrillation risk calculations methods

The application of statistical techniques to estimate the risk associated with earthing related hazards, and the development of earthing safety standards on that basis, have been the focus of some investigation since late last century [38][41][43][44][46][47][49][50][51][52][55][56][57][58][59][60][62][63][69][79][80][81][82].

The experimental results of the human physiological response to electric shock [55] are described by the following probabilistic functions:

- Population current tolerances with respect to the duration that the current is present; and
- Population body impedance with respect to the voltage applied to the body.

Much of the original experimental data is presented in terms of *'percentile values'* of the population. These percentile values correspond to points on a Cumulative Distribution Function (CDF), and therefore may be used to fit a probability distribution to the data.

Under the model presented in Section 6.5.4, exposing a *specific* person to a given voltage hazard will either result in that individual surviving or succumbing to Ventricular Fibrillation (VF). The outcome for a specific individual is deterministic and can be found by calculating the current flow when that individual's body impedance characteristic is placed in the shock circuit, and comparing it to their fibrillation current threshold.

Using this interpretation it may not initially appear to make sense to talk about the 'probability of fibrillation' associated with a voltage hazard since it is either true (=1) or false (=0). However, this is only correct for the specific individual considered. Instead, the probability of fibrillation calculated here is interpreted as the probability that an individual selected at random from the population enters VF as a result of the voltage hazard.

This interpretation of the fibrillation probability associated with a voltage hazard could be said to be the average individual probability of fibrillation, and is equivalent to the fraction of the population that would enter VF if the entire population was exposed to the voltage hazard. Framing the problem as such tends to provide explanations that are more easily and intuitively understood. Accordingly, the proposed algorithm is presented as a method for estimating the fraction of the population that would enter VF if exposed to the voltage hazard.

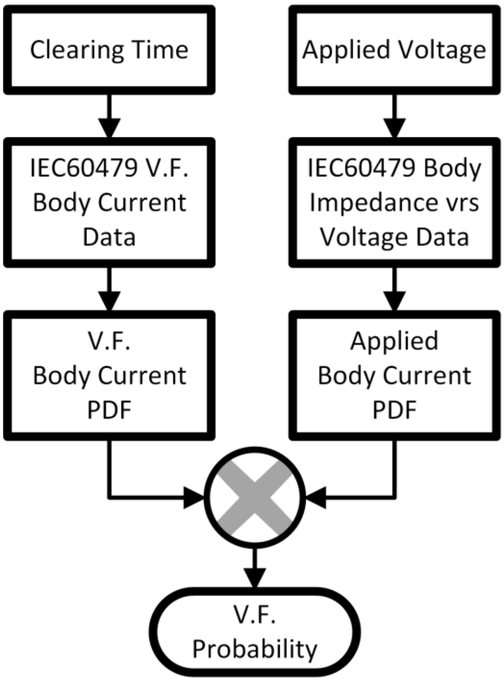


Figure 6.5.3: P_{VF} calculation method using random variables [79]

There are numerous calculation frameworks available for calculating the fibrillation probability as outlined in [55, 91]. Reference [87] applies the framework to the derivation of step voltage criteria. There are a number of methods to consider, including:

1. Stress-Strength Distributions;
2. Random Sampling; and
3. Structured Sampling.

6.5.5.1 Stress-Strength Distributions

One classical statistical approach to calculating the probability that an individual will enter VF when exposed to a specific electric hazard scenario is based on the concepts of 'stress & strength distributions', as described in Figure 6.5.4 [1][79]. This class of analysis is commonly used in reliability engineering where classes of objects have a 'strength', which may vary from sample to sample, but the overall distribution characteristic is well-defined and can be easily compared to a applied stress distribution characteristic to determine expected failure probabilities. Convolution of distributions is a commonly used technique for implementing these calculations.

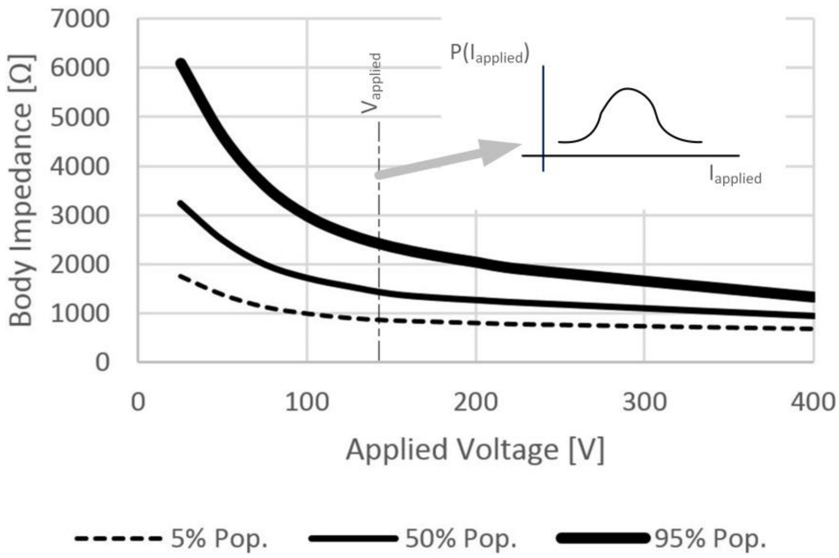


Figure 6.5.4: Calculation of P($I_{applied}$) for a constant voltage hazard

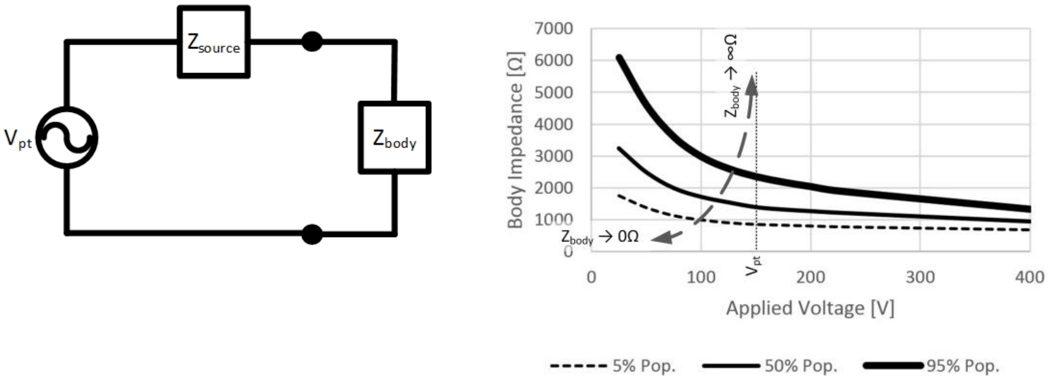
To apply convolution in this case, a probability density function, or p.d.f., describing the range of currents that a person may experience, denoted $P\,(I_{applied})$, must be constructed. However, the non- linear nature of the body impedance curves makes the calculation of $P\,(I_{applied})$ difficult except in the 'ideal' case of a constant applied voltage where $P\,(I_{applied})$ is a vertical profile through the body im- pedance $Z_{body}(V, X\%)$ surface, as shown in Figure 6.5.4.

The situation where a source impedance acts to modify the voltage across the body, whether it is non-linear or not, makes the description of the resulting Vt response due to the circuit across the Zbody(V, X%) surface difficult to describe as it results in a transcendental solution (Equation 6.5.2). This implies that the definition of an independent 'strength' characteristic for this situation is not possible except where the applied body voltage is constant.

$$Vt = \frac{Zb(Vt, X\%)Zs}{+ Zb(Vt, X\%)} Vpt$$

Equation 6.5.2

Consider the simple situation described in Figure 6.5.5a where a constant prospective touch voltage is applied to a body through a source resistance. The curve of the applied voltage across the body impedance curve is typically described by the response shown in Figure 6.5.5b.



(a) Simple Contact Scenario Circuit (b) V_t Response considering both Source and Body Impedances

Figure 6.5.5: Implementing stress-strength distribution analysis

6.6 Fault Frequency and Person Contact Frequency and Durations

To fulfil the goal of quantifying the risk associated with hazards from an earthing system we need to calculate both the probability of fibrillation and the probability of coincidence. The last section presented the theory and techniques behind determining the probability of a given voltage and length of exposure leading to ventricular fibrillation. In this section, we summarise the theory relevant to the calculation of the probability of two events being coincident (in our case the coincidence of a hazard being realised and a person being in the applicable touch voltage situation). We then provide and explain a simplified formula for the calculation of coincidence for two low probability, short duration events and provide guidance on the inputs to this calculation and some commonly used figures. Lastly, we provide examples of how variations in these input parameters affect the calculated risk.

6.6.1 Coincidence probability theory

While the term ‘Coincidence Probability’ is technically correct, it may be slightly misleading as the common usage of the term ‘coincidence’ implies some remarkable sequence of events leading to an unexpected happenstance. Instead the sense of the term in this context is about two independent events being ‘coincident’ with each other, that is occurring at the same time.

In the earthing QRA framework presented in Chapter 4 the Coincidence Probability is the factor that accounts for the likelihood of an earthing hazard causing harm, in other words it is the probability of a person being *exposed* to a voltage hazard (i.e. receiving a shock) as a result of an earth fault[5]. So, the events which must be coincident for an ‘exposure’ to occur are:

- An *earth fault, and*
- At least one person *contacting* an item which has impressed upon it a voltage hazard during an earth fault.

As a key aspect of the QRA process is the quantification of the factors involved in earthing related risk, practitioners must be able to calculate a numerical value for the coincidence probability. This typically means using mathematical models for the processes causing the events that factor into coincidence probability. An overview of the data needed, and modelling approaches are provided in 6.6.1.1 and 6.6.1.2 respectively.

6.6.1.1 Data Gathering

Perhaps the most important aspect of any mathematical model is that it provides a reasonable representation of the actual data. In this case that means collecting data regarding the occurrence of earth faults, and people’s behaviour is key to enabling reliable calculation of coincidence probability.

[5] Perhaps another phrase such as ‘Exposure Probability’ or similar would better capture the central concept than ‘Coincidence Probability’, at the cost of ‘breaking backwards compatibility’ with the existing literature.

Historical network data can be a good source of information about the occurrence of earth faults, however the disclaimer that ‘past performance does not necessarily indicate future performance’ applies here. Future changes to network configuration, or operation, may lead to changes in earth fault characteristics.

It is also possible to undertake surveys or observations to characterise the behaviour of people who might be exposed to voltage hazards as a result of earth faults. In some circumstances, such as employees who follow standard work practices, this approach may be reasonable. However it might be significantly more difficult to adequately capture the behaviour of all members of the general public though such methods.

A number of characteristics of these factors should be considered, such as frequency of occurrence, duration of events, distribution of events and variation over time (e.g. seasonal variation).

6.6.1.2 Mathematical Models of coincidence probability factors

Any mathematical model is a simplification of the true behaviour of a system into something that is suitably representative, but simpler to work with. Assessing the ‘suitability’ of a model requires reliable data to compare the model against, as described in Section 6.6.1.1.

In cases where detailed historical data, surveys, or observation can *adequately* capture the behaviour of the coincidence probability factors (e.g. the behaviour of *all* the people who might be exposed to an earthing related voltage hazard), then it is possible to derive custom, or empirical, probability distributions to describe parameters such as how often people touch various items, or how often earth faults occur. The essential aspect of this approach is to ensure the initial sample data are broad enough to capture any outliers, or some other special consideration is given to ensuring the derived distributions include some measure of conservatism to account for behaviour that wasn’t captured in the initial sample.

Another common mathematical model to use is that of the Poisson Process [83][84][85], which describes a system where *events* occur at some fixed rate over a period of time. Models based on Poisson Processes are widely used in other areas of electrical engineering ranging from lightning protection, to insulation defects in manufacturing. There is a range of well-known mathematics associated with Poisson Processes including calculations for the time between events, the probability of observing some number of events in a given period, and the probability of observing no events in a given period.

For application to the calculation of coincidence probability, Poisson Processes may be used to model both the occurrence of earth faults, and a person contacting an item that might present a voltage hazard. Extensions of the previously mentioned well-known mathematics of Poisson Processes can then be used to derive expressions for the probability of observing simultaneous ‘events’ from the ‘fault process’ and the ‘contact process’. An example of a simplification based on this approach Is provided in Section 6.6.2. However more complex variations are also possible, including the use of non-homogeneous Poisson processes to account for aspects such as seasonal variation.

There are of course many subtleties to consider when applying mathematical models to a system as complex as power networks and the behaviour of people. One obvious example of this is that for this application ‘coincident’ events do not have to start at the same time. Instead, any form of overlap between a ‘fault’ and a ‘contact’ event should be considered as a coincidence, as the person was still exposed to the voltage hazard (even if for some fraction of the ‘contact’ and ‘fault’ durations). Simply multiplying the probability of a fault occurring in a given time by the probability of a contact occurring within the same time period does not adequately address this.

Another subtlety arises in how the behaviour of groups of people are considered. A naïve approach might be to ignore groups of people all together, or alternatively to model the behaviour of each person in the group as another Poisson Process and then look for coincident events between the fault process and any of the contact processes. In some cases this might be correct, however the physical interpretation of this mathematical model is that the behaviours of each person is entirely independent of every other person. There are cases where this assumption is unrealistic, for instance a significant number of people at a sporting event might all spend a long time in contact with a metallic fence around the perimeter of the playing field. It is important to correctly consider groups of people, since society generally has a lower tolerance for events which result in multiple fatalities, and if the behaviour of people with a group is correlated in some way, then there could be a higher chance of multiple people being in contact with an item, and therefore possibly all being exposed to a voltage hazard at the same time.

6.6.2 Simplified calculation method for individual coincidence probability

The simplest case for calculating coincidence probability is that of considering a single individual who might be exposed to a hazard resulting from a single earth fault scenario. While this case is simple it can still be a very useful model for practical applications of the QRA process by considering the *worst case* earth fault frequency, and the so-called *reasonably-behaved maximally-exposed individual*. If conservative approximations are used for the variety of earth fault scenarios and range of behaviours of people, then this single case of coincidence in the QRA can provide conservative estimates for other cases by extension.

If the stochastic distribution of the influencing parameters (i.e. occurrence of earth faults, or people contacting items which might present earthing voltage hazards) is known, then the risk of coincidence can be calculated.

The formula to calculate the risk of a fatality was presented in Section 4.4.1. This section provides following a simplified formula for the calculation of the third term in that formula, the probability of coincidence (Pcoinc).

$$P_{coinc} = \frac{f_{\text{earth fault}} \times f_{\text{contact}} \times (T_{\text{earth fault}} + T_{\text{contact}})}{365 \times 24 \times 60 \times 60}$$ Equation 6.6.1

$f_{\text{earth fault}}$ … frequency of dangerous earth fault situations for the considered equipment (number of earth faults per year), typical values: see table below

$T_{\text{earth fault}}$ … typical duration of an earth fault situation [seconds], typical values: see table below

f_{contact} … frequency of contact of a single individual with the structure under consideration (number of contacts per year), typical values: see table below

T_{contact} … typical duration of each contact of a single individual with this structure (seconds/contact), typical values: see table below

A derivation of the above formula can be found in Appendix E. Further reading is also available in ENA EG0 [1].

6.6.3 Risk calculations with multiple people

Taking multiple people into account in the QRA process complicates the risk calculations compared to the previously discussed case of a single individual, but it is also the basis for calculating different styles of risk, such as societal risk, and business risk which may be more pertinent for some applications. The additional complication arises from the different ways of modelling the behaviour of the individuals who make up a group, and the possibility of considering multiple fatalities as a result of a single earth fault event.

One simplification that may be applied to modelling the behaviour of groups of people is to assume that all the individuals who make up the group behave independently and, with a similar application of Poisson processes as the individual case, model the occurrences of each individual coming into contact with the earthed item. Then, by extension of the mathematics for the individual case, the coincidence probability may be calculated.

It is important to highlight the fact that this simplifying assumption of independent behaviour may not always hold, which could lead to non-conservative results from the mathematical modelling. There are many instances where the behaviour of the individuals making up a group is correlated, and these correlations can significantly alter the coincidence probability outcomes. Oftentimes the correlation in behaviours is due to external influences such as public transport timetables, the location and duration of some special event such as a football match, or other social conventions such as typical working hours. There are many approaches to modelling this correlated behaviour, including the use of non-homogeneous Poisson processes. This has the benefit of building upon the same approach used for the individual case, but the rate of events in a non-homogeneous Poisson processes may vary over time, and this variation can be used to model the correlations in behaviour. Of course, there are other more complex models of group behaviour that may also be employed.

Examples of the coincidence probability calculations for both independent and correlated behaviours may be found in Appendix A of ENA EG-0 [1].

The impact of the differences between independent and correlated behaviour are most apparent when considering multiple fatalities in the QRA process. Obviously, the chance of multiple people being exposed to a voltage hazard as a result of an earth fault event is much greater if there are multiple people touching the same item, at the same time, or within a window of time, that is if the individual's behaviours are correlated. This means a critical aspect of assessments involving multiple fatalities is to identify cases when an assumption of independent behaviour is not reasonable, and use an appropriate model for coincidence probability calculations, because the assumption of independent behaviour may dramatically underestimate the chance of multiple people being in contact with an item at the same time.

Often, applications of the QRA process to scenarios involving multiple fatalities from a group of people are known as *societal* assessments. This terminology arises from the generally accepted notion that societies have less tolerance for events that cause multiple fatalities, and that tolerance is not linear with the number of fatalities. Accordingly, these assessments are often carried out with different notions of 'tolerable risk' than individual assessments, and the level of tolerable risk is dependent on the number of fatalities being considered. It is important to understand that these societal risk calculations are not simply multiplying an individual risk level by the number of individuals in the group, especially when taking correlated behaviour into account. While the fibrillation probability associated with a particular voltage hazard remains constant for all individuals in the group, the coincidence probability calculations must be adjusted based on the behaviour model being used.

Conversely, assessments considering any fatality from a group of people may be seen as assessments of *business risk*, where the group of people could constitute employees, or the general public for instance. This terminology arises because it can be as a measure of the risk posed by a business's activities on the members of the group under consideration, commonly the business owners.

6.6.4 Coincidence variables

6.6.4.1 Fault Frequency

We know that the occurrence of a shock incident requires two things (at least): an earth fault event and a coincident contact. The rate of earth faults depends on many things and may have great variation, however across the surveyed countries some consistency was seen. The local utility should be able to provide this data. Table 6.6.1 and Table 6.6.2 following presents the recommended starting point should more specific data not be available.

Table 6.6.1 Typical earth fault frequency values [1]

System Voltage (phase to phase)	Overhead Line Fault Rate (faults/100km/year)
Low Voltage	20-150
<40kV Unshielded	10-40
<40kV Shielded	5-10
40-100kV	2-5
100-150kV	1-4
150-300kV	<1
>300kV	<0.5

Table 6.6.2 Austrian fault frequency data[6]

Location	Fault frequency		
	MV (10-30 kV)	HV (110 kV)	EHV (400 kV)
Overhead Lines (faults /100km /year)	6	3-4	1.0-2.5
Cables (faults /100 km /year)	2-2.5	0.9-1	0.5-2.3
RMUs (faults /100 RMUs /year)	0.01-0.03	n.a.	n.a.
Substations (faults /100 bays /year)	0.03-0.06	0.04-0.12	0.05-0.15

[6] Data provided by Graz University of Technolgy

The above tables are for guidance only and any figures subsequently relied upon should be substantiated.

6.6.4.2 Fault Duration

Under most circumstances the duration of the fault is the time it takes protection to isolate supply. Guidance on this is provided in Section 6.1. Sometimes more complicated circumstances exist where protection and equipment operating time (to clear the fault) is not the only time to be considered. With some neutral treatments, the first fault may not be cleared for hours. During this time hazards may be at a lower level than without restricted earth fault current but the fault duration is not the time it takes for the system to stabilise to the current that will be allowed for the extended period. It is actually the extended period.

Another case is where reclosers may re-energise the fault resulting in a second and possibly third shock hazard. Guidance on the treatment of reclosers has been provided by ENA EG0 [1] where it is recommended that reclosing times are not included in total fault/contact duration [72].

There may also be a need to consider voltage hazards that occur during non-fault situations, such as low frequency load current interference onto metallic pipelines, fences, railway lines, conductive telecommunications cable or isolated power lines. Another example is power transmission or distribution operating with earth as part of the circuit (such as unipolar DC or single wire earth return (SWER) distribution). If these hazards are present due to load current then the exposure time is the time that the load current is flowing.

6.6.4.3 Contact Frequency & duration

The establishment of reliable data on how often and for how long reasonably behaved people (staff or public) will be in potential touch voltage situations is both important and somewhat challenging. As hard as it can be to estimate human behaviour it is very easy to simply watch and count. Such simple observation may give significant insight into reasonable exposure rates but equally so sensitivity analyse can be used to see just how important the particular input is to the risk assessment. It has also been recognised that reverse calculation can be used to determine the amount of exposure that may be considered the negligible threshold, which may be an easy number to either dismiss as not possible or to decide further mitigation is warranted.

There are many places to start with respect to estimating contact frequency & duration, however, for the reader with no starting estimate for their ‘exposed individuals’ the values in Table 6.6.2 are recommended based on those published in ENA EG0 [1].

Table 6.6.2 Example contact frequency and duration

Scenario	Description	Contacts/year	Duration (s)
Remote	A remote location where the same person is rarely in repeated attendance	10	4
Urban Interface	Within 100m of homes, where people visit occasionally	100	4
Urban	Around homes, where the same person is more regularly but is not in regular contact with a common potential source (such as the low voltage earth or neutral)	416	4
Bonded Contact	Around homes and where the same person will be regularly in contact with different locations that are bonded (such as the low voltage earth or neutral)	2000	4

The above table is for guidance only and any figures subsequently relied upon should be substantiated.

At the mitigation stage where a designer is looking to further lower the risk and is resorting to lowering the probability of coincidence, controls can be implemented such as signs or shrubbery that lower the probability of contact by a person. The contact rate and duration can be estimated with the control in place and the risk recalculated. Another method which may be used is to apply a coincidence reduction factor (CRF). This method estimates the net affect a control is expected to have on contact rates and directly scales the risk as shown in Equation 6.6.2 following. Further explanation can be found in EG0 [1].

$$P_{fatality} = P_{coincidence} \times P_{fibrillation} \times CRF \qquad \text{Equation 6.6.2}$$

Where:

CRF … coincidence reduction factor (p.u.)

As has been indicated previously societal risk levels are rarely the determining factor in establishing what controls ought to be implemented to further reduce voltage levels, with the exception of some gathering type activities, where a group of people concentrate a relatively small number of contacts into a short period of time while they are together. Examples of gathering behaviour include attendance at aquatic centres or football games. It should be remembered that for societal calculations average group behaviour rather than maximum reasonable exposure is the appropriate input data. Further guidance can be found in EG0 [1].

6.6.5 Impact of variable changes on risk

It should be clear that increasing fault and contact rates and durations will increase coincidence probability. It should also be clear that increasing fault clearing time also increases fibrillation risk, which means fault clearing time has an effect in two ways. What is probably less clear is the degree of the increase.

As a simple example, if the fibrillation risk is already very low, say 10^{-7}, then changes in fault rate or contact rate will not increase in risk beyond the negligible level. However, if the fibrillation probability is very high due to long fault times, then the coincidence probability will also be high and the risk will be high. On that basis the risk posed by earthing related risks, both theoretically and by experience, can and do cover the range of negligible to high risk. The wide range of possibility means there is no typical risk range. Further examples of how the variables of fault rate, fault clearing time, contact rate and contact duration are provided in Section 9.

7. Life Cycle Management

Good engineering is required to concern itself with more than just a design for construction. Engineering principles and obligations should extend to management of the asset performance over all of the stages of its life. The same is true for earthing systems, which despite often not being recognised as such, are assets with life cycles and cannot be simply buried and forgotten. Figure 7.1 following depicts the common life cycle of earthing systems.

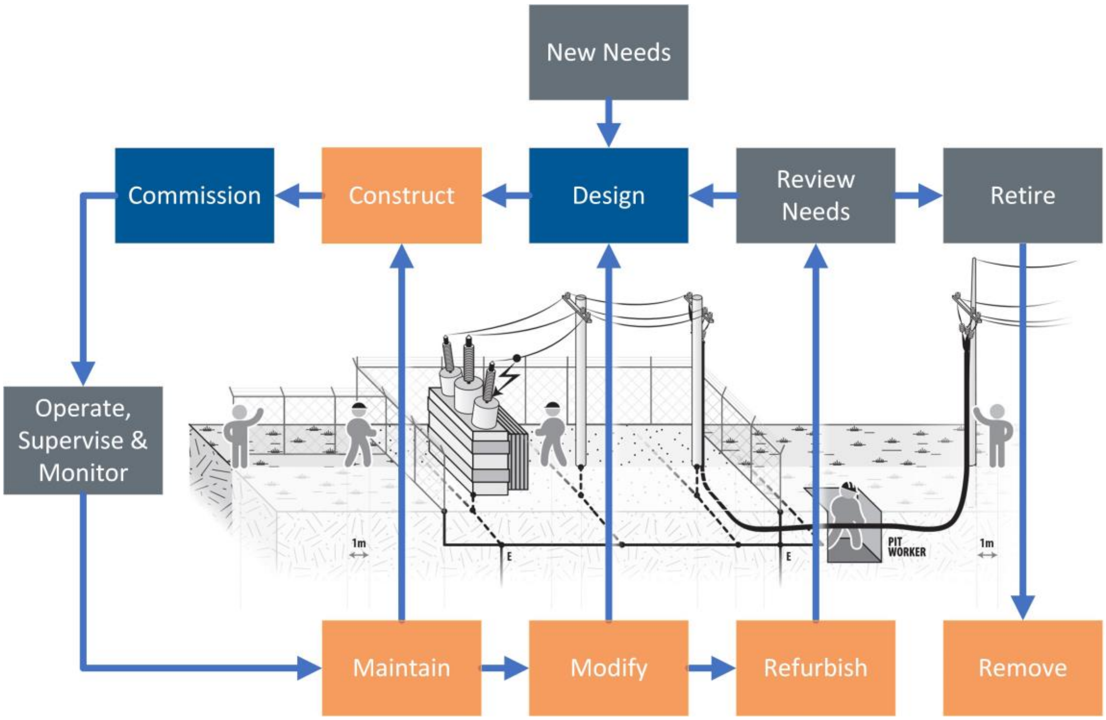


Figure 7.1: Earthing system life cycle model

Managing these life cycles is necessary and may create obligations for designers, asset owners and operators; it is however not necessarily onerous. Chapter 8 will cover the key stage of design. The following sections explain the broad range of what may be required. It may be seen that many engineering systems have close alignment with the recommendations here including ‘Safety In Design’, which is a legal requirement in some countries [61][76][93].

7.1 Construction

Construction should be considered in two ways. Firstly, construction is in and of itself an activity that increases exposure and possibly risk for workers to earthing related hazards and this should be assessed and managed. Secondly the activities of construction may directly or indirectly affect the outcomes of the design, potentially in positive or negative ways. This should mean that foreseeable variations or even errors in construction should be expected and either relied less upon by way of contingency in the design or confirmed and validated through appropriate commissioning tests.

7.2 Commissioning

All new or modified earthing systems should be commissioned to validate the adequacy of the design, relevant design inputs, and installation, in most cases prior to energisation. The plan for commissioning should consider closely the key performance criteria identified in the hazard identification and mitigation analysis phases. The commissioning inspection and testing plan should prove adequacy of the earthing installation (basic material selection, installation quality and as-built drawings), as well as design criteria compliance, and provide the ongoing supervision process with benchmark or baseline figures (e.g. continuity test results). Field testing should include visual inspection and proving continuity. Other tests may include earth resistivity testing, and current injection testing. Measurements may include the earthing system impedance, current distributions within and from the system, prospective touch and step voltages at relevant locations, and transfer voltages (transfer out of a component of EPR or transfer in of a lower voltage). Loaded voltage measurements (i.e. across a resistor simulating the body impedance) are susceptible to errors introduced by contact impedances and care should be taken to ensure contact impedances in the measurement circuit are appropriate and do not unduly dominate the measurement. 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 (e.g. monitoring separation distances). The condition of the earthing system components should be examined or assessed periodically. Visual inspection possibly including excavation at representative locations and/or component testing are appropriate means. Other field activities should generally follow the commissioning program including continuity tests and measurements (and/or calculations) of the earthing system performance. These activities should be carried out at intervals appropriate to the operating environment and operational risks of the system or following major changes to the installation or power system which affect the fundamental requirements of the earthing system.

Testing is essential as a validation step for the design, installation and maintenance of earthing systems. In most cases tests shall measure the performance outputs of the earthing system in terms of produced voltages and current distributions rather than solely earth resistance. The testing should consider the key performance criteria identified in the hazard identification and treatment analysis phases. Earthing system testing normally consists of the following 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.

7.3 Ongoing Supervision and Monitoring

A supervision program should monitor aspects of the installation critical to maintaining safe operation and consider ‘external risks’ identified during the design phase (e.g. monitoring changes that could lead to transfer in or out, or changes in fault current level). 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 be compared to results obtained during the commissioning. Continuity tests should also be undertaken.

Appropriate inspections and tests intervals should be determine based on knowledge of the earthing installation and design standards, and on its understanding of environmental conditions and assessment of risk (e.g. soil conditions, theft of copper).

7.3.1 Inspection and test intervals

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.

If changes occur they can produce significant change in risk. The focus is on remediation of changes that have negatively affected risk, or where remediation is difficult or expensive, a reassessment may be appropriate to decide on the reasonable practicability of remediation. A first step could be to determine if the risk criteria determined in the design have been violated. If required mitigation strategies including those discussed in Chapter 8 should be assessed.

7.3.2 Foreseeable changes

As an earthing system progresses through its lifecycle it must continue to fulfil its purpose in spite of various threats posed to its condition and performance. This section describes what the most foreseeable forms of threat are and what asset managers and designers may be required to respond to during the asset's lifetime. To ensure that they are dealt with appropriately is a matter of either planning appropriately or reacting swiftly.

Reasonably foreseeable changes that may affect earthing system performance, and therefore may need to be addressed and ideally identified through ongoing supervision and monitoring, include:

- Network Changes
  - ✓ Changes in fault level (inc generation type and nature, e.g. renewable, inc neutral treatment changes (e.g. from resonant grounding to resistance grounding, and vice versa)
  - ✓ Protection changes (inc trip time (for main protection),
  - ✓ LV network changes (possibly TN v TT changes)
  - ✓ Network expansion (new feeders)
  - ✓ Encroachment by other utility assets (e.g. pipelines, telecommunications lines and railways)
  - ✓ Changes in maintenance strategy (e.g. ownership or restructure type changes)
  - ✓ Gaps in maintenance due to organisational or contractual boundaries
- Environmental Changes
  - ✓ Seasonal changes (freeze etc)
  - ✓ Pollution
  - ✓ Salination or soil flushing
  - ✓ Sand or soil ingress into the substation
  - ✓ Mud or wash comes into the substation
  - ✓ Vegetation changes in the substation (weeds growing through rock)
  - ✓ Vegetation control (eg weed poison) leading to changes in the soil (eg corrosion threat)
  - ✓ Changes in lightning profile – leading to more faults
  - ✓ Changes in the presence or behaviour of birds or other animals leading to increased fault rates
- Damage & Deterioration
  - ✓ Decrease or loss of continuity of cable sheaths (inc terminals)
  - ✓ Decrease or loss of continuity of overhead earth wires (inc mechanical terminations being used as the electrical connection)
  - ✓ Neutral treatment device deterioration (eg arc suppression coil cabling loss of insulation leading to increased earth fault levels)
  - ✓ Deterioration of insulation (inc cable networks and overhead lines) leading to more frequent earth faults
  - ✓ Deterioration of surge arresters etc leading to more frequent earth faults
  - ✓ Corrosion affects
  - ✓ Latent failures (the issue that some failures remain undetected until a second failure occurs)
  - ✓ Robustness
  - ✓ Copper theft
  - ✓ Vehicle movement over poorly compacted ground can damage buried earthing including connectors
  - ✓ Poor utility coordination eg water pipes or telecoms not being modified correctly
  - ✓ Deterioration in the access protection against birds or other animals, leading to increased fault rates
- Societal Changes
  - ✓ Encroachment (fences, informal settlements)
  - ✓ Changes in human behaviour (individual or societal), bus stop, play ground
  - ✓ Use of the landscape (e.g. holiday parks, caravans, leisure use, and childrens playgrounds)
  - ✓ Changes in technology

7.3.3 Likely consequences

Each of the changes presented in Section 7.3.2 may have a small or significant effect on the earthing system residual or changing risk. To assist the reader in their considerations the following potential or likely consequences should be considered, along with the expected variations.

- Fibrillation Effects
  - ✓ Change in EPR
  - ✓ Change in touch, step and/or transfer voltages
  - ✓ Change in shock series impedance
  - ✓ Change in fault clearing time
- Coincidence Effects
  - ✓ Change in fault clearing time (repeated from above)
  - ✓ Change in fault frequency
  - ✓ Change in contact rate
  - ✓ Change contact duration

7.3.4 Risk guided supervision

The QRA process can significantly impact the ongoing supervision of a substation. As has been demonstrated the quantitative risk management process allows different hazards to be compared. This is true of both past, existing and future risks and threats to an earthing system. On this basis the supervision of an earthing system can be adapted through its lifetime depending on its threats. This is in contrast to the other approaches which predominantly deal with earthing system supervision by routine rigid procedure or 'bury and forget' attitudes.

Some general points which will assist in the use of QRA to guide risk guided supervision include:

- Think about each of the foreseeable changes and act accordingly
- From case to case each change may have a different effect on changes in risk
- From case to case each risk control (mitigation method) may have a different cost
- By analysing the change in risk using QRA and determining the cost each control can be assessed by risk cost benefit analysis

Further general guidance on possible or specific risk changes can be found in Section 6 and Section 9.

7.3.5 Design impacts on ongoing supervision

One area of design which is commonly overlooked is the cost involved with maintaining earthing systems once constructed. Again, the QRA process can be used to compare the cost and risk posed by ongoing supervision requirement post construction. The following process can be used at design time to assess the impacts of various design choices on the ongoing supervision requirements:

- Consider all listed potential changes, and any others applicable, in the design
- Consideration should include: likelihood, expected consequence, possible controls, mitigations, methods or detection and suitable response
- All considerations should be documented and where life cycle management actions are recommended or required they should be documented in the design or maintenance manual for the station/asset

7.4 Maintenance, Modification and Refurbishment

Maintenance is repair including like for like replacement. No design work should be required and re-commissioning may be limited to proving the change has no net affect and is properly completed.

Modification is where changes are made to the system and a competent earthing designer should be included to determine if the changes could affect the earthing system performance and therefore what design work and re-commissioning is required.

Refurbishment is where a significant number of changes are required constituting a significant change overall. It may include an overall upgrading or renewing. Refurbishment requires design, construction support and commissioning.

Care must be taken to ensure the installation or removal of connections or bonds does not expose workers to hazards produced by operational conditions. Operational hazards, due to their potentially long term of coincidence, will require the hazard levels to remain below ELV levels unless the hazards can be proven temporary. Temporary hazards can be considered in line will hazards produced by earth faults.

7.5 Retirement

Effectively not used under all normal circumstances and is no longer in ‘care & maintenance’, however it may still be connected to an earthing network that is in service. Care must be taken when an earthing system is considered retired. There may be no clear or obvious connection to a live installation but hidden connections may remain. This is particularly true where substations have been decommissioned but cables have been left buried and connected to the operational network. These circumstances allow energy to be transferred to the retired earthing system in the event of a fault within the operational network.

7.6 Removal

The removal of an earthing system requires a special kind of careful construction support. It is very similar in activity to the refurbishment of an in-service earthing system. Care must be taken that for the breaking of all connections and in many cases such work should be treated as a possible ‘live’ operation. Further, bonds used to protect workers from transfer hazards or operational circulating currents may need to be protected or installed in a redundant manner to ensure ongoing safe working conditions.

8. Design Process Summary

Safety for both utility staff and the public in the event of an earth fault is one of the primary purposes of an earthing system. The goal of earthing system design optimisation is to ensure adequate robustness in the functionality and safety of the design at the same time as finding a balance between cost, practicality and management of risk.

The key components of a quantified risk analysis and assessment process applied to management of earthing related shock hazards were introduced in Section 4. Section 6 took the findings of the case study analysis and used quantified risk analysis to examine the impact of the key parameters on risk profiles. This section illustrates how risk quantification may be incorporated within an earthing system design procedure.

For such a process to be successful it should provide flexibility to cover as wide a range of cases as possible, lead designers to make conscious (and articulated) decisions, identify all significant hazards, meet appropriate risk targets and facilitate ongoing compliance.

A number of existing traditional design methodologies are outlined in Appendix A. The various design methods exhibit a common framework which includes:

- Data acquisition e.g. fault current level, fault current duration, soil resistivity, area of installation, details of surrounding installations
- Design with respect to thermal and mechanical requirements
- Design to meet touch and step voltages requirements
- Verification of design based on calculations and measurements

The following two sections provide insights into how the new QRA processes may be integrated within the earthing design process.

8.1 Generic Design Procedure

Appendix A provides examples from current standards which incorporate some form of QRA within an earthing design process. A generic design procedure that incorporates QRA within the process is shown in Figure 8.1. The main elements of the existing traditional design procedures have been encapsulated in the simplified design procedure. The design steps shown in Figure 8.1 are discussed in Section 8.2 with particular focus upon the findings of the Chapter 6.

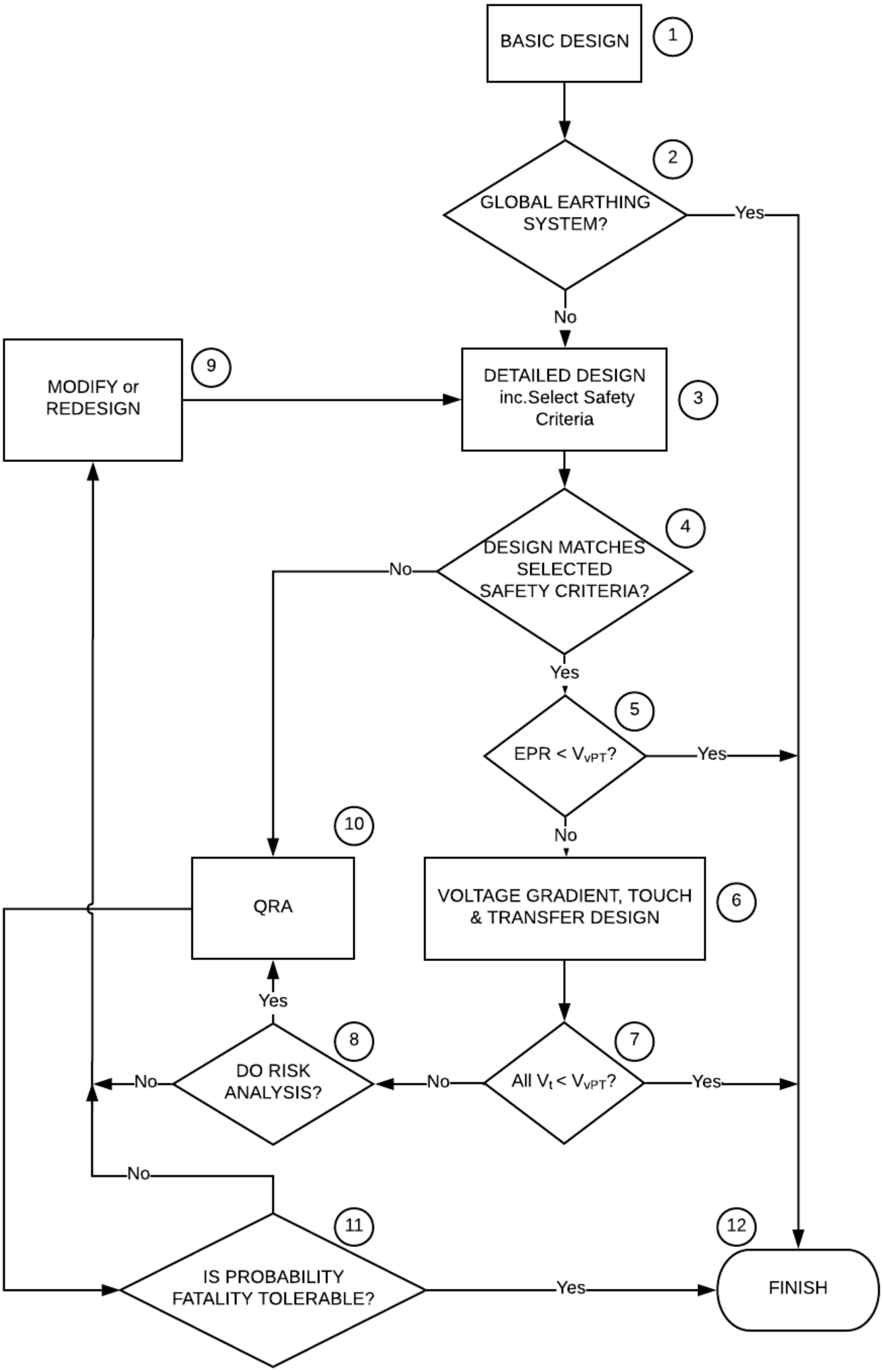


Figure 8.1 Generic earthing system design procedure incorporating QRA

8.2 Generic Design Procedure Process Description

Each of the steps shown in the generic design procedure are briefly discussed in the following points:

Step 1) Basic Design

Data collection

The validity of any design is contingent on the accuracy of the data used. The data is usually collected in a staged manner, as required by the designer. 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, the following data would generally be required:

- fault levels and primary and backup 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 (including services search and neighbouring infrastructure).

Initial design concept

Determine the earthing system layout that will likely meet the functional requirements and calculate an initial EPR estimate. The first pass sets a conservative upper limit for the EPR and enables assessment of which fault scenarios should be the focus of the detailed design effort.

First pass safety criteria

Determine a conservative value of tolerable prospective touch voltage (V_{ptt}).

Step 2) Assessment of Global Earthing

Is the installation part of a global earthing system?

Prove or verify that the installation is or is not part of a global earthing system, where there are no relevant potential differences (i.e. the maximum touch voltages are less than V_{ptt}). This outcome will usually be met where the EPR is less than V_{ptt}.
A global earthing system will best manage risk by limiting the EPR through distributing earth fault current to interconnected systems or dissipating fault current into a low impedance local earthing system. While the notion of gradient control through the creation of a 'quasi equipotential surface' has popular appeal, it should not be readily relied upon, as testing experience has shown non-compliant exceptions.
The 'multi grounded neutral' (MGN) scheme that is common in many North American systems relies upon the use of a continuous underslung conductor interconnecting all structures carrying MV lines as well as the MV source and downstream substations, with earth electrodes installed at regular intervals (e.g. every 3rd structure). Such a system can be very effective in returning a large percentage of the fault energy directly back to the source and distributing the remainder into adjacent MV and LV earthing. Care should be taken to recognise that only limited energy will couple through a single, often high resistance (e.g. steel) 'groundwire'. An additional consideration is the theft of copper down-conductors that can significantly weaken the performance of the MGN network. Therefore, as for the 'global earthing system', an MGN network is not inherently 'safe' unless shown to be.

Step 3) Detailed Design

The following steps are usually included within the detailed design stage for a substation earthing system:

a) Functional earthing requirements
b) Soil resistivity
c) Current flowing into the earthing system
d) Impedance
e) Earth potential rise
f) Standard permissible touch voltage criteria applicable at hazard locations

a) Functional earthing requirements

The design of the earthing system should consider the following functional considerations:

- Provide current paths, from equipment housing or supporting HV and LV power circuits, that are capable of carrying maximum current over maximum time (ie backup protection clearing time) without mechanical damage, considering mechanical impact on the conductor, mechanical impact from current forces, temperature rise, corrosion, redundancy to manage reasonable contingencies (ie at least N-1).
- Corrosion resistance
- Joint ratings
- Rating and efficacy of embedded earthing (ie use of metallic reinforcement embedded within concrete) to carry earth fault and lightning currents without damaging the integrity of the concrete, as well as providing voltage gradient control.
- Ability to inspect and validate the integrity of critical earthing system components (eg cable sheaths, counterpoise conductors, bonds to remote earth electrodes)

Additional guidance regarding functional earthing requirements is provided in the following guides and standards: EN50522 [6], IEEE80 [27], ENA EG-1 [83].

b) Soil resistivity
Determine the soil resistivity models needed to calculate local and interconnected earthing system response to locally dissipated current as well as inductively returned currents. Robust soil resistivity models are vital if the expected EPR as well as voltage gradients are to be adequately characterised. Section 6.3 provides guidance regarding acknowledging the variability in the soil resistivity (eg seasonal effects, variations in resistivity across the installation), and overcoming testing pitfalls and result analysis and interpretation errors.

c) Current flowing into the earthing system
For each of the relevant fault cases determine the magnitude and duration of the incident fault current at the fault point and the distribution of return current through the local earthing system as well as the interconnected network. Future conditions should be considered regarding additional circuits increasing the current magnitude whilst providing additional paths for dissipating current into the soil and possibly returning currents directly to the source.

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.

- For personal safety the fault clearing time of primary protection relays (or first upstream protection device) and circuit breakers shall be used. The duration of the initial fault and consequent auto reclose events should not be aggregated.
- For conductor and connecting joint thermal requirements back-up relay protection operating time, plus circuit breaker operating time shall be used as a minimum. 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.

d) Impedance
To enable the EPR to be calculated accurately the impedance through which a component of fault current will be dissipated locally must be calculated or measured.

e) Earth potential rise
Based on soil characteristics and the likely proportion of the total earth fault currents flowing into the local earthing system (see Section 6.1 and 6.2), determine the expected earth potential rise (EPR) for each fault case. 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.

f) Standard permissible touch voltage criteria applicable at hazard locations
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 e). Determine if a predetermined or standard voltage/time (V/t) curve is applicable for the identified hazard scenarios.
When developing or assessing touch voltage criteria to be used in the design of earthing systems for a class of asset, a group of practitioners in a workshop environment may agree on values based upon the best estimates of the group.

When designing a specific new substation an alternative method may be used. Once the basic functional earthing requirements are included in the design (ie a first pass layout), contact frequency data may be varied until the risk matches a predetermined figure (eg 10^{-6}) for each exposure location, as it is often easier to make a decision based upon the reasonableness of a calculated figure. An iterative process can then be followed to determine the risk/cost benefit. This process of 'reverse engineering' is also useful when reviewing the performance of an existing station and developing a business case to justify mitigation works or prepare a defence for not mitigating further.

Step 4) Case Study Match Check

Do the hazard scenarios match the assumptions behind the typical safety criteria curves?

During each of the earth fault conditions associated with a substation a range of hazard scenarios are created. The hazard scenarios relate to sites where people may come into contact with a voltage created during an earth fault event and are characterized by contact type (eg hand to feet), contact frequency and duration as well as fault frequency and duration. If all the hazard scenarios lie within the boundary conditions associated with at least one of the typical safety criteria curves then the design may progress using the standard curves. Otherwise a site-specific risk analysis (see Step 10) may be undertaken to either determine an applicable curve or calculate the risk profile for the site-specific hazard scenario.

Step 5) EPR Check

Is EPR lower than all selected permissible touch voltages?

If the EPR is less than the lowest permissible touch voltage, then the shock safety requirements of the design are met. It is usual that there will be more than one EPR to consider, depending upon the range of fault sources and locations. Note that the inductive effects of incident and return fault currents upon parallel services may still require assessment and mitigation.

Step 6) Voltage Gradient, Touch and Transfer Design

Calculate or measure resultant touch voltages, transfer potentials and stress voltage to LV either as an absolute value or as a percentage of the substation EPR. It is usual to begin the analysis with a conservative estimate of the maximum EPR, however, in many cases such an approach yields excessive mitigation requirements, particularly when managing risk associated with transfer hazards beyond a substation perimeter fence line.

Fault voltages may be calculated or measured at locations where staff or public may be in contact with metalwork (both within a substation, and on any metalwork or utility service outside the station) or walking in areas of high voltage gradient (area immediately surrounding a station) and able to receive an electric shock during earth fault occurrences. Each point is characterized by: contact location, contact voltage (%EPR), contact configuration (e.g. hand to feet), series impedance (e.g. footwear). Contact frequency and duration estimates will be required for each site if a QRA is undertaken (Step 10).

Step 7) Touch Voltage Check

Are touch voltages lower than permissible touch voltages?
If the expected contact voltages exceed the permissible touch voltages a designer may either undertake additional mitigation measures to reduce the hazard magnitude (Step 9), or use QRA to undertake a direct probabilistic design (Step 10).

Step 8) Decide Whether to Apply QRA

A designer may choose to either modify or redesign the earthing system (Step 9) in order to reduce the hazard level (ie EPR and hence Vptt) and then re-evaluate the resultant hazard level, or undertake a quantified risk analysis (Step 10).

Step 9) 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:

- reduction of the impedance of the earthing system (including additional conductive return paths such as cable sheaths or counterpoise conductors).
- 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-compliant infrastructure.

Step 10) Direct QRA

Undertake a direct probabilistic design (in contrast to using QRA derived curves in Step 4).

For each shock hazard location determine:

- contact configuration
- shock circuit impedances (for example, footwear and asphalt)
- the fibrillation probability (based upon the prospective fault voltages)
- the fault/presence coincidence probability
- the resultant probability of fatality.

The probability of fatality will fall in one of three categories: intolerable, intermediate, and tolerable (see Section 3). A risk cost benefit analysis may be used to assess and justify the cost of the risk treatment against a range of criteria [1].

Step 11) Assessment of Risk Tolerability

Based upon calculated fatality probability, is the risk tolerable or not?

Tolerable safety limits have previously been defined as a single touch voltage time characteristic for each exposure/clearing time couplet. The QRA process provides the ability to determine the total fatality probability by summation of the contribution from any number of fault scenarios by analysis of discrete cases or by Monte Carlo analysis. Tolerable risk limits are usually defined with an upper and lower boundary and assessed using an ALARP process. If the risk does not meet tolerable guidelines the designer may either further reduce the hazard levels (see Step 9) or undertake a risk cost benefit analysis to determine whether or not the cost of the mitigation measure is grossly disproportionate to the resultant risk reduction. Chapters 3 and 4 and Appendix B provide additional guidance on assessment of risk.

Step 12) Design Finalisation

The following steps may be considered to form the final steps in the design process.

a) Lightning and transient design

Consider the need to implement any particular design precautions to manage the impact of lightning and other transients. Other transients could include those during routine switching as well as fault initiation and fault clearance (e.g. reactive compensation, cable switching, transformer energisation and disconnector switching in GIS).

b) Construction support

Provide installation support as necessary to ensure design requirements are fulfilled and that construction staff safety risk is effectively managed.

c) 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. A staged inspection and test plan will ensure that the physical configuration and electrical response of the installed system meets the design requirements.

d) 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.

The shock risk quantification process may be integrated within existing design frameworks and provide designers with a defensible way to either support maintaining the present risk profile, or develop a business case to justify a site-specific risk mitigation strategy. Appendix B provides an example of how QRA may be integrated within a traditional earthing design procedure such as EN50522 [6].

9. Case Studies

This chapter is intended to bridge the gap between the theory of Chapter 6, where the variations in inputs to earthing systems were examined and their range of effects on output residual risk was shown, and real world assets that we might be working with in the application of Chapter 8.

9.1 Case Studies – Transmission

9.1.1 Introduction

To illustrate how a QRA process may be applied to practical earthing system design and assessment for large transmission substations two case studies are presented: one with overhead lines feeding and distributing power from a 400/110kV substation, and the second with buried cables feeding and distributing power from the transmission substation. The aim is to assist practitioners gain insight into how various design factors impact the risk profile of earthing systems, not to provide rigid guidance that may be applied by rote in all circumstances.

While the specific systems under consideration for these case studies are fictitious, they have been selected to be representative of large transmission systems. The first case study, presented in Section 9.1.2 considers a typical substation in an overhead transmission network, whereas the second, presented in Section 9.1.3, considers a typical substation in an underground transmission system.

A range of system modelling and analysis is performed for each case study with the aim of characterising the expected variability of various parameters so their impact on the QRA outcomes may be investigated. Since the primary aim of these case studies is not to provide a detailed example of a design process, but rather to illustrate the sensitivities of the QRA a number of simplifying assumptions have been made when performing the system modelling. These simplifications are often based on assuming a parameter to vary across of a range of values instead of attempting to calculate a precise value. In a real design scenario, practitioners could, and likely should, use additional information and modelling to produce singular design outcomes.

The QRA process applied in these case studies is consistent with the risk calculation process outlined in Appendix C of EG-0 (Energy Networks Association Limited, May 2010). The main stages of this process are:

i. **Data Gathering and System Description** - The details and parameters of the system under consideration are defined.

ii. **System Analysis** - The performance of the system is determined. This includes aspects such as fault levels at various locations, contributions by various elements of the earthing network and the resultant EPRs throughout the network.

iii. **Hazard Analysis** - Determining the magnitude and duration of hazards, nominally in the form of touch voltages, present within and around the network.

iv. **Risk Analysis** - The determination of the risk to an exposed individual, and subsequently what the risk posed by the network is to an asset owner. This starts by using the previously calculated hazard levels at various locations to calculate the probability of fibrillation (P_{FIB}) and then incorporate some description of the likelihood of an individual being at those locations and exposed to the hazards, which allows the probability of coincidence (P_{COINC}) to be determined. The overall probability of fatality (P_F) is then *simply* the product of P_{FIB} & P_{COINC}.

There are a large number of parameters that might impact the risk calculated by the QRA, for example: soil resistivity and layering, fault level, behaviour of people, earth-wire performance, fault clearing times, etc. As there are two main aspects to the calculated risk in this QRA framework (P_{FIB} & P_{COINC}) the parameters will be grouped when performing the sensitivity analysis. One set of parameters will primarily impact P_{FIB}, another set will primarily impact P_{COINC}, and another may have effects on both.

9.2 Case Study A – Transmission Substation (Overhead Network)

9.2.2 System description

This case study centres on the earthing associated with a transmission substation, nominally 400kV/110kV, whose terminating lines are all of overhead construction.

The substation has two incoming 400kV lines which are greater than 20km long, and 6 outgoing 110kV lines of various lengths from 10km to 40km. The nominal bus fault levels at the substation are 40kA and 20kA for the 400kV and 110kV systems respectively. The nominal fault clearing times are 0.1s for both 400kV faults and 110kV faults in Zone 1 (80% of line), and 0.4s for 110kV fault in Zone 2. The substation earth grid is 220m ×100m, with a 20m mesh spacing, and the nominal soil model is 300Ωm. A diagram of the network configuration is provided in Figure , and detailed data, such as line construction, is provided in Appendix C.

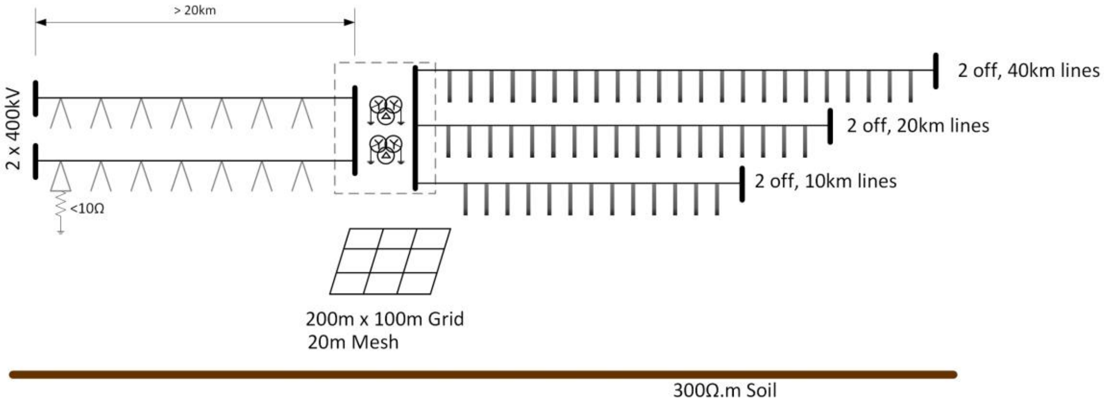


Figure 9.2.1 Transmission substation earthing system

9.2.2 System and hazard analysis

Before earthing risks can be quantified, the magnitude of the hazards (i.e. voltages) must first be characterised, however, to do this the performance of the system as a whole must be known, so as to determine how much current will flow out into other parts of the earthing network versus through the earth grid, since it is the current through the grid that is the primary cause of EPR at the substation.

A number of approximations and simplifications have been made in the modelling and analysis of the system for this case study. The motivation for these simplifications is to remove extraneous complexity, while still enabling the derived results, trends, and conclusions to be extended to realistic systems.

One such simplification is to reduce the analysis of the earthing performance of the transmission lines to use *conductive input impedances* as much as possible. In general, this means assuming there is only a single line supplying any fault, and all other lines are assumed to have no inductive coupling to this line. This dramatically simplifies the modelling, as inductive coupling effects need only be considered to the earth wires of the single line that supplies the fault. Taking the 400kV fault scenario as a concrete example of this simplification, it means the case study considers a single supply fault, that is, with one 400kV line out of service. The most significant impact of this is that the fault levels considered for the case study analysis are lower than when both 400kV lines supply the fault. While the fault levels would be higher for the dual line fault case, the inductive coupling effects would also be greater on the earth wires on the 400kV lines, causing more current to be returned via the earth wires. The key factor in analysing risk associated with the earthing system is the EPR, which is driven by the amount of current flowing through the earth grid at the substation, therefore neglecting the specific details of the interplay between increased fault current and inductive return inherent to the dual supply case allows the general principles to be illustrated without the additional modelling complications that would be required for a full consideration of the dual supply case. Obviously, any real substation design or assessment should consider all fault scenarios and determine the worst case, which may be either the single line, or dual line case depending on the specifics of that particular site.

Another simplification is to assume there is a break in the zero-sequence at the substation under consideration. The power system described in Section 9.1.2.1 includes $Y\nabla Y$ auto-transformers at the substation, which in reality do not break the zero-sequence network and earth faults on the 110kV network transfer energy to the 400kV network. In practice this is beneficial, as the transferred energy reduces the hazards at the substation for 110kV faults, however it also makes the example needlessly complicated. For any actual design or assessment the contribution of the 400kV network to the overall earthing system performance should be characterised, and the resulting reduction in EPR considered [77].

Nominal Values

The performance of the system under nominal conditions was modelled to be used as a baseline for use in the QRA sensitivity analysis. This modelling included determining parameters such as the earth grid resistance, input impedances, touch voltages as % or EPR, etc. The full details of this analysis are presented in Appendix C, however the key parameters are reproduced here for ease of reference.

Table 9.2.1 Nominal system performance parameters

Parameter	Nominal Value		
	400kV Fault	*110kV Zone 1 Fault*	*110kV Zone 2 Fault*
Soil Model	300Ω m		
Grid Resistance	1Ω		
Earth Fault Current	40 kA	20 kA	
EPR	2785 V	1740 V	1190 V
Clearing Time	0.1 s	0.1 s	0.4 s
Fault Rate	0.1/year	4/year	1/year

A summary of the nominal values of various system performance parameters may be found in Appendix C. Note that it is assumed that faults on the 110kV line are equally likely to occur at any location, so 80% of the faults will fall into Zone 1 of the protection scheme and the remaining 20% will be in Zone 2.

Three hazard locations are considered in this case study:

- **Mesh**: The maximum mesh voltage calculated for the substation. This is a reasonable approximation for the maximum touch voltage that could be expected anywhere inside the substation yard, even when ‘long reach’ or ‘transfer situations’ are considered.
- **Gate**: Touch voltage from an open gate 3m from the edge of the Substation 1 earth grid.
- **Shower**: House touch voltage, assuming the house pipes/neutral are remotely earthed and the individual’s feet are positioned 10m from the edge of the Substation 1 earth grid. This case includes TN & TT system (unless the TT system has no conductive transfer beyond the individual premises via plumbing, fences or concrete reinforcing for example). Alternatively, this touch voltage is the transfer out via neutral interconnections to places where the soil voltage has dropped away (TN only).

The nominal parameters for each of these hazard locations are shown in Table 9.2.2, again the full details of how these values were derived can be found in Appendix C, including line details. Note that the hazard voltages presented in Table 9.2.2 are normalised as a percentage of EPR, the actual voltage hazards for the nominal baseline scenarios are shown in Table 9.2.3.

Table 9.2.2 Nominal normalised hazard parameters

Hazard Location	Voltage as %EPR	Surface Layer	Contact Rate	Contact Duration
Mesh (interior)	25.9 %	Crushed Rock	1000 / year	4s
Gate (exterior)	36.8 %	None	1000 / year	
Shower	52.0 %	None	2000 / year	

Table 9.2.3 Nominal hazard voltages

Hazard Location	Hazard Voltage		
	400kV Fault	*110kV Zone 1 Fault*	*110kV Zone 2 Fault*
Mesh	725 V	450 V	310 V
Gate	1030 V	640 V	440 V
Shower	1455 V	900 V	620 V

Variation in Parameters

To perform the QRA sensitivity analysis a range of values will be considered for a number of key parameters. The range of values used has been determined via further modelling and analysis of the system performance, the details of which can be found in Appendix C. The parameters that will be considered in the QRA analysis are:

- EPR
- Fault Clearing Time
- Fault Rate
- Electrical Soil Model
- Contact Rate
- Contact Duration

Some of these parameters (e.g. contact rate) are entirely independent of the earthing system performance, whereas other parameters such as the electrical soil model have an impact on numerous aspects of the system performance.

As it is a major contributor to the expected variation in system performance a range of electrical soil models were considered, including two layer and homogeneous models. The nominal homogeneous soil model was varied from 300–3000Ωm, along with a variety of *high-on-low* and *low-on-high* soil models. For the *low-on-high* models the upper layer was fixed at 300Ωm, and the lower was varied from 300–3000Ωm, whereas for the *high-on-low* models the lower layer was fixed, and the upper layer varied across the same range of values. For all two-layer soil models the transition depth was fixed at 10m.

For each of the soil models under consideration the earth grid response was modelled to determine revised values for the grid resistance, and the hazard voltages as a %EPR. A selection of these values is presented in Table C1.1 (Appendix C). As might be expected the factor of 10 variation in soil resistivity lead to a tenfold variation in grid resistance for the homogeneous case, and less for the multi-layer soil models. On the other hand, the normalised hazard voltages as a percentage of EPR varied from approximately half to double with different soil models.

It is important to highlight that there are flow-on effects as a result of the grid resistance and surface voltage profiles varying. Higher grid resistances will lead to a higher EPR per kA of fault current, but at the same time it will also tend to reduce the fault levels. Furthermore, changes in fault level may lead to changes in the clearing times depending on the protection scheme in place, and changes in the soil voltage profiles (and therefore the hazard voltages as %EPR) may lead to lower hazard voltages even taking the higher EPR into account. So, there is a complex interplay of factors in determining the actual hazard voltages and risk levels. Details of the variation in intermediate factors with soil model changes are provided in Appendix C, but the key outcome is that the calculated hazard voltages varied over a range of just less than half, to just over double their base values.

9.2.3 Risk assessment

Taking the results of the system modelling into account, the general approach for the QRA sensitivity analysis was to consider a range of fault, and hazard, scenarios and take one parameter at a time and vary it across a range of 50% - 200% of its nominal value for each scenario, while holding all other parameters constant. There are two main exceptions to this general approach: fault clearing time and soil model.

The fault clearing time was varied over a fixed range of 100ms – 500ms as this range is expected to include representative values for the majority of large transmission systems. For similar reasons, the same collection of soil models used in system modelling were also used in the risk assessments. The parameters under investigation, and the ranges used, are presented in Table 9.2.4.

Table 9.2.4 System performance parameters considered for Case Study A

Parameter		Values Considered		
		400kV Fault	*110kV Zone 1 Fault*	*110kV Zone 2 Fault*
EPR		1400—5300 V	870—3300 V	600—2300 V
Fault Rate		0.05—0.2 / year	2—8 / year	0.5—2 / year
Clearing Time		0.1—0.5s		
Contact Rate		500—4000 / year (location dependant)		
Contact Duration		2—8s		
Soil Model	Homog.	300—3000Ω m		
	High / Low	600—3000Ω m / 300Ω m @ 10m		
	Low / High	300Ω m / 600—3000Ω m @ 10m		

The results of the investigation into the effects of these parameters will be collected into two groups: those that primarily impact on the fibrillation probability (EPR, soil models, and clearing time[7]), and those that primarily impact on the coincidence probability (fault rate, contact rate and contact duration).

The QRA process used for this sensitivity analysis is described in Chapter 4 Section 4.4.4.

9.2.4 Fibrillation probability factors

Since the EPR is effectively the source of all the voltage hazards under consideration, it might well be expected that changing the EPR will also change the risk associated with all of the hazards, but the nature of the relationship is far more complex than the simple fact that changing one also changes the other.

A sample of the outcome of the investigation for all fault scenarios at one particular hazard location is reproduced in Figure 9.2.2, however, the complete set of results may be found in Appendix C. Note that both probability of fatality (P_{FATAL} (solid lines)) and probability of fibrillation (P_{FIB} (dashed lines)) are plotted, whereas probability of coincidence (P_{COINC}) is not shown since it is effectively a constant for these investigations.

[7] Observant readers will note that clearing time is also one of the factors in the calculation of coincidence probability, but for this case study the variation in clearing time from 0.1–0.5 s has relatively little impact on the calculated coincidence probability as the baseline contact duration is much larger than the baseline clearing time (40 × larger).

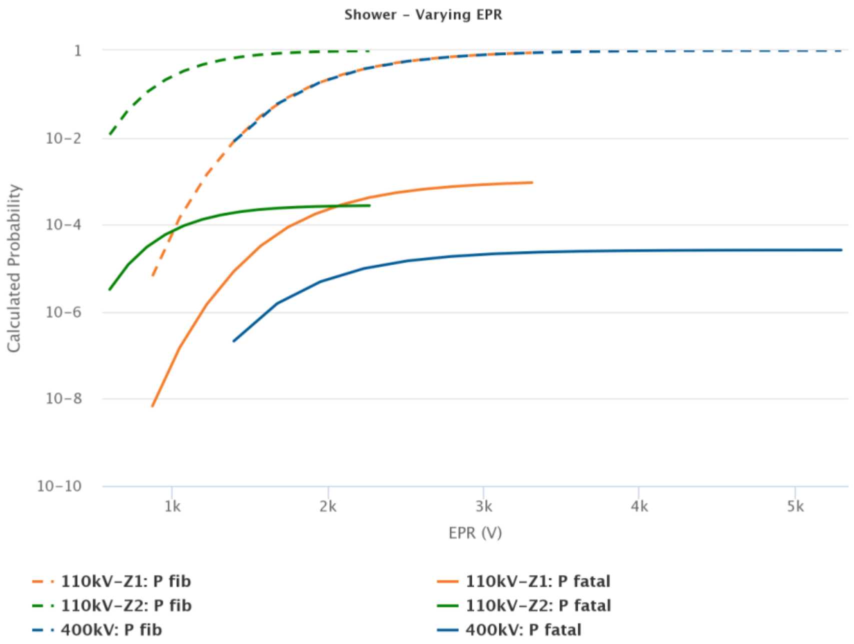


Figure 9.2.2: Calculated risks for shower hazard location with varying EPR

A number of conclusions may be drawn from this graph, the most obvious being the relationship between EPR and risk is decidedly non-linear, and quite sensitive to changes in the EPR by a factor of 4 can lead to changes of many orders of magnitude in the calculated risk. As can be seen this variation stems from the calculated fibrillation probability as the computed fatality probability curves are simply copies of the fibrillation probability curves offset by the relevant coincidence probability. The root cause of the sensitivity and non-linearity in the relationship can therefore be traced back to the factors in the calculation of fibrillation probability, essentially, the non-linear nature of the impedance of the human body, and distribution of current sensitivities across the population.

Another interesting aspect that these results highlight is the difference between the quantified *risk* and *hazard*. Consider the P_{FIB} curves over the range from 1.5kV to 3kV for the various fault scenarios. Both the 400kV and 110kV Zone 1 faults have identical P_{FIB} characteristics, whereas the 110kV Zone 2 fault scenario is different. In all of the cases the EPR, and hazard locations are identical, which also means the hazard voltages are identical. The difference between the characteristic is caused entirely by the differing clearing times. Both the 400kV and 110kV Zone 1 faults are cleared in 0.1s, whereas the 110kV Zone 2 clearing time is slower, which correspondingly means P_{FIB} is higher for the same applied voltage.

Now consider the P_F curves over the same range, and note that they are all different, even though some fault scenarios had identical fibrillation probabilities over that range. This is caused by differences in the coincidence probability factors between each fault scenario. The baseline fault rate for the 110kV fault scenarios are higher than the 400kV scenario, which means the coincidence probability, and therefore overall risk is also higher.

Another parameter that primarily impacts the fibrillation probability (at least in this case study) is the fault clearing time, and a sample graph of the results is reproduced in Figure 9.2.3.

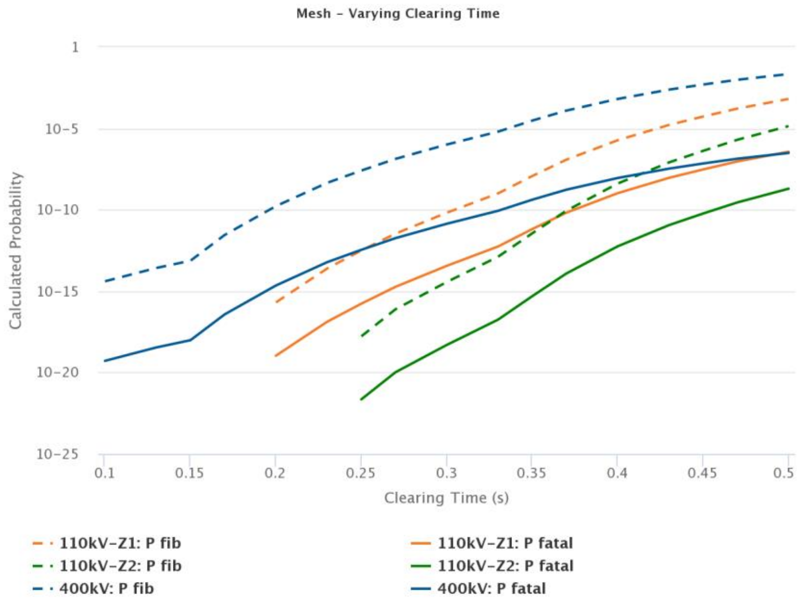


Figure 9.2.3: Calculated risks for mesh voltage hazard with varying clearing time

The primary feature of note in this case is the range of the computed probabilities. Taking the 400kV fault scenario as an example, the fastest clearing time has an associated risk of $\simeq 5 \times 10^{-20}$, and the slowest has a risk of $\simeq 3 \times 10^{-7}$ a difference of 13 orders of magnitude, which is caused by only a factor of 5 change in the clearing time.

While varying the EPR obviously does not change the coincidence probability, as previously noted, the clearing time is a factor in the calculation of coincidence probability. Despite this, the coincidence probability characteristics are not shown on these graphs because over this range of clearing times, the computed coincidence probability only changed by a factor $1.1 \times$ which pales into insignificance next to the many orders of magnitude impact it had on the fibrillation probability.

It is important to highlight that the relative impacts of clearing time on fibrillation probability and coincidence probability observed here may not hold for all circumstances, particularly when the clearing time is similar in magnitude to the contact duration. In fact, the range of clearing times under investigation here are likely to encompass the region in which the fibrillation probability is most sensitive, and coincidence probability is least sensitive to changes in clearing time.

The reason for the dramatic sensitivity of fibrillation probability to clearing time in this range can be traced back to the underlying current sensitivity characteristics of human beings. The data in IEC60479 [18] show that for exposures below about 0.2s the body can generally tolerate a much higher level of current flow than for exposures of 1s or greater. There is of course a transition in tolerances over the intermediate range, and the clearing times considered in this investigation predominantly fall into that range of transition.

It is also interesting to highlight that although the 110kV curves appear to be truncated for fast clearing times (below about 0.25s) they are not. Instead this is due to the calculated fibrillation probability (and therefore risk) being so small it is indistinguishable from zero, which of course cannot be plotted on a logarithmic axis.

This leads to another interesting observation about the relative magnitudes of the risk levels associated with the baseline scenarios of these two locations. Taking the 400kV fault scenario as an example, the baseline risk level for the mesh voltage hazard is on the order of 10^{-20} (see 0.1s in Figure 9.2.3), by contrast the baseline risk level for the Shower hazard location is on the order of 10^{-5} (see ≃3kV in Figure 9.2.2). So, for this particular system the hazards outside the substation carry a higher risk than those inside. Perhaps the most significant cause of this is that the baseline hazard voltage associated with the Shower location is twice that of the baseline Mesh voltage, but, note that again a comparatively small difference in an input parameter (factor of 2 change in voltage) leads to a much larger change in the quantified risk level (15 orders of magnitude).

The final class of parameters that primarily impact on the hazard level (fibrillation probability) is the electrical soil model. As has been discussed, a range of soil models have been considered including homogeneous and two-layer models. A sample of the results for a single hazard location are reproduced in Figure 9.2.4 through Figure 9.2.6.

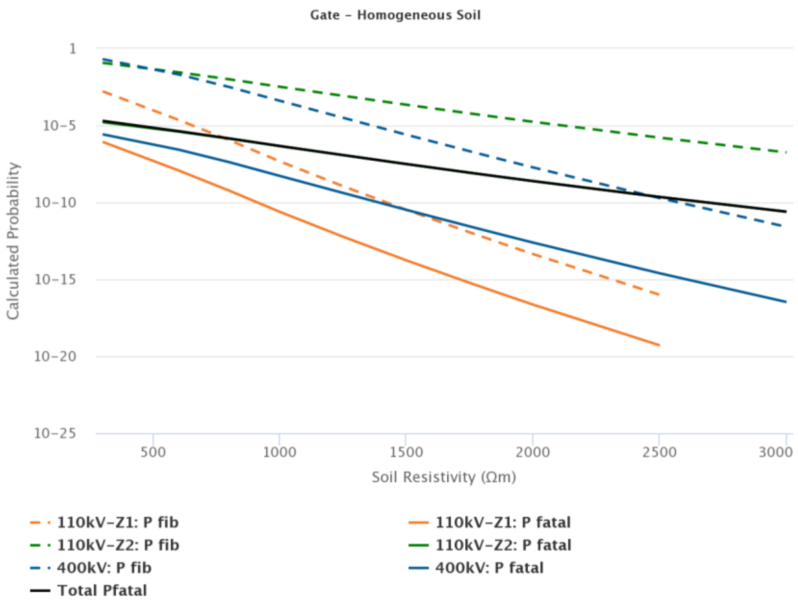


Figure 9.2.4: Calculated risks for gate hazard location with varying homogeneous soil models

The results for the homogeneous soil models presented in Figure 9.2.4 may be somewhat counterintuitive in that higher soil resistivity values corresponded with lower risk levels even though higher soil resistivity is typically associated with higher EPR as a result of increased grid resistance. The explanation for this outcome is that the system modelling described in Section 9.2.2 took the numerous impacts of changing soil resistivity into account. While higher soil resistivity does indeed lead to higher grid resistance, it also means additional impedance is inserted into the earth fault circuit, and therefore fault levels are reduced, and current distribution in the earthing system may change. An examination of the various impacts of changing soil resistivity on the intermediate factors that lead to these results may be found in Appendix C. In addition to those effects which alter the hazard voltage, increased soil resistivity also impacts on the fibrillation probability, as the additional impedance in the shock circuit acts to limit the current flow through the body and thereby reduce the fibrillation probability. This is effectively the same principle that underlies the use of high impedance surface layers such as crushed rock or asphalt.

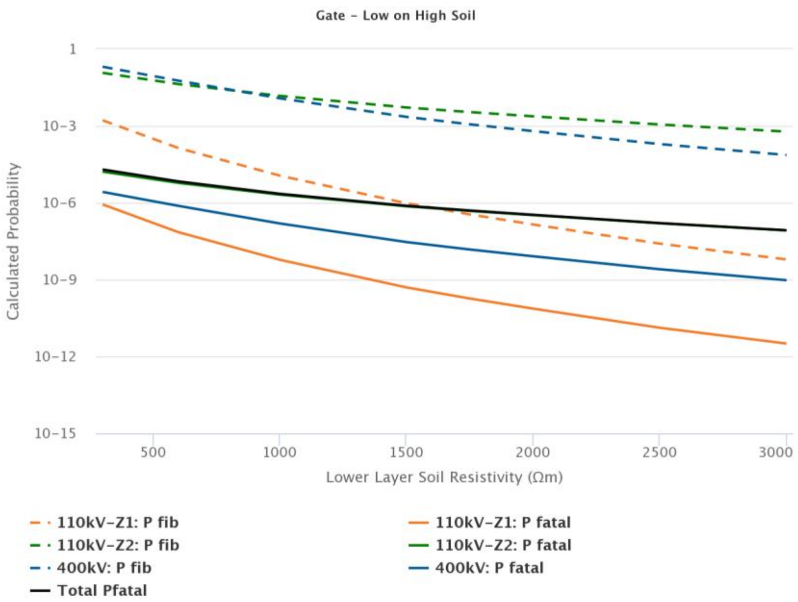


Figure 9.2.5: Calculated risks for gate hazard location with varying low-on-high soil models

Similar trends can be identified in the results for the *Low-on-High* and *High-on-Low* soil models presented in Figure 9.2.5 and Figure 9.2.6 respectively. The trends for these two-layers models are of course different to the homogeneous case dues to changes in the layering structure altering the surface voltage profiles and therefore also changing the touch voltages as a percentage of EPR.

For the case of a gate opened outward from the edge of the substation, more extreme high-on-low soil models produce higher voltage hazards as a percentage of EPR. This is because high-on-low soil models tend to result in very 'steep' soil voltage contours as the current tends to preferentially 'dive down' into the lower resistivity underlying layer. This means at the fixed location of the gate outside the substation the soil voltage would be lower, and therefore the voltage hazard (the difference between the soil voltage and the substation EPR) is greater.

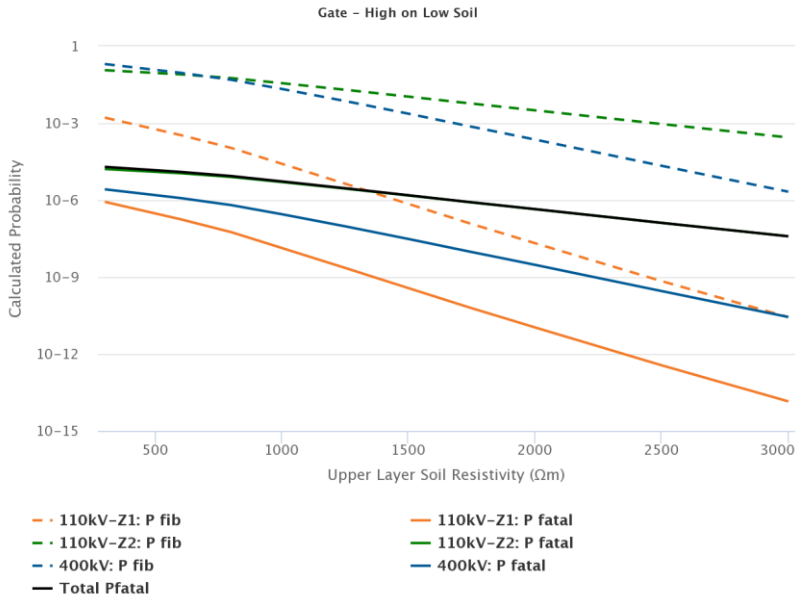


Figure 9.2.6: Calculated risks for gate hazard location with varying high-on-low soil models

Despite the high-on-low soil models tending to produce greater voltage hazards, it can be seen that there are situations where the calculated risk levels are actually lower than for the low-on-high soil models. This illustrates the complex interplay of all the factors dependent on soil resistivity, where higher hazard voltages resulting from a larger EPR may also be associated with less risk due to additional impedance in the shock circuit, and *vice versa*.

As with the other parameters, soil model variation demonstrates a much larger change in calculated probabilities than the range of variation in the input parameter. All of the results from these sensitivity investigations are summarised in Table 9.2.5. Note that in this table the ranges are computed as the ratio of the largest value to the smallest value. For all of these parameters the variation in computed risk (P_F) is much larger than the variation in the input parameters.

Table 9.2.5 Variation in quantified risk with fibrillation probability factors

Parameter		Input Variation Range	Computed Risk Variation Range
EPR		$4\times$	$>10^{10}\times$
Clearing Time		$5\times$	$>10^{12}\times$
Soil Model	Homogeneous	$10\times$	$>10^{13}\times$
	High / Low		$>10^{8}\times$
	Low / High		$>10^{9}\times$

9.2.5 Coincidence probability factors

The parameters investigated in Section 9.2.4 all primarily impacted the *fibrillation* probability, however there are also a number of parameters that primarily impact the other factor in quantified earthing risk, namely coincidence probability. In the simplified equation for calculating coincidence probability fault rate, contact rate, and contact duration are all featured, along with clearing time. As the impact of fault clearing time on quantified earthing risk has already been examined in Section 9.2.4 here the other parameters will be considered. As before a small sample of the results will be reproduced and discussed, with the full collection of results available in Appendix C.

The presentation of these results is slightly different from those in Section 9.2.4 as the relationships between the parameters are somewhat simpler, which makes it feasible to include both *fibrillation* and *coincidence* probabilities on the same graph with the overall quantified risk value. However, there are still a large number of combinations of fault scenario and hazard location, so to improve legibility each graph will only present a single combination. As before, risk of fatality (P_{FATAL}) is plotted with solid lines, fibrillation probability (P_{FIB}) with dashed lines, and now coincidence probability (P_{COINC}) is included with dotted lines.

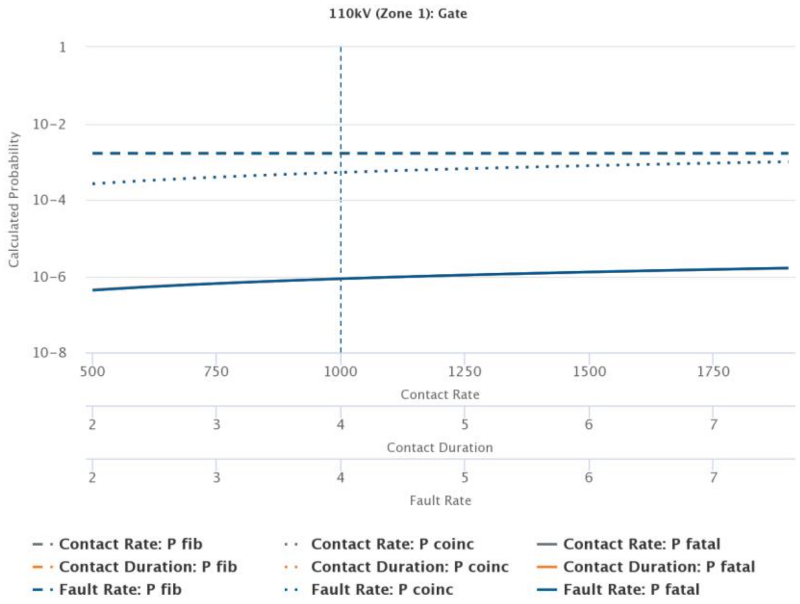


Figure 9.2.7: Calculated risks for 110kV zone 1 faults at gate hazard location with varying coincidence probability factors

Figure 9.2.7 shows how variations in these coincidence probability factors impacted the outcomes of the QRA process for hazards at the substation gate, under 110kV Zone 1 fault conditions.

Perhaps the most obvious difference between these results and those of the fibrillation probability factors is that the each of these parameters has the same relationship characteristic, so the lines for each parameter lie on top of one another when plotted on normalised axes. The vertical line is aligned with the nominal baseline values of the parameters, and again each parameter was varied over a range from $0.5\times$ — $2\times$ their nominal baseline value.

The main cause of this is that the calculation of coincidence probability from these factors is far more straightforward than the corresponding calculation of fibrillation probability from its input parameters. The simplified equation for calculating coincidence probability doesn't involve any of the non-linear relationships inherent in the fibrillation probability calculations.

The other major difference between these coincidence probability factors and the fibrillation probability factors is that the quantified risk is much less sensitive to changes in the coincidence probability factors as it is effectively a linear relationship. Whereas a factor of 4 variation in one of the fibrillation probability factors could lead to many orders of magnitude changes in the associated risk level, changes to these coincidence probability factors had a more direct impact of the associated risk a factor of 4 change in the input results in a factor of 4 change in the output. These results are summarised in 9.2.6.

Table 9.2.6 Variation in quantified risk with coincidence probability factors

Parameter	Input Variation Range	Computed Risk Variation Range
Fault Rate Contact Rate Contact Duration	$4\times$	$4\times$

9.2.6 Summary

There are a number of key insights in these results that can provide general guidance to practitioners tasked with designing or assessing similar transmission substations in overhead networks.

Firstly, the factors in this study which influence fibrillation probability (EPR, clearing time and soil model) can have a more dramatic impact on the quantified risk level than those which primarily impact coincidence probability (fault rate, contact rate and contact duration).

While the largest numerical changes in risk level were due to differences in the electrical soil model, this is not always a design variable that practitioners have control over. In fact, as the only real *control* a designer has over the electrical soil model is exercised through site selection it may be possible to situate the substation somewhere else with a more favourable soil model. However, in practical situations there are often many constraints that might severely limit the range of acceptable sites, and therefore available soil models from which to choose.

The magnitude of the EPR is one parameter the designer has more control over, and a large part of what might traditionally be thought of as *earthing design* comes down to controlling EPR. There are of course, many ways in which EPR might be reduced, from burying a more extensive earth grid, to using auxiliary earthing conductors to keep current out of the ground, or using different neutral earthing techniques to suppress EPR for the certain faults. No matter how a reduction in EPR is achieved it will (all other things being equal) lead to a reduction in earthing related risk.

Reducing the EPR reduces the risk primarily because it makes the hazard voltages smaller, another approach that has a similar effect is that of equipotential bonding. This principle is employed extensively inside substations with operator mats, and in fact one of the goals of substation earth grids is to ensure the entire substation acts like an equipotential plane. This may be seen in the case study results where the mesh voltage hazards fairly consistently resulted in lower risk than the hazards outside the substation. Sometimes it is appropriate for the designer to extend the equipotential plane concept beyond the boundaries of the substation to reduce the magnitude of voltage hazards.

One parameter that was demonstrated to have a very large impact on the level of risk was the fault clearing time. However this is frequently considered to be outside the domain of the earthing design and historically earthing practitioners may have had little say in the selection or design of protection systems. The clear message from these results is that reducing the fault clearing time can significantly reduce the earthing related risk, especially around the transitional zone of the current sensitivity curves (about 0.2s – 1s). The human body can tolerate much higher levels of low frequency ac current for short durations, and there may be dramatic reductions in earthing related risk available if protection systems are able to be changed or improved to reduce clearing times. However, as is the case with site selection there will be many factors in any practical situation that may limit the acceptable options.

The primary coincidence probability factors (fault rate, contact rate and contact duration) present an interesting conundrum to the practitioner, as there is very little control over these parameters. In most cases, modifying the behaviour of the people exposed to earthing related voltage hazards may not be feasible so the contact rate and contact duration might be fixed assumptions, but in other cases such as controlled work environments, improved education and training can lead to effective behavioural changes.

Similarly, the earthing designer may not have direct control over the fault rate. However improvements in network reliability can lead to positive reductions in earthing related risk. In the extreme case, if the system never experiences an earth fault, then it will never produce the associated voltage hazards. So, if all other avenues have been exhausted reliability improvements to the system as a whole may be the only remaining option for reducing earthing related risk.

When employing strategies based on these coincidence probability factors, there are a few things for practitioners to keep in mind. Firstly, in this case study the coincidence probability factors had a much smaller impact of the risk level than the fibrillation probability factors, and secondly these approaches will not reduce the magnitude of the hazards, only the likelihood of people being exposed to them.

The suggested strategy for reducing earthing related risk associated with the system considered in this case study is then to follow the standard *hierarchy of controls* approach and minimise the hazard level by searching for all reasonable methods of reducing the fibrillation probability. This might involve selecting a site with favourable soil properties, or employing a protection scheme that can guarantee a fast clearing time, or reducing the EPR by bonding auxiliary earthing conductors into the earthing system. Once those options have been exhausted the coincidence probability factors may be considered, but as discussed there may be very little control the earthing practitioner can exercise over parameters such as contact rate and duration, although there may be the possibility of improving overall system reliability.

9.3 Case Study B – Transmission Substation (Underground Network)

9.3.1 System description

This case study is an example of an inner-city substation, nominally 400/110kV with cable construction on all connecting transmission lines. The substation under consideration is supplied via three 400kV cables and supplies several 110kV circuits. A summary of the system is provided in Figure 9.3.1, and detailed data may be found in Appendix C.

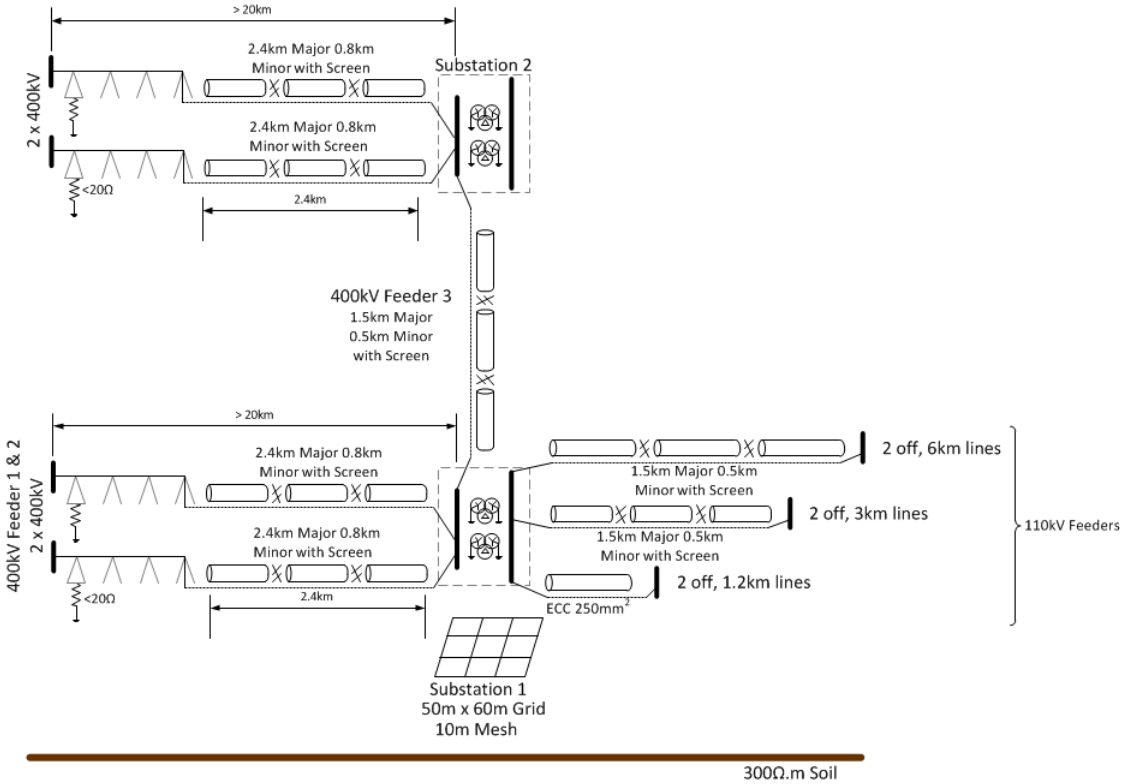


Figure 9.3.1: Schematic of transmission substation - cable case study

9.3.2 System and hazard analysis

As with the previous Case Study a number of simplifying assumptions and approximations have been made in the analysis of the complete system performance to reduce complexity. Examples of these simplifications and the application to the previous Case Study can be found in Section 9.2.2, and a similar methodology has been applied here.

9.3.3 Nominal values

As before, the performance of the system under nominal conditions has been used as a baseline for QRA sensitivity analysis. The same parameters as used in the previous Case Study were also considered. The full details of the nominal performance analysis may be found in Appendix C, including cable and line details, however the key parameters are reproduced in Table 9.3.1.

Table 9.3.1: Nominal system performance parameters – Case Study B

Parameter	Nominal Value	
	400kV Fault	*110kV Fault*
Soil Model	300Ω m	
Grid Resistance	2.6Ω	
Earth Fault Current	40 kA	20 kA
EPR	1595 V	115 V
Clearing Time	0.1 s	0.1 s
Fault Rate	0.1/year	5/year

The same hazard scenarios were considered as for the previous Case Study. Full details of these scenarios may be found in Section 9.2 however the key parameters are given below in Table 9.3.2 and Table 9.3.3.

Table 9.3.2: Nominal normalised hazard parameters – Case Study B

Hazard Location	Voltage as %EPR	Surface Layer	Contact Rate	Contact Duration
Mesh (interior)	24.5 %	Crushed Rock	1000 / year	
Gate (exterior)	43.5 %	None	1000 / year	4s
Shower	42.4 %	None	2000 / year	

Table 9.3.3: Nominal hazard voltages – Case Study B

Hazard Location	Hazard Voltage	
	400kV Fault	*110kV Fault*
Mesh	390 V	28 V
Gate	695 V	50 V
Shower	675 V	48 V

9.3.4 Variation in parameters

The QRA sensitivity analysis has been performed by varying key parameters over a range of values. Details may be found in Appendix C, where for the same reasons as the previous Case Study (described in Section 9.2) the same parameters were varied over a range of 0.5× to 2× their nominal values.

9.3.5 Risk assessment

The same process used for Case Study A (as described in Section 9.2) was used to investigate the sensitivity of the QRA process to various system performance parameters. A summary of the parameters considered, and the range of values analysed can be found in Table 9.3.4.

As with the previous Case Study the results have been grouped into those parameters which predominately impact the fibrillation probability and those which impact the coincidence probability. A selection of these results, along with a brief discussion may be found in Sections 9.3.6 and 9.3.7 respectively. The complete set of results may be found in Appendix C.

Table 9.3.4: System performance parameters considered – Case Study B

Parameter		Values Considered	
		400kV Fault	*110kV Fault*
EPR		795—3030 V	60—220 V
Fault Rate		0.05—2 / year	2.5—10 / year
Clearing Time		0.1—0.5s	
Contact Rate		500—4000 / year (location dependant)	
Contact Duration		2—8s	
Soil Model	Homogeneous	300—3000Ω m	
	High / Low	600—3000Ω m / 300Ω m @ 10m	
	Low / High	300Ω m / 600—3000Ω m @ 10m	

9.3.6 Fibrillation probability factors

As discussed for the previous Case Study (Section 9.2) the following parameters primarily impact the fibrillation probability:

- EPR
- Clearing Time
- Soil Model

The outcome of the investigation into varying the EPR at one particular hazard location is shown in Figure 9.3.2. Note that only the 400kV fault scenario appears as a line on this graph, and the fibrillation probability values for the 110kV scenarios under consideration were so small that the calculation resulted in zero values, which cannot be plotted on the logarithmic axes.

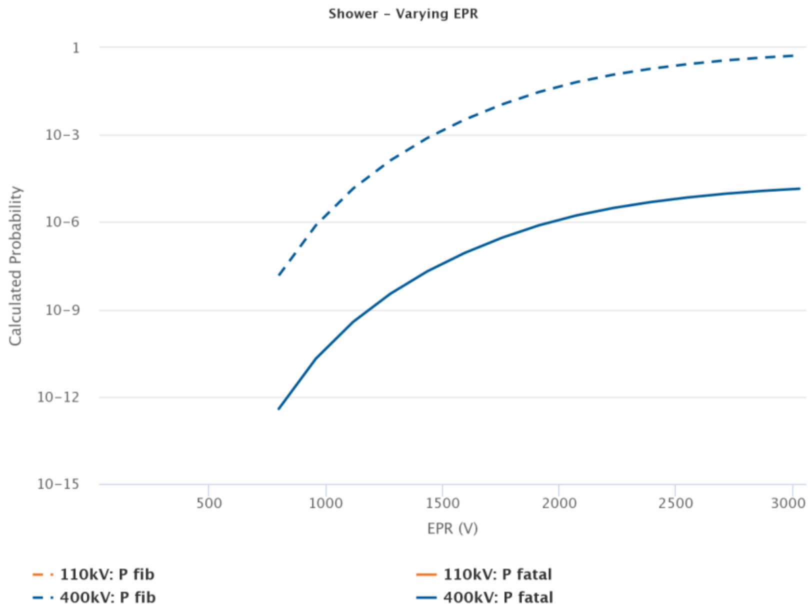


Figure 9.3.2: Calculated risks for shower hazard location with varying EPR (Case Study B)

Again, it can be seen that the relationship between EPR and fibrillation probability is non-linear, and quite sensitive. This relationship directly translates to the calculated fatality probability as well, since the coincidence probability is effectively a constant value for this analysis.

Figure 9.3.3 shows the results of one investigation into the impacts of variation in clearing time at one particular hazard location. Notice that again the 110kV fault scenario has a significantly lower fibrillation probability, since the applied voltages are much lower (see Section 9.3.2 Table 9.3.1), and for fault clearing times less than 0.35s the computed values were zero so the line is not shown on the graph.

As with the previous case study, changes in clearing time can lead to many orders of magnitude difference in the calculated probabilities, and the relationship is non-linear.

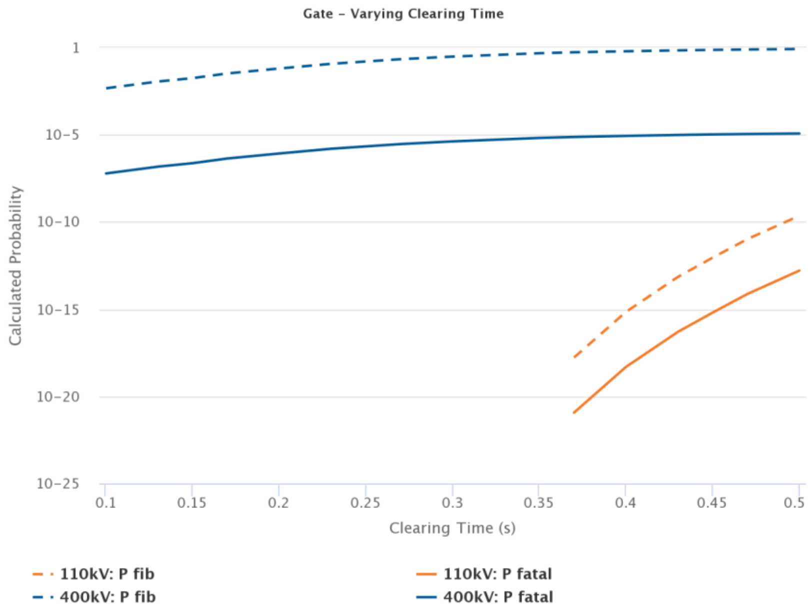


Figure 9.3.3: Calculated risks for gate hazard location with varying clearing time (Case Study B)

The results of the analysis at one particular location (shower in neighbouring home), with various soil models can be found in Figure 9.3.4 (Homogeneous), Figure 9.3.5 (Low-on-High), and Figure 9.3.6 (High-on-Low).

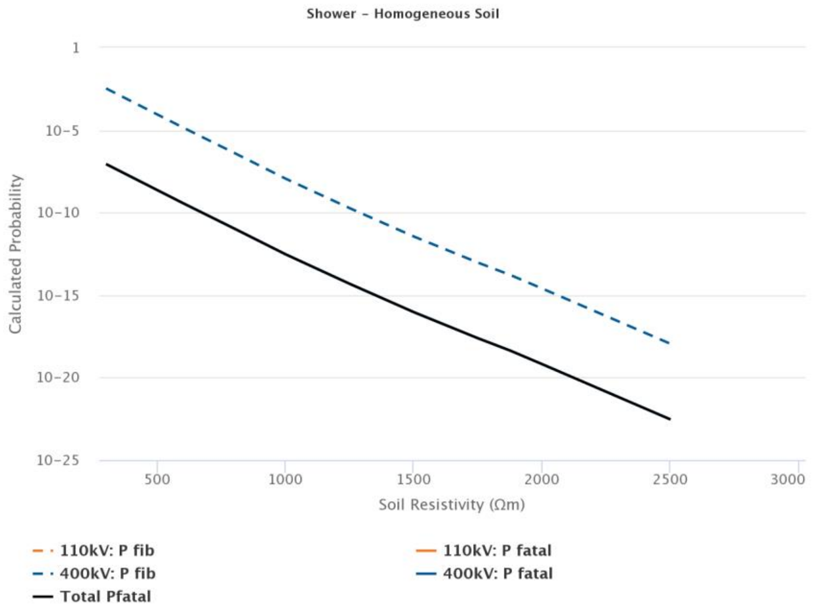


Figure 9.3.4: Calculated risks for shower hazard location with varying homogeneous soil models (Case Study B)

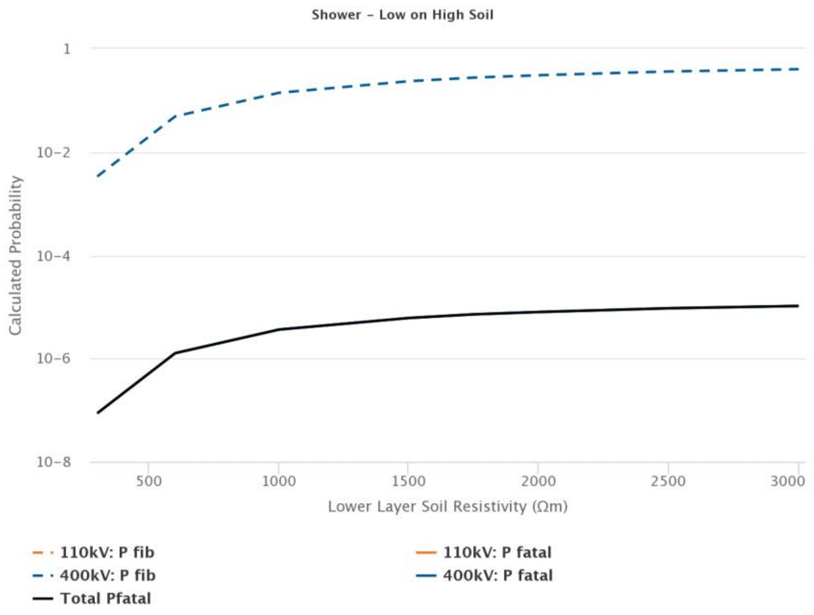


Figure 9.3.5: Calculated risks for shower hazard location with varying low-on-high soil models (Case Study B)

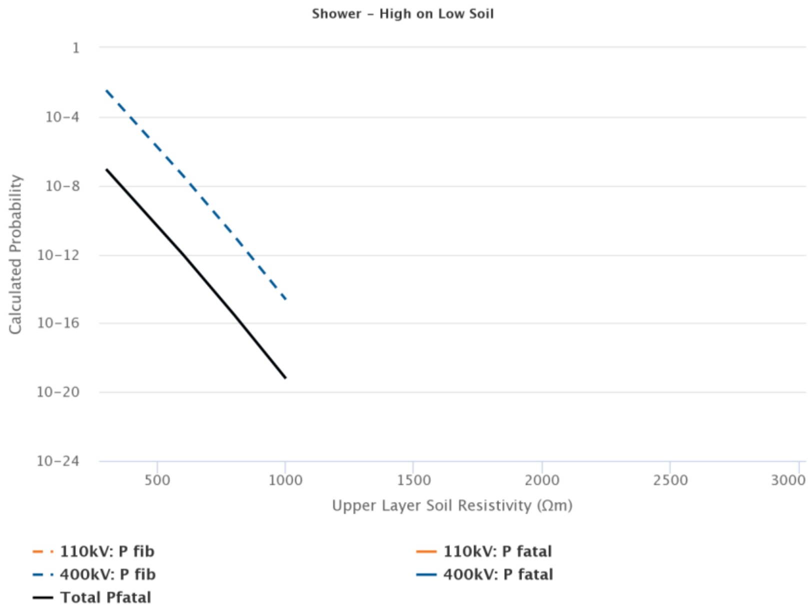


Figure 9.3.6: Calculated risks for shower hazard location with varying high-on-low soil models (Case Study B)

The results are consistent with the both the general trends observed in the previous results, and the results of the previous Case Study. The 110kV fault scenario results in zero values in the computed probabilities, so the lines do not appear on the graphs.

One interesting point of difference is to compare the trends observed in the Low-on-High soil model graphs in both Case Studies (Figure 9.2.5 and Figure 9.3.5) – noting that these graphs are for different hazard locations. For the Gate Location shown in Figure 9.2.5: there is a general concave trend to the graphs, whereas for the Shower Location in Figure 9.3.5 there is a general convex trend. This difference is because at the Gate location the voltage hazards are the result of a 'transfer-out' of EPR (i.e. the open gate is at EPR, whereas the person's feet are at the soil voltage, which has somewhat dropped off outside the substation), whereas the hazards associated with the Shower location are a result of a remote earth potential being 'transferred-in' to the zone of influence of the substation EPR (i.e. the hypothetical tap is at 0V, whereas the person's feet are at the soil voltage). As the resistivity of the lower layer is increased the equipotential contours around the substation earth grid spread out which increases the magnitude of 'transfer-in' hazards (e.g. Shower), but reduces the magnitude of 'transfer-out' hazards (e.g. Gate) as the soil voltage at each location is increased.

9.3.7 Coincidence probability factors

As described in Section 9.2.5, some of the parameters under consideration primarily impact the coincidence probability. Namely: clearing time, fault rate, contact duration, and contact rate. Since the clearing time results have already been presented, the other parameters are be presented here in Figure 9.3.7.

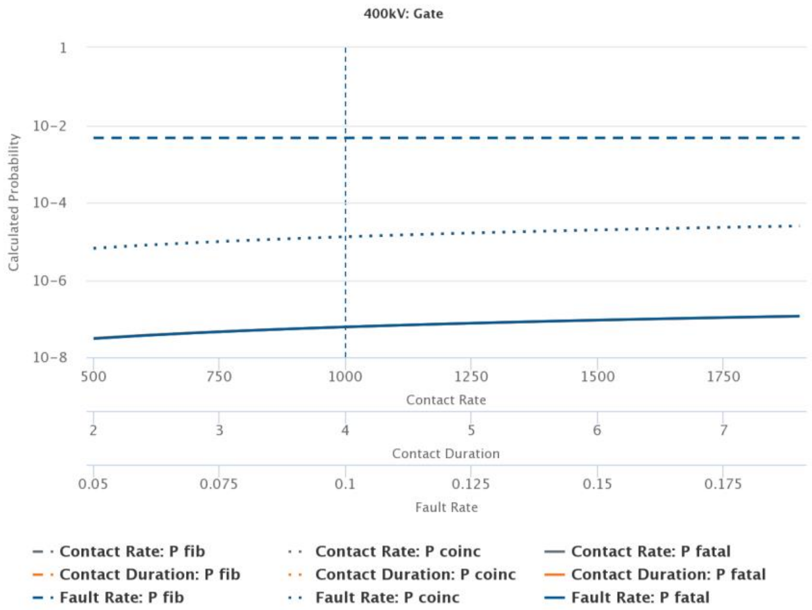


Figure 9.3.7: Calculated risks for 400kV faults at gate hazard location with varying coincidence probability factors (Case Study B)

Here, the characteristics are very similar to those from the previous Case Study, so the discussion in Section 9.2.5 is equally applicable to these results.

9.4 Conclusion

A sensitivity analysis for the QRA process has been performed on two different transmission level systems: a predominately overhead network in Section 9.2, and a cable fed network in Section 9.3. A number of conclusions may be drawn from the results of this analysis.

Perhaps the most obvious difference between the two different networks is that the magnitudes of the voltage hazards associated with the cable-fed network were much smaller than for the overhead network. This is largely due to the better earth return performance characteristics of cable screens compared to overhead earth wires. Inductive coupling drives more current back in cable screens than earth wires, and therefore there is less current passing through the substation earth grid, leading to lower EPRs and voltage hazards.

Despite these differences the Case Studies do illustrate some common trends in the outcomes of the QRA process.

Firstly, the relationship between the input parameters and the computed risk levels is generally non-linear, and different parameters have different impacts on the risk levels. The factors which primarily impact coincidence probability (fault rate, contact rate, contact duration) generally had a more straightforward impact on the computed risk values, and over the range of values considered there was an approximately 1:1 relationship (a 4× variation in input lead to ≈4× change in output).

By contrast, the factors that primarily impacted fibrillation probability (EPR, clearing time, and soil model) had a more complex relationship with the calculated risk levels. In addition, the calculated risk levels were much more sensitive to variation in these parameters – changes of 4-5× resulted in many orders of magnitude difference in the calculated probabilities.

Since the fibrillation probability is a measure of the magnitude of the hazard posed at a particular location, these ‘fibrillation probability factors’ are the parameters that designers should focus on when managing earthing related voltage hazards.

Historically the realm of the earthing designer may have been constrained to specifying how much copper to bury, and in what configuration, however these Case Studies demonstrate that significant reductions in risk may be achieved if earthing considerations are factored into aspects such as site selection, or protection design.

The soil resistivity has a significant impact on the risk levels associated with an earthing system, as it impacts the grid resistance and therefore EPR, and also acts as a series impedance in the shock circuit. However, unless the earthing designer is involved in the site-selection process there is very little design control that may be exercised over the electrical soil model. Instead, in many practical situations the earthing designer must focus on other approaches, such as lowering the grid resistance, to manage the EPR.

While reducing the EPR *is* an effective way to manage earthing risks, reducing the clearing time may be even more effective – particularly if faults can be cleared faster than about 0.3s. The clearing time is the only factor which appears in both the fibrillation and coincidence probability calculations, so faster clearing faults are not only associated with a lower hazard level, but it is also less likely that someone will be exposed to the hazard.

So, while aspects such as site-selection and protection design may be beyond the traditional scope of earthing designers, there may be significant benefits to the overall risk profile of the network as a whole if earthing considerations are taken into account in these traditionally segregated aspects of electrical engineering. These are in addition to consideration of substation footprint (earth grid area) and conductive interconnections such as cable sheaths.

9.5 Case Studies – Distribution

This case study is based on a representative distribution network, incorporating most of the basic aspects of commonly used distribution systems. The aim of the case study is to calculate the individual risk probability associated with an earthing system (ES) of distribution transformer station (DTS) located on a radial MV feeder (see Figure 9.5.1). The network configuration and characteristic parameters are chosen to reflect the operating conditions seen in the majority of distribution networks. A range of HV/MV transformer neutral point connection configurations are considered e.g. solidly earthed, insulated, compensated (resonant earthed), compensated with auxiliary resistor and earthed through resistor.

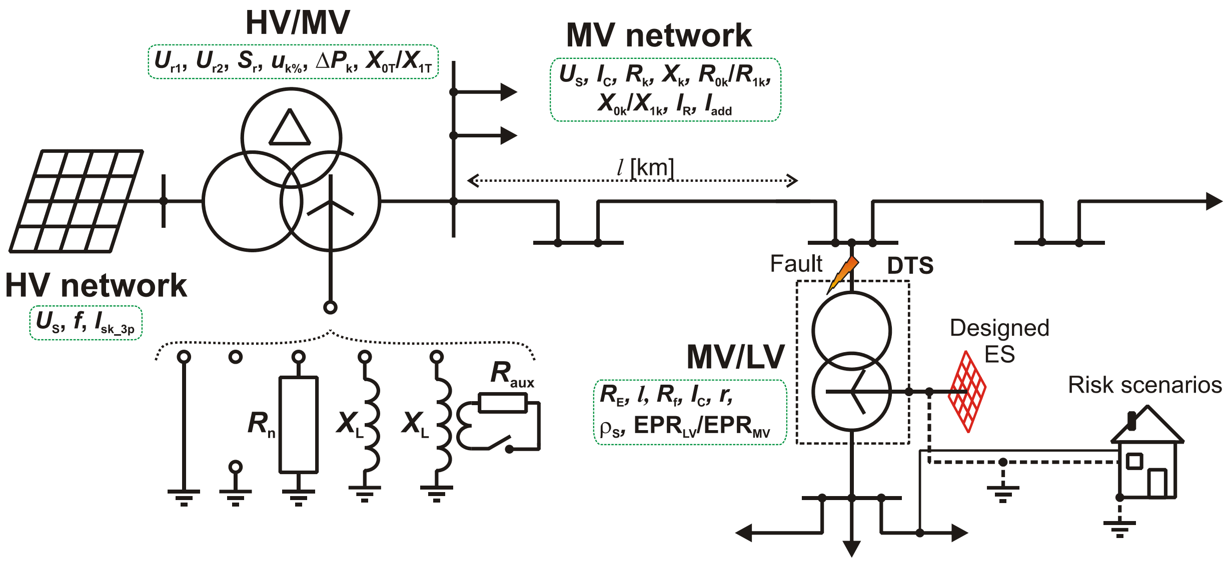


Figure 9.5.1: Simplified scheme of distribution network for demonstration of individual risk probability calculation – case study

The characteristic parameters of the network used in the base case (see Figure 9.5.1) analysis are described in detail in Appendix D. The MV and LV earthing systems may or may not be interconnected. Figure 9.5.2 illustrates how the voltage drop between the two systems is used in the case study.

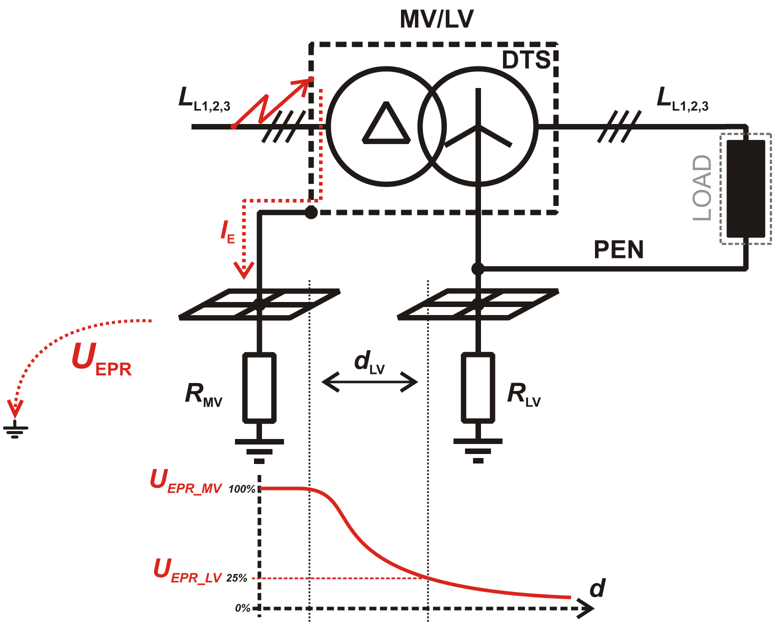


Figure 9.5.2: ***Potential transfer from MV to LV earthing system***

9.5.1 An example of individual risk probability calculation process

This section presents the process used to analyse the individual risk probability for the case study where the characteristic distribution network is operated with the neutral point earthed through a resistor. The procedure of individual risk probability calculation can be summarized in the following steps:

a) Determination of the network parameters and earthing resistance of designed or other relevant earthing systems
b) Fault frequency determination (see Appendix D, Table D.3.1)
c) Hazard scenario definitions (e.g. typical situations where people could be exposed to a fault voltage)(see Appendix D, Table D.2.1)
d) Earth fault current calculation and determination of protection tripping/clearing time based upon given protection relay setting (see Table D.4.1 in Appendix D)
e) Calculation of the EPR of the earthing system for individual earth faults considering the potential transfer to the contact exposure points identified in the hazard scenarios, followed by the determination of the prospective touch voltage or load voltage for the various hazard scenarios
f) Determination of probability of fibrillation for the various hazard scenarios
g) Calculation of coincidence probability and probability of fibrillation for the various hazard scenarios
h) Calculation of total value of the individual risk probability, evaluation of its value, and sensitivity analysis

On the basis of this approach, this section provides the results of shock risk calculations for the case where the distribution network is earthed through a resistor (R_n - shown in Figure 9.5.1). A detailed description of the determination process for all neutral point earthing configurations, with the analysis results, are presented in Appendix D.

The fault current in case of line to earth short circuit (L-N) and of simultaneous line-to-earth short circuits (Cross L-L-N) is calculated based on the respected configuration of the distribution network (resistor earthed network) and its characteristic parameters with respect to the impact of fault resistance and resistance of affected earthing system. Finally, the clearing time is given by the definite time over-current protection setting. The results of calculated fault current in resistor earthed network and appropriate clearing time is summarized in Table 9.5.1. The results of fault current calculation and determined clearing times for other types of neutral point connection are presented in Table D.4.1 in Appendix D.

Table 9.5.1: Table of earth fault currents magnitudes and clearing times

Neutral point connection	Type of fault	Earth fault current (A)	Clearing time t_P (s)
Earthed through resistor	L-N	538	0,3
	cross L-L-N	946	0,3

The intermediate results leading to the determination of the final value of individual risk probability P_{risk_tot} of resistor earthed network are listed in Table 9.5.2 for the various fault types and hazard scenarios. The frequency of cross country fault (cross L-L-N) is 'zero' for this case of neutral point connection (Table D.3.1 in Appendix D), therefore this fault will be neglected from the calculations. Detailed example of the calculation process is introduced below only for the first row of the Table D.2.1 (risk scenario 'a' – person in a shower). In the first step, the potential rise of LV earthing system U_{EPR_LV} is calculated as follows:

$$U_{EPR\_LV} = R_E \cdot I_F \cdot r \cdot \left(EPR_{LV} / EPR_{MV}\right) = 1{,}39 \cdot 538 \cdot 1 \cdot 1 = 748V \text{ ,} \qquad \text{Equation 9.5.1}$$

where

$$R_E = \frac{R_{DTS} \cdot R_{PEN}}{R_{DTS} + R_{PEN}} = \frac{0{,}04556 \cdot 100 \cdot 2}{0{,}04556 \cdot 100 + 2} = 1{,}39\Omega \text{ ,} \qquad \text{Equation 9.5.2}$$

Then the prospective (or open circuit) touch voltage of the scenario 'a' can be expressed as:

$$U_{vT} = U_{EPR\_LV} \cdot U_{T/EPR} = 748 \cdot 30/100 = 224{,}4V \ , \qquad \text{Equation 9.5.3}$$

where $U_{T/EPR}$ is the prospective touch voltage related to the EPR of evaluated ES in percentage terms, with the value given for the various hazard scenarios (see Table D.2.1, Appendix D).

During an electric shock incident, the prospective touch voltage is applied to the series combination of human body impedance and impedance of any additional insulating layers present (e.g. footwear). Thus, only a portion of the whole prospective touch voltage might be applied on the human body impedance (in case of presence of additional insulating layer) and this voltage is denoted here as the loaded touch voltage U_{load} (Table 9.5.2).

As the human body impedance is voltage dependent, an iterative routine was used where an initial value of loaded touch voltage was taken as equal to the prospective touch voltage and was changed throughout each iterative step in order to meet the Ohm´s law of series combination of human body impedance and impedance of additional insulation layer (only for case of hazard scenarios 'e' and 'f' in Table D.2.1). The prospective touch voltage was assumed to be a constant voltage source with zero internal impedance. The next column of Table 9.5.2 express fault clearing time t_{fault} for respected asymmetrical faults as presented in Table 9.5.1. Column I_{HB} contains resulting shock current through human body for the given loaded touch voltage for the circumstances defined in Table D.2.1, Appendix D.

Table 9.5.2: Table of results of evaluated risk scenarios and calculated individual risk probability for a resistor earthed network

Type of Fault	U_{EPR_LV} [V]	Risk scen.	U_{vT} [V]	U_{load} [V]	t_{fault} [s]	I_{HB} [mA]	P_{Coinc_RS} [-]	P_{Fib_RS} [-]	P_{Risk_RS} [-]	P_{Risk}
L-N	747,88	**a**	**224,36**	**224,36**	0,3	**281,49**	**1,09E-06**	**1,06E-03**	**1,16E-09**	**5,70E-08**
		b	373,94	373,94		585,39	1,09E-07	2,66E-01	2,90E-08	
		c	149,58	149,58		164,13	3,27E-06	5,74E-07	1,88E-12	
		d	224,36	224,36		457,42	3,27E-07	7,35E-02	2,40E-08	
		e	299,15	148,08		262,71	1,09E-07	4,73E-04	5,16E-11	
		f	598,31	265,74		578,34	1,09E-08	2,53E-01	2,76E-09	

The coincidence probability for risk scenario 'a' can be calculated based on basic Equation 9.5.4 following:

$$P_{\text{Coinc\_RS}} = \frac{f_n \cdot p_n \cdot (t_{\text{fault}} + p_d)}{365 \cdot 24 \cdot 60 \cdot 60} = \frac{(16/2000) \cdot 1000 \cdot (0{,}3 + 4)}{365 \cdot 24 \cdot 60 \cdot 60} = 1{,}09 \cdot 10^{-6} \qquad \text{Equation 9.5.4}$$

where f_n is number of earth faults per year (the fault frequency statistic is summarized for the case study in Table D.3.1 Appendix D), p_n is number of human presences per year and p_d is the typical human presence duration (seconds). Both of these values are estimated for each risk scenario in Table D.2.1 (Appendix D).

The probability of fibrillation P_{Fib_RS} is determined by Matlab routine based on the method described in reference [29].

Then individual risk probability is calculated for each risk scenario as follows:

$$P_{\text{Risk\_RS}} = P_{\text{Fib\_RS}} \cdot P_{\text{Coinc\_RS}} = 1{,}09 \cdot 10^{-6} \cdot 1{,}06 \cdot 10^{-3} = 1{,}16 \cdot 10^{-9} \qquad \text{Equation 9.5.5}$$

and the final individual risk probability considering all risk scenarios in a resistor earthed distribution network is given as sum of P_{Risk_RS}

$$P_{\text{Risk}} = \sum_{n} P_{\text{Risk\_RS (n)}} = \underline{\underline{5{,}7 \cdot 10^{-8}}} ,\qquad \text{Equation 9.5.6}$$

where n is number of all respected risk scenarios.

The resulting individual risk probability for the resistor earthed distribution network is $5{,}7 \cdot 10^{-8}$, which confirms that the design of the earthing system does not expose a typical person to risk above the tolerable risk probability limit 10^{-6}. Therefore, the basic design of this ES can be realized without any further modification.

9.5.2 Sensitivity analysis of case study parameters

As for any earthing system design, many of the input variables can have relatively high variation due to insufficient or incomplete information, or variation due to changes such as the seasonal effect on soil resistivity. Therefore a sensitivity analysis has been performed considering the impact of the variation in the relevant input variables on the resulting value of the individual fatality probability. Sensitivity of calculated individual fatality probability to differences in the input variables is carried out for each type of neutral point connection individually and the results presented in full in Appendix D. An example of sensitivity analyses in the case of the resistor earthed distribution network is presented in the Figure 9.2.4. The impact of the variation of the following parameters on the individual risk probability was studied:

t_{clear} - clearing time, vary from 33 % up to 500 % of basic values listed in Table D.4.1

d_{feeder} - fault distance, vary from 0,5 km up to 50 km

r - reduction factor, vary from 0,1 to 1

ρ_s - soil resistivity, vary from 100 Ωm to 5000 Ωm

R_f - fault resistance, vary from 0 Ω to 20 Ω

$EPR_{LV}/EPR_{\_MV}$ - ratio of transferred potential EPR from MV to LV earthing system, vary from 50 % to 100 %

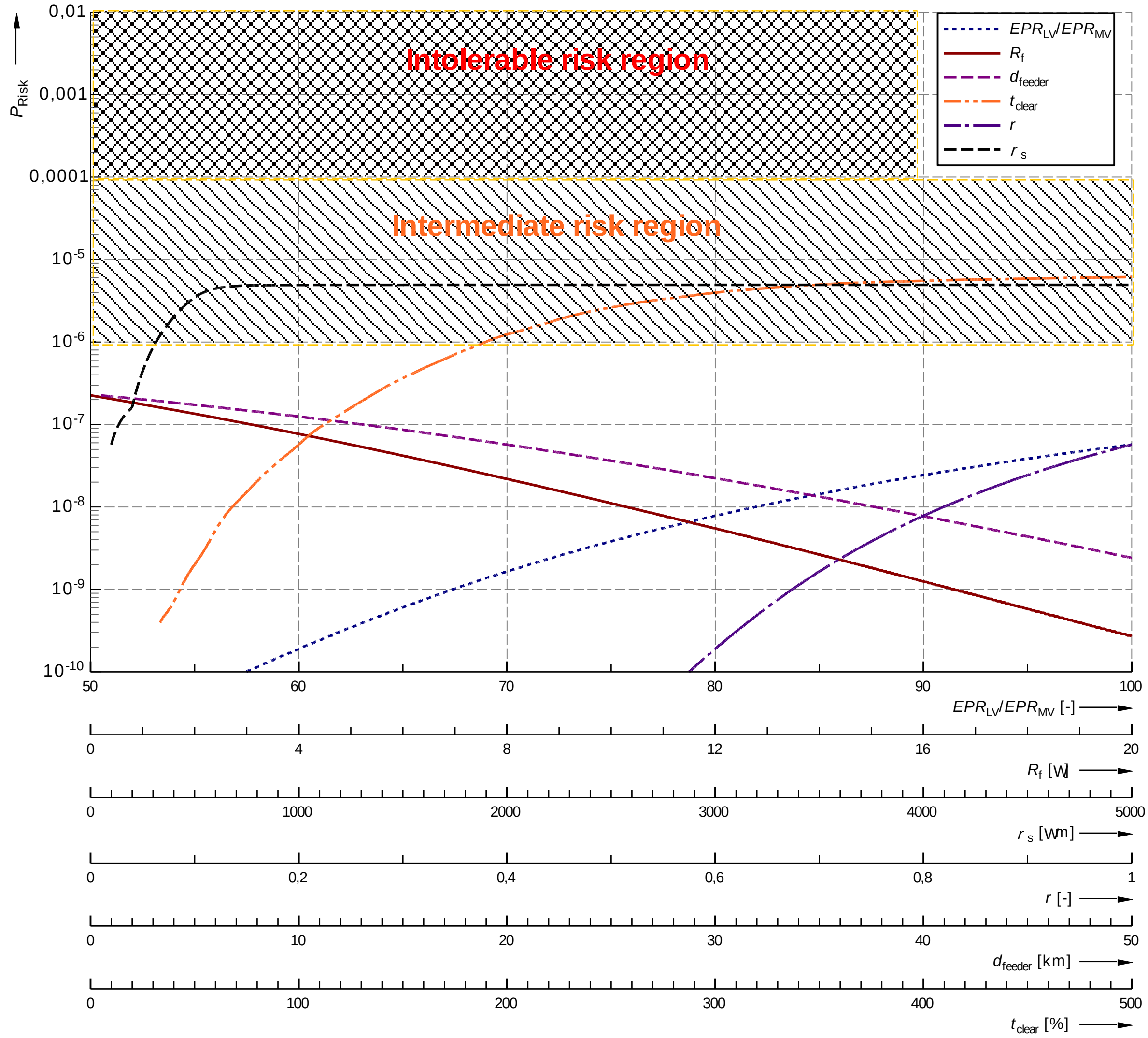


Figure 9.5.3: Sensitivity analysis of the case study parameters for resistor earthed network

9.5.2.1 Summary of the results

Soil resistivity (ρ_S) - The significant gradient of the risk probability is in the range of soil resistivity 100 - 600 Ωm. The risk probability converges on the total coincidence probability of $4{,}92 \cdot 10^{-6}$ when soil resistivity exceeds 600 Ωm (the probability of fibrillation is nearing the maximum value). The first minor irregularity in this curve (100 - 200 Ωm) is caused by the simplified approach to calculating the total earthing resistance. The earthing resistance of the LV earthing system is calculated as $R_{PEN} = \rho_S/100$ for $\rho_S > 200$ Ωm and $R_{PEN} = 2$ Ω for $\rho_S < 200$ Ωm.

Clearing time (t_{clear})- The risk probability converges to the coincidence probability of L-N fault $6{,}29 \cdot 10^{-6}$ which is calculated with respect to the maximal value of clearing time (500 % in case presented in Figure 9.2.4). This means that the probability of fibrillation caused by a L-N fault nears 100 % value when the real clearing time will be > 3 times the base value (Table 9.2.2).

Fault resistance (R_f) and fault distance (D_{feeder}) - The impact of these variables to P_{risk} is insignificant, because the length of the line to fault is given by network topology and increasing the fault resistance reduces P_{risk}. The gradient of these curves is not as steep as in case of soil resistivity or clearing time.

Reduction factor (r)- The gradient of the reduction factor is substantial especially in the case where a value lower than 1 is used for the case study. It is necessary to respect influence on P_{risk} caused by increasing of this value during the life-time of the earthing system.

Potential transfer EPR_{LV}/EPR_{MV} - The impact of the ratio of potential transfer from MV to LV earthing system to risk probability is substantial and follows the same characteristic as for the reduction factor.

The highest gradient of P_{risk} can be seen for the cases of change of soil resistivity and clearing time. Deviation of both these variables can significantly affect the real risk probability as it is shown in Figure 9.2.4. In this case, the risk probability enters to the intermediate risk region when soil resistivity reaches value 315 Ωm and clearing time 190 % value of preset tripping time (e.g. due to change of protection settings).

Conclusions and recommendations

Earthing systems are safety critical systems, and as such need to manage the transfer of fault energy in such a manner as to limit the risk to people, equipment and system operation to tolerable levels. As for protection systems, earthing systems are required to operate during irregular, short duration fault events (i.e. low probability). However, the result of an electric shock that leads to ventricular fibrillation is clearly a high consequence event requiring that due diligence be demonstrated to prove that shock risk profiles have been designed and managed to meet tolerable risk targets. Furthermore, power system asset owners are being challenged through changes in earth fault levels and risk profiles arising as a result of; reconfigured transmission networks and changing interaction with 3rd party utilities and properties.

The document demonstrates that for traditional safety criteria to meet societally tolerable risk exposure they rely upon the low likelihood of the coincidence of an earth fault and a person being in a position to receive a hazardous voltage. The document then demonstrates the means by which quantified risk analysis may be used to determine the tolerability of risk exposure for a person in a given situation, and that voltage criteria alone are unable to prove compliance with tolerable risk criteria. The impact of individual parameters on the risk profile was then examined through the use of case studies and it was concluded that the following parameters and processes play a significant role in determining the risk that an electrical asset creates in the surrounding environment:

- Earth fault current magnitude and duration
- Return current distribution
- Soil electrical resistivity
- Earth fault voltage distribution
- Body current and voltage withstand criteria
- Fault frequency and person contact frequency and durations

Furthermore, it is critical that the design, installation, commissioning and ongoing supervision processes be integrated within the overall life cycle of the environment and network in which the asset is to operate if the risk to staff and the public is to be managed responsibly.

Based upon the analysis undertaken by the working group it is recommended that asset owners, design houses and standards setting bodies:

1. Work toward the explicit inclusion of QRA within earthing design processes.
2. Communicate clearly the fact that the application of QRA is able to produce 3 key outcomes:
   - Reduction of waste where traditional approaches produce overly conservative requirements.
   - Reduction of 'risk of fatality' from earthing related (indirect) electric shock where such reduction is justified.
   - Provide a measure of risk that allows broad comparison and understanding by non-specialists.

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Appendix A – examples of QRA applied to earthing system design

Quantified or probabilistic risk analysis and assessment has been explicitly incorporated within earthing system design processes in both technical publications and standards documents since the early 1960's, as outlined in Section 4.2. This section provides an overview of the steps involved in quantifying earthing related risk, as presented in more recent technical publications and applied within design processes incorporated within standards documents.

A.1 QRA in Technical Publications

The simplified fault tree diagram shown in Figure A.1 is further developed in the Figures A.2 and A.3 following:

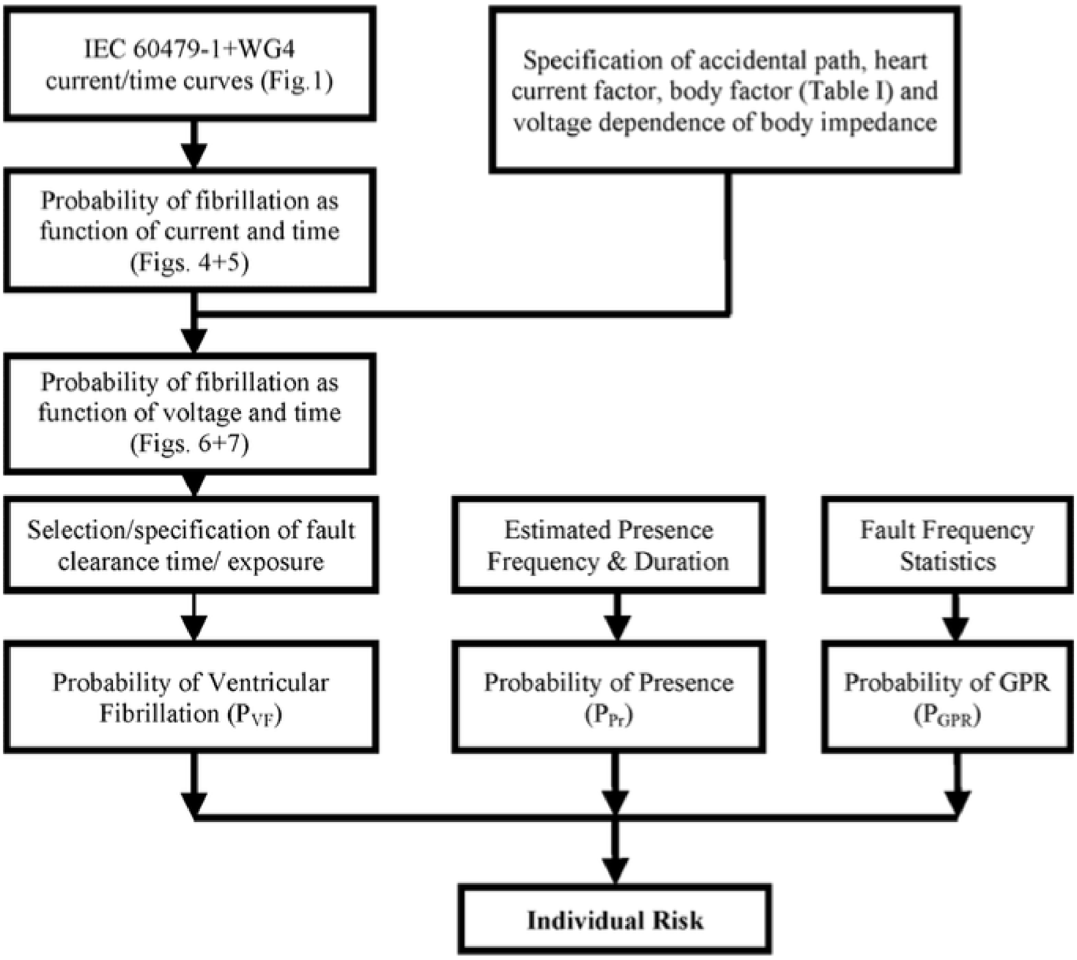


Figure A.1: Earthing related individual shock risk quantification process: Dimopoulos [29]

The forgoing process is further expanded in Figure A.2 [29].

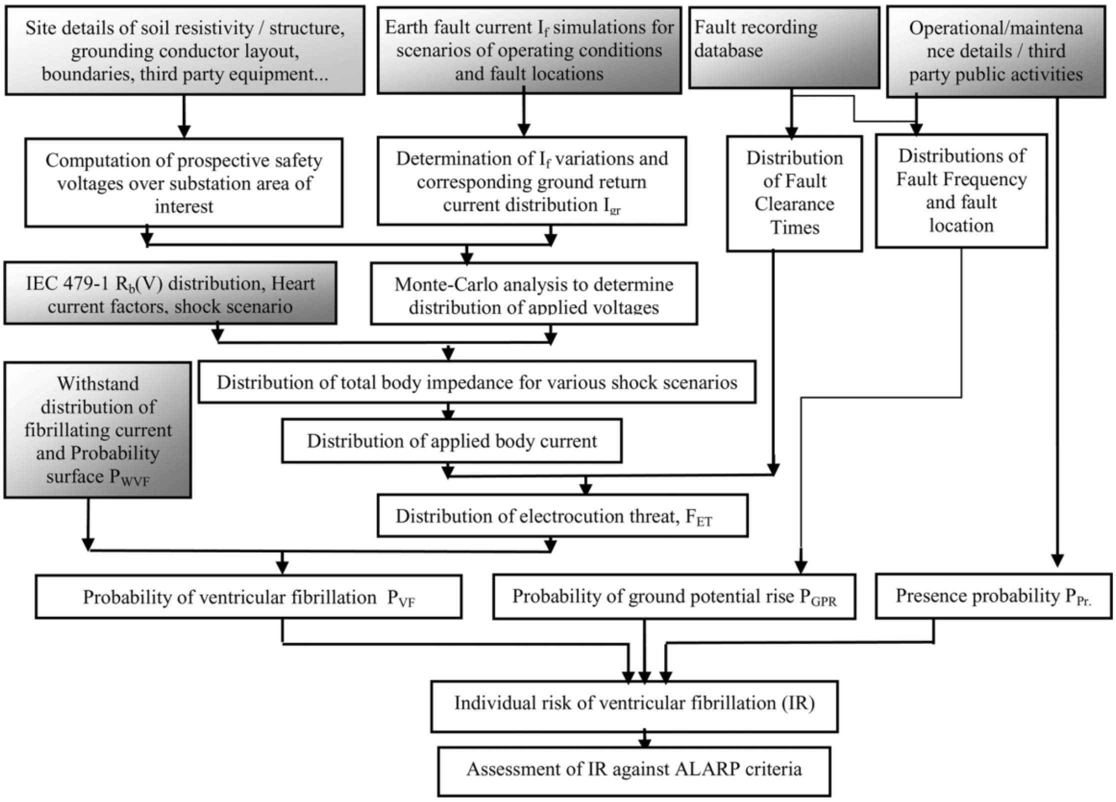


Figure A.2: Earthing related individual shock risk quantification process: Dimopoulos [29]

A.2 QRA in National Standards

QRA has been explicitly incorporated in a number of earthing related national standards, including the standards from UK, Australia and New Zealand.

A) QRA in United Kingdom Earthing Standards

The 2010 British edition of the CENELEC standard covering ‘Earthing of power installations exceeding 1 kV a.c.’, BS EN 50522:2010 [46] includes in an informative national appendix the explicit recognition that the parameters involved in assessing safety are probabilistic in nature, with regard to the fault current magnitude and duration, as well as the probability of the fault occurrence, and the presence probability of a human being. This has led to the introduction of a new additional approach to earthing system design in the UK based on quantified probabilistic methods.

The UK National Annex NA to the European standard EN50522 [46] includes a design flow chart that enables the designer to undertake a Risk Assessment during a final stage of the process, as shown in Figure A.3.

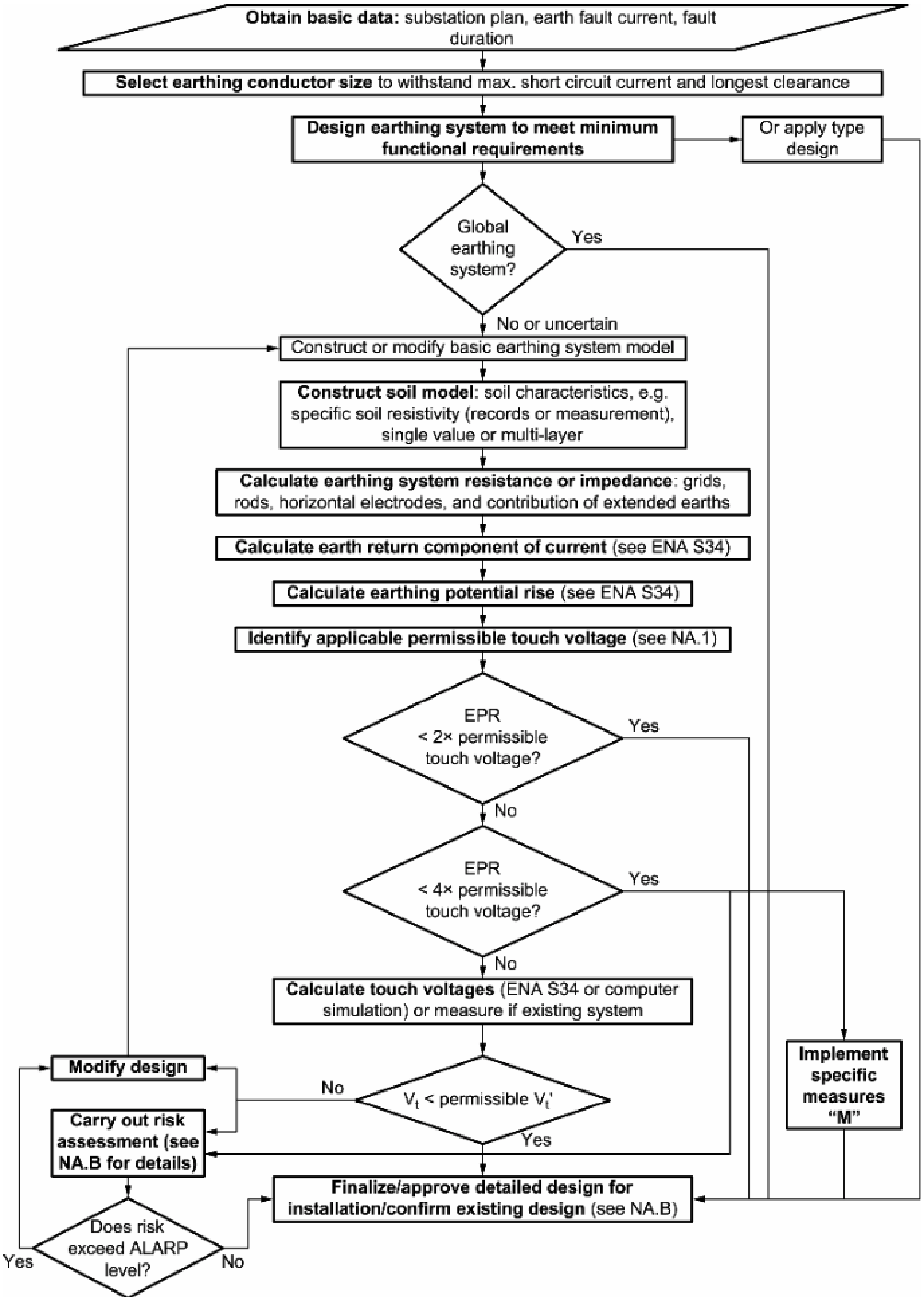


Figure A.3: UK Earthing design methodology including the option for QRA and assessment

The process for calculating the risk to which an individual will be exposed is summarized in the flowchart included in Annexure NB Figure NB.2, and reproduced in Figure A.4 following.

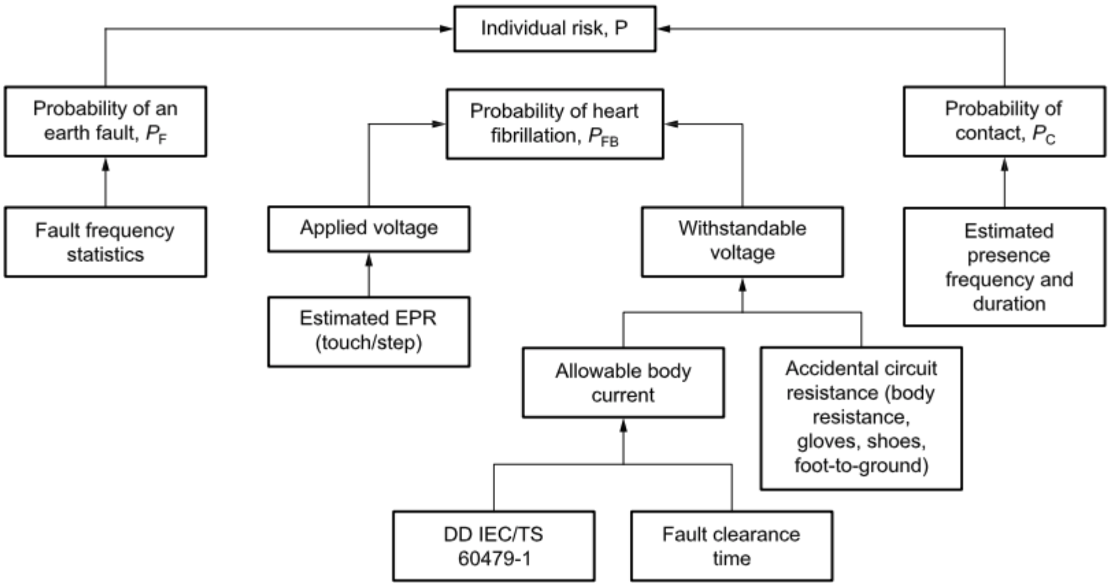


Figure A.4: UK Outline of QRA approach applied to earthing system design [46][8]

Once the individual risk of fatality has been calculated it is recommended that the risk be assessed using the ALARP process, as shown in Annexure NB Figure NB.1 [46], reproduced in Figure A.5 following.

[8] It is believed this figure should include an arrow from 'Probability of heart fibrillation, P_{FB}' to 'Individual risk, P'.

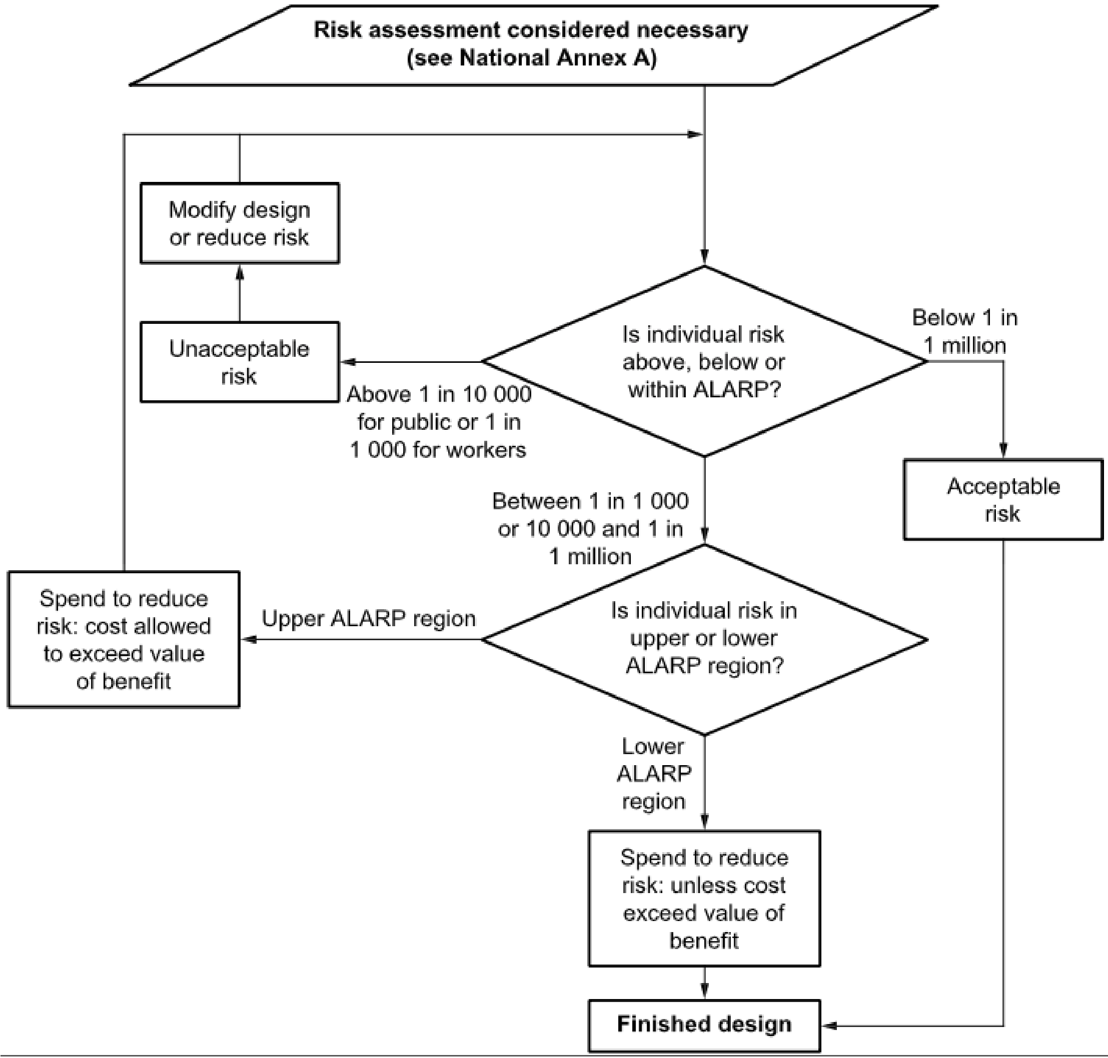


Figure A.5: UK BS EN50522 quantified risk assessment ALARP decision making

B) QRA in Australian Earthing Standards

Quantified risk analysis has been incorporated explicitly within Australian earthing safety standards for many decades as outlined in Section 4.2. Since 2010 and the publication of ENA EG-0 [1], all earthing safety related standards have introduced a two stage approach, whereby either standard curves or a direct probabilistic method may be followed.

- **Standard Curves (Case matching):** A series of standard (or predetermined) prospective touch voltage/clearing time curves have been developed by each standards committee. This process provides engineers with design curves complete with their acceptable boundary conditions clearly identified. The scenarios have been selected to cover a number of hazard scenarios that are commonly met by design engineers. 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 fits well with previous design processes. Figures A.6 and A.7 provide examples of prospective touch voltage criteria published for use when assessing the indirect shock safety of transmission and distribution assets during earth fault events [52][50][1].

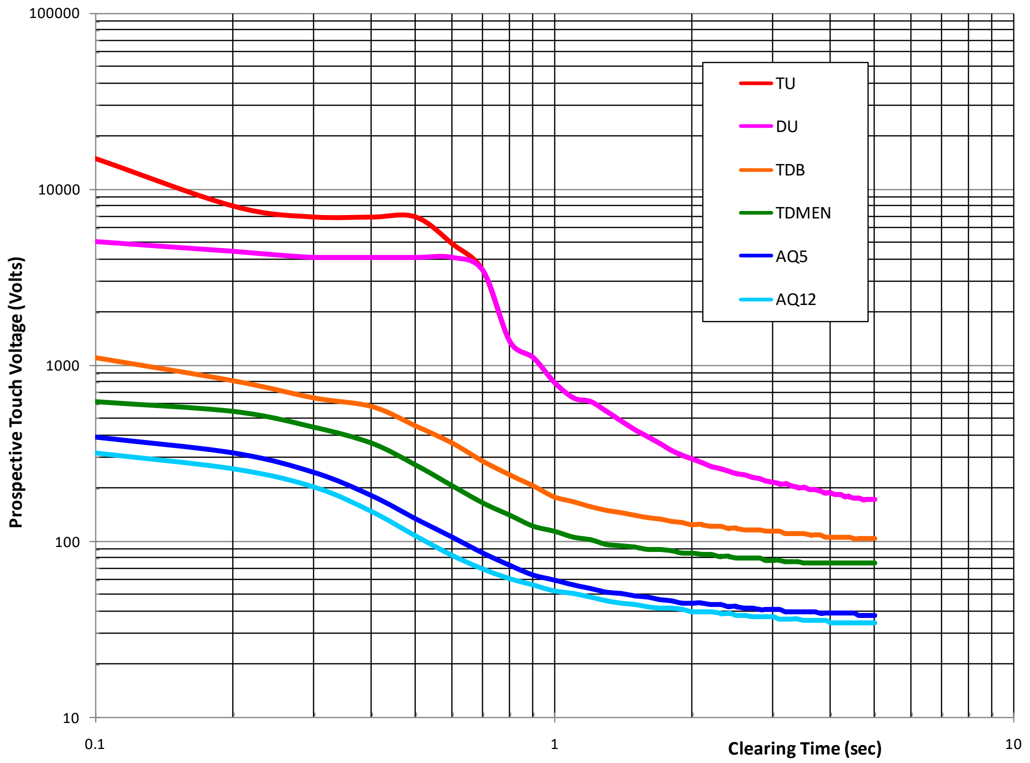


Figure A.6: ENA EG-0 Transmission and distribution asset prospective touch voltage criteria

Case	Description	Acronym
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

Figure A.7: Case study descriptions

While Figure A.7 provides a general description of each case study, further details are included within ENA EG-0 [1].

- **Direct Probabilistic:** Direct calculation of contact and fault incidence coincidence and fibrillation probability is used to derive the probability of a fatality occurring a specific hazard scenario as shown in Figure A.8 following (from ENA EG-0 [1]).

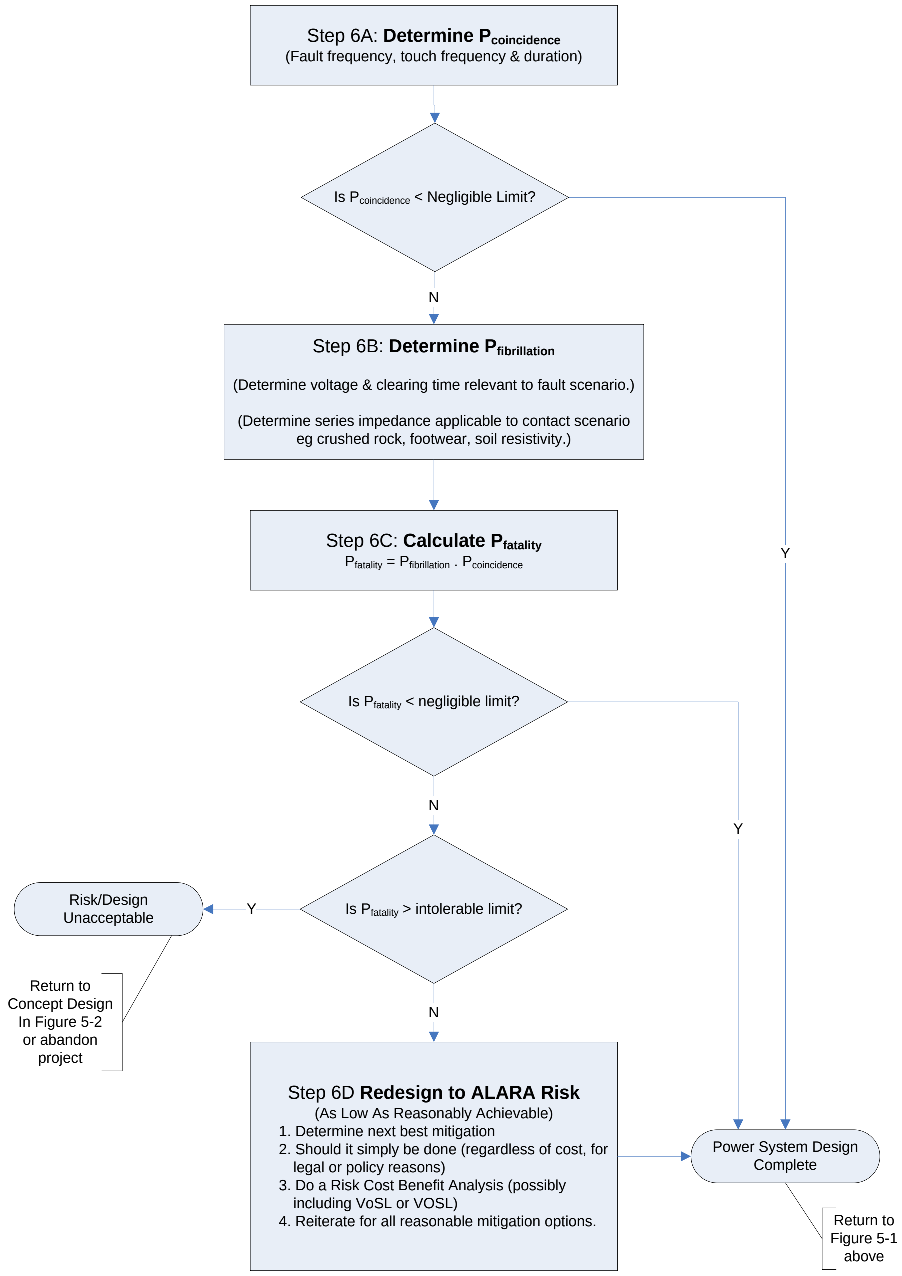


Figure A.8: ENA EG-0 quantified risk assessment ALARP decision making process [1]

The QRA process may be used to assess the risk associated with a particular hazard scenario, or to develop a safety criteria or tolerable voltage curve that may be used for a range of situations (see Figure A.6).

Most allowable voltage curves have a probability of fibrillation that is non-linear and dependent upon distribution of clearing times [1]. This adds an extra undesired variable when assessing a particular installation, and does not provide equity across power systems. A method has been published with the ENA EG-0 guide 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. The standard curves used in Australian standards are ‘constant probability curves’.

If it is determined that the risk level lies within the ALARP region a risk cost benefit process is recommended as outlined in Figure A.9 following.

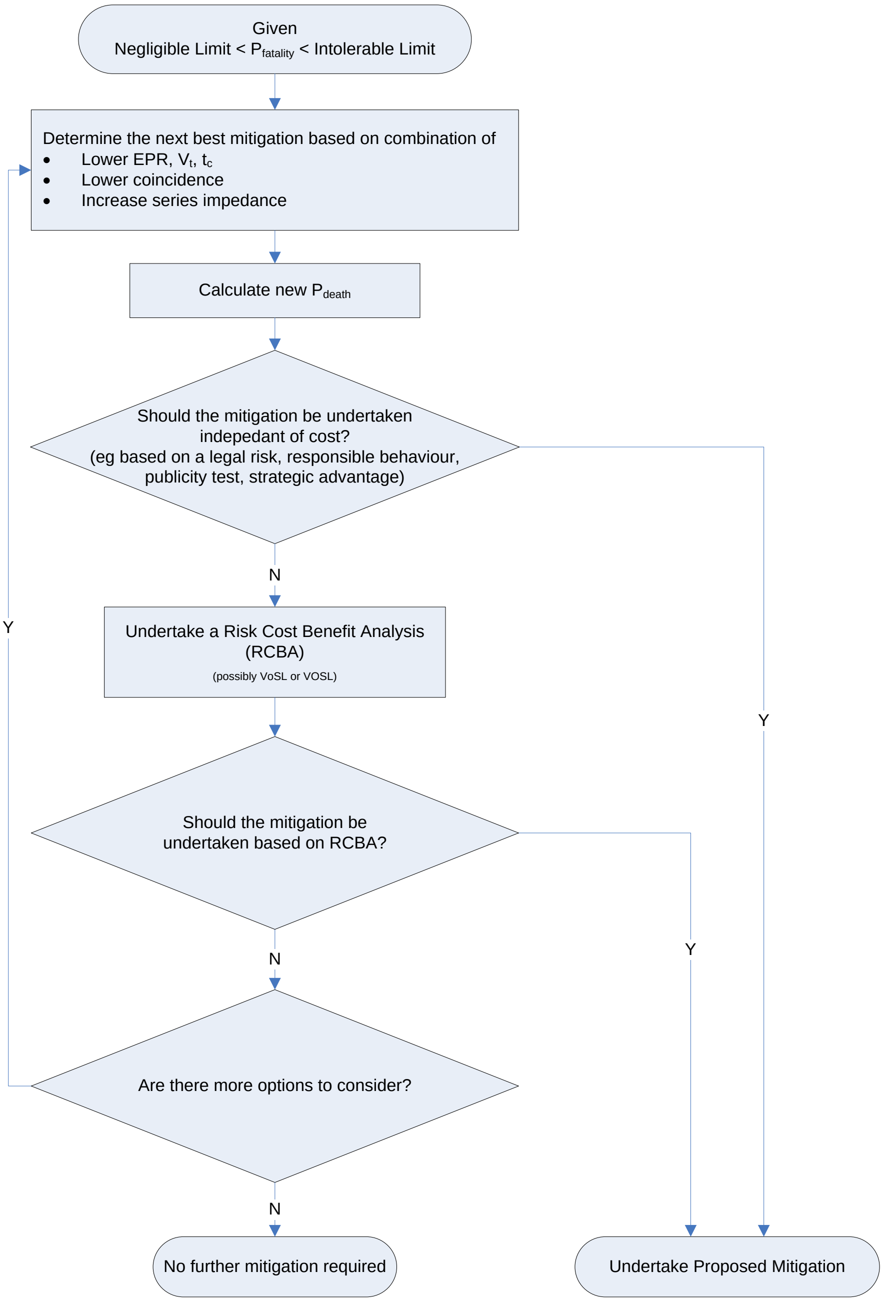


Figure A.9: Risk cost benefit process [1]

Associated with the ENA EG-0 document a software based approach (Argon [48]) has been developed that provides designers with the capability to calculate risk levels or develop safety criteria to match actual risk profiles or typical hazard scenarios. An alternate tool based on the same methods and source data has been made available at the request of the Study Committee B3 Chairman to ensure the ongoing availability of a tool to provide a point of reference. The web based tool is called Argonium and can be found at [100].

C) QRA in New Zealand Earthing Standards

In 2003 New Zealand Electricity Engineers Association (EEA) prepared a guide entitled Risk based earthing design' [73] which focused upon the likelihood of a person being within a region affected by touch voltages and/or step voltages, and conservatively assumed that the probability of fibrillation was equal to unity (ie fibrillation always occurs). The guide was re-released in 2009 in conjunction with the 'Guide to power system earthing'[80]. The latter document provided an overall design procedure whereby designers could use predetermined 'safety curves' from IEEE80 [27] or IEC61936 [28] in certain 'controlled' environments such as major substations, or alternatively calculate the probability of a person being in an exposed position at the same time as an earth fault occurred. The same ALARP process for assessing tolerability of individual fatality risk as used in the UK and Australia is followed in New Zealand.

The overall design procedure is summarized in Figure A.10 from the EEA NZ ‘Guide to Power System Earthing Practice’ [73].

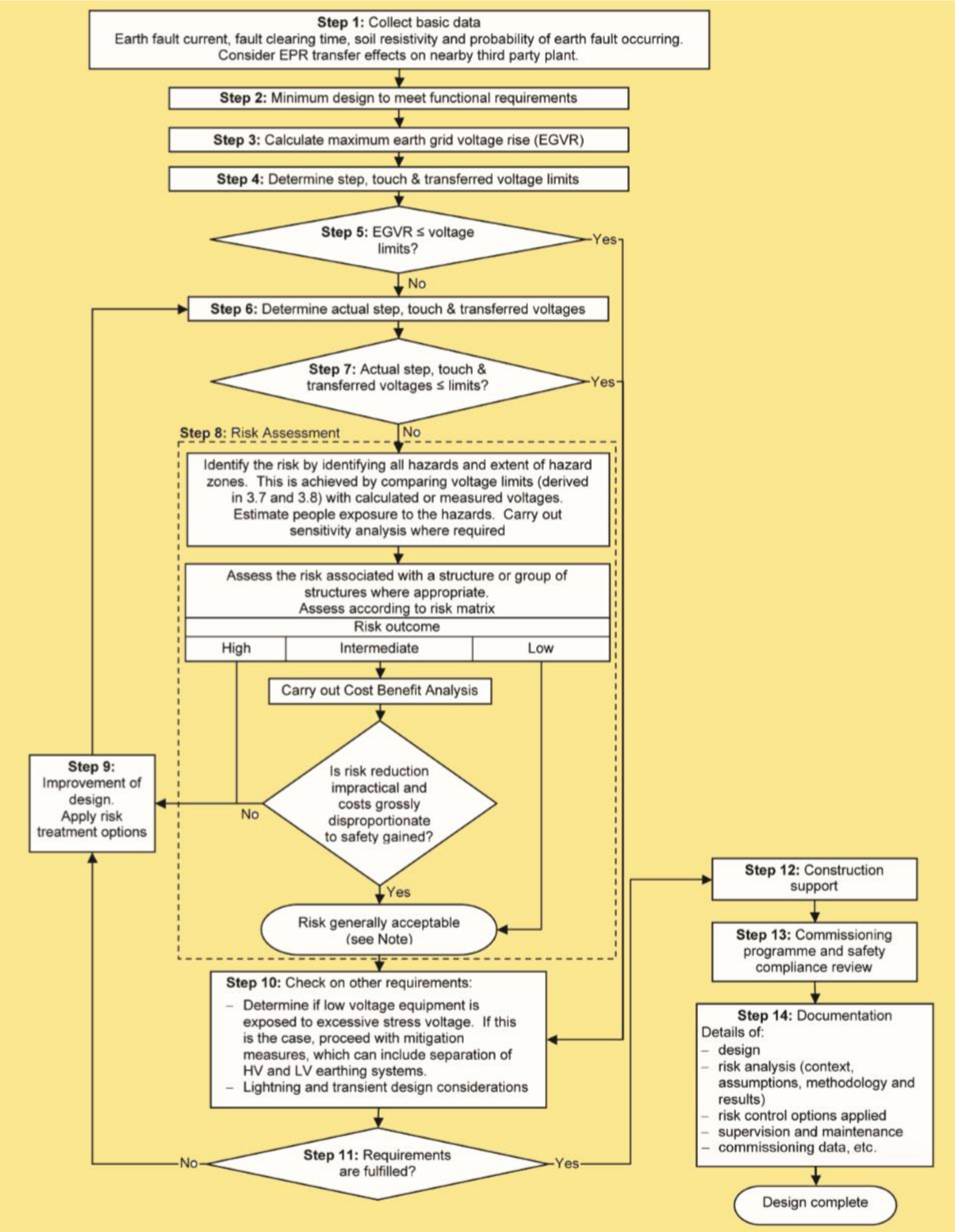


Figure A.10: Guide to power system earthing practice – design procedure

Appendix B – Traditional Design methodologies

This appendix provides a brief overview of the earthing design methodologies of the main international standards, and an example showing how QRA could be incorporated within EN50522 [6].

B.1 Traditional Earthing Design Approaches

The methodology used for the design of earthing systems for high voltage substations is very similar for each of the main international standards. This section summarises three of the key standards being:

- International standard IEC 61936-1 (Power installations exceeding 1 kV a.c.),
- European standard EN 50522 (Earthing of power installations exceeding 1 kV a.c.), and
- IEEE std. 80 (IEEE Guide for Safety in AC Substation Grounding).

B.1.1 Approach according to IEC 61936

The design process is described in an earthing system design flow chart.

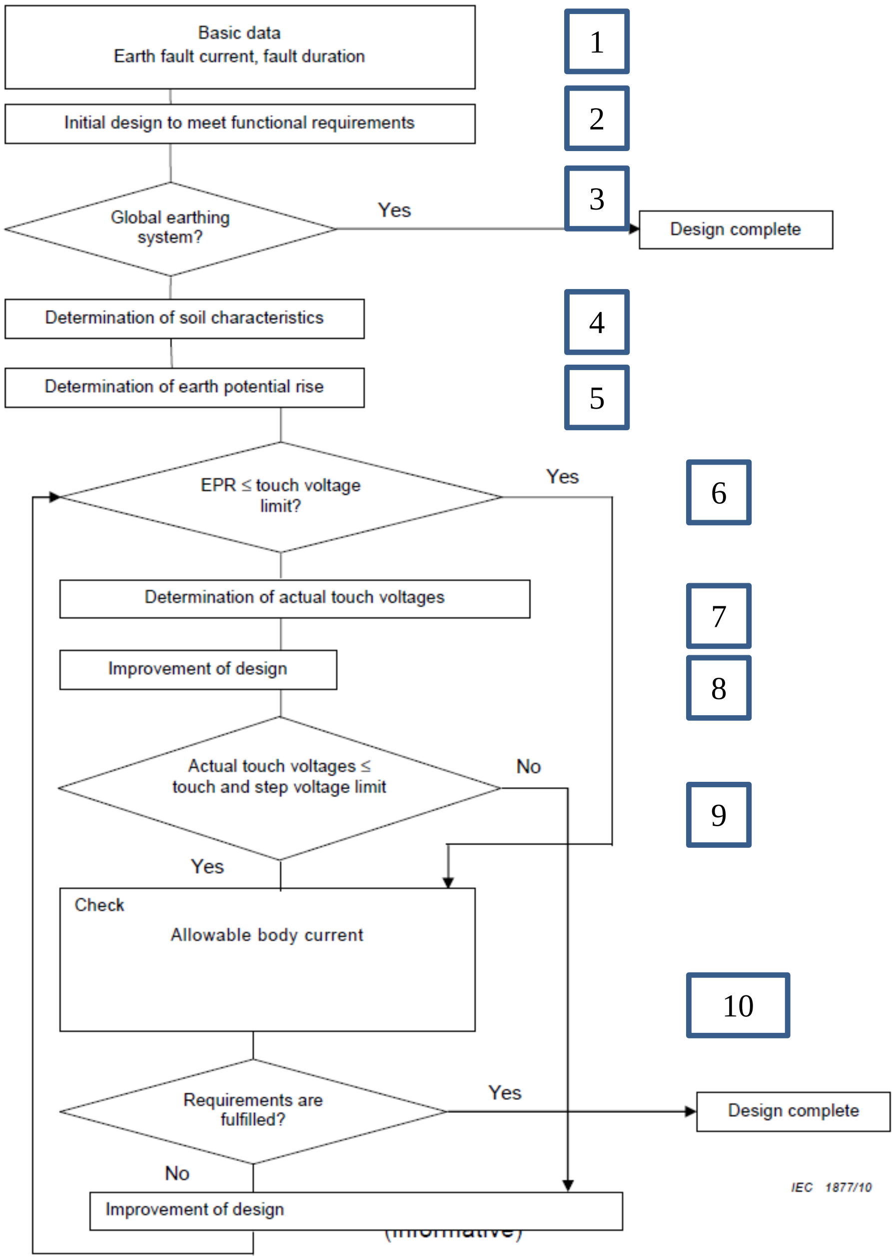


Figure B.1: Assessment scheme of an earthing system according to IEC 61936

The individual steps are as follows:

1. Collection of basic data like fault current level and fault duration
2. Execute initial design to meet the functional requirements
3. Check if the configuration is part of a global earthing system
4. Determination of soil characteristics
5. Determination of earth potential rise
6. Check if earth potential rise is smaller or equal than the touch voltage limit
7. Determination of actual touch voltages
8. Improvement of design
9. Check if actual touch and step voltages keep voltage limits
10. Check if allowable body current limit is kept
11. Modify design: to reduce EPR and/or touch voltage as a percentage of EPR
12. Detail design: Prepare detailed design specification

B.1.2 Approach according to EN 50522

If the design approach according to EN 50522 is chosen, the compliance concerning the permissible touch voltage U_T and the permissible body current I_B are to be ensured for each fault point of the electrical grid by the following steps (see Figure A-2):

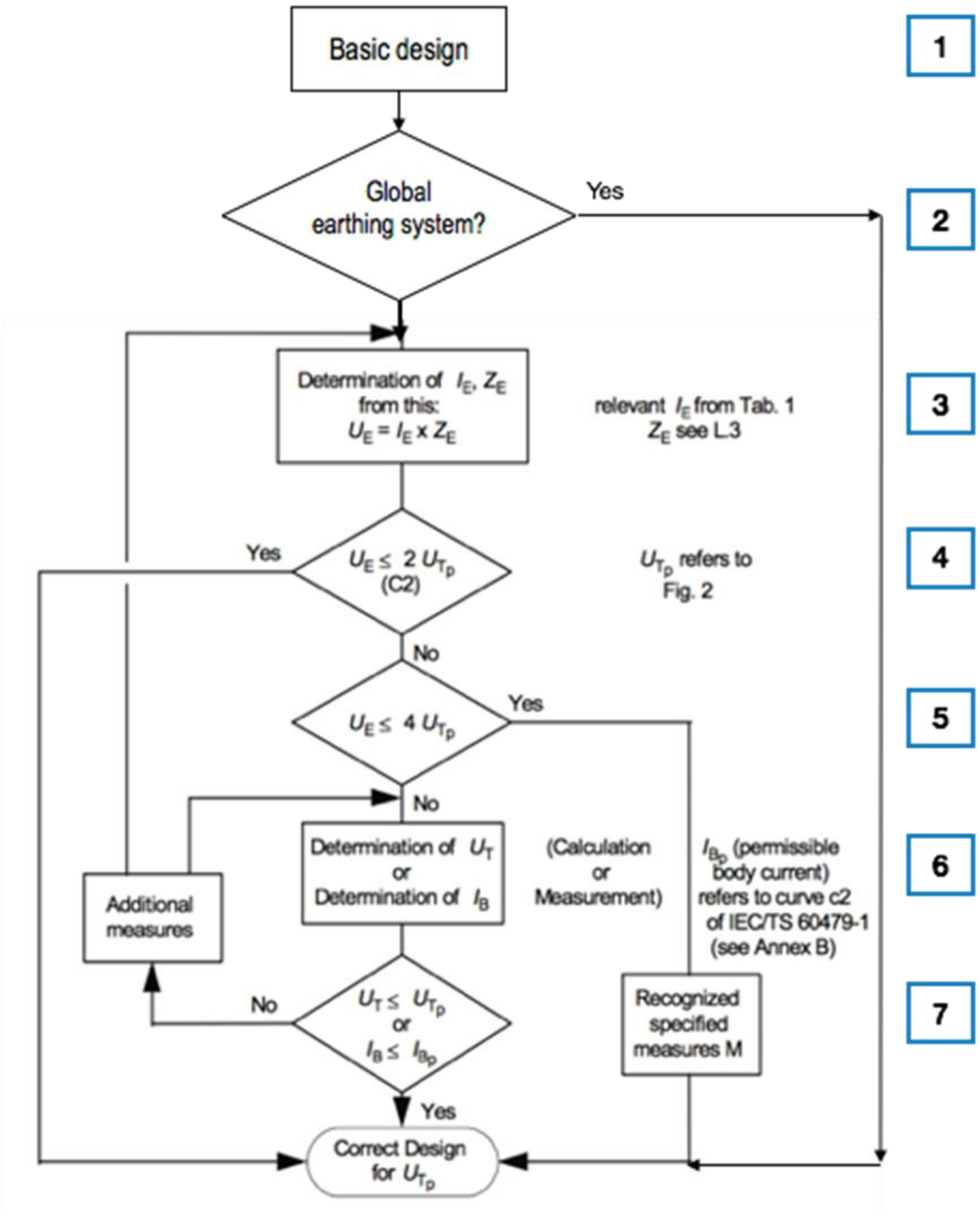


Figure B.2: Assessment scheme of an earthing system according to EN 50522

In order to achieve this, the following algorithmic steps are to be taken:

1. Basic design
2. Check, if a global earthing system exists. If this condition is not fulfilled, the next step is necessary.
3. Determination of the expected current flowing into the earth I_E and the total earthing impedance Z_E. From this, the earth potential rise U_E is calculated as $U_E = I_E \times Z_E$

4. Check, if the earth potential rise U_E is less than two times the tolerable prospective touch voltage U_{TP} which depends on factors like duration of the fault current flow, the body impedance, transition impedances and the specific earth resistivity and foot print. It can be determined from a set of curves for a certain variation of these parameters which is also provided in the standard EN 50522. If this condition is not fulfilled, the next step is necessary.

5. Check, if the earth potential rise U_E is less than four times the tolerable prospective touch voltage U_{TP}. In this case recognized specified measures can be taken. If this is not possible, the next step is necessary.

6. Determination of either the touch voltage U_T or the body current I_B which refers to IEC/TS 60479-1, curve c2 by calculation or measurement.

7. Check, if the touch voltage U_T or the body current I_B are below the values for the permissible prospective touch voltage U_{TP} or the permissible body current. If these conditions are not fulfilled, the design of the earthing system has to be modified and the process must be repeated starting again from step 3 or step 6.

B.1.3 Approach according to IEEE Std 80

If the traditional approach according to IEEE Std 80 is chosen, the following steps are to be applied:

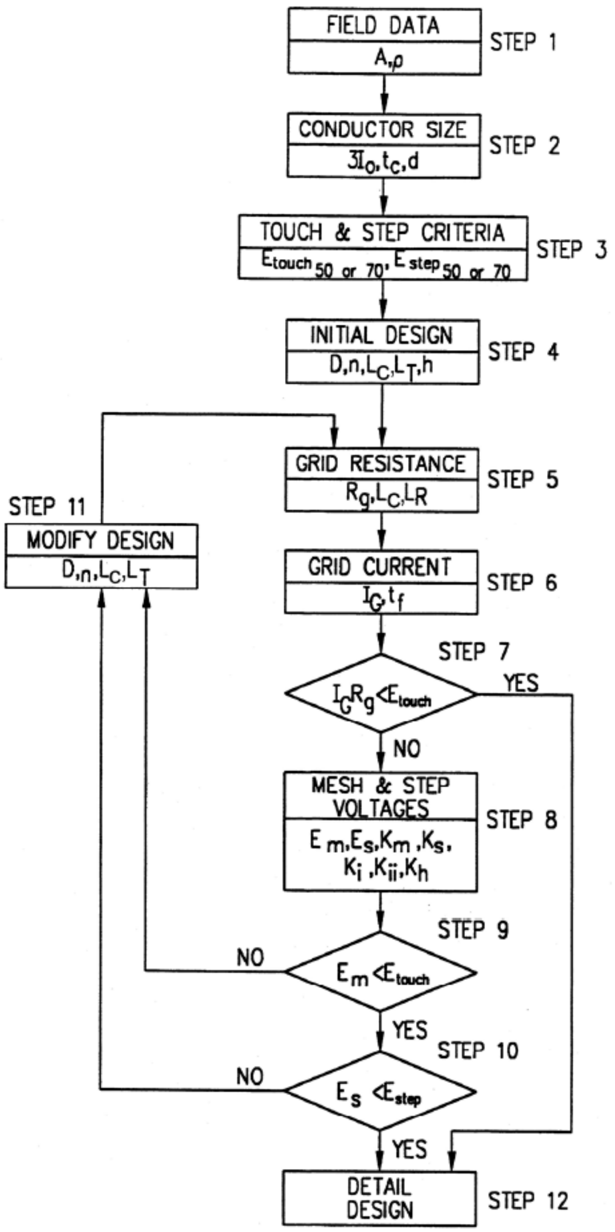


Figure B.3: Assessment scheme of an earthing system according to IEEE Std 80

A detailed summary of all symbols, indices and applied formulas as well as comments to each step is given in the standard.

Short summary of steps:

1. Collection of field data like area covered and relevant soil resistivity
2. Determination of conductor size based on current magnitude and duration
3. Determination of tolerable touch and step voltage based on relevant fault duration

4. Preliminary design of earthing system
5. Determination of grid resistance
6. Determination of grid current under consideration of worst fault location
7. Check if total earth potential rise is less than tolerable touch voltage
8. Calculation of mesh and step voltages
9. Check if mesh voltages are less than tolerable touch voltage
10. Check if step voltage is less than tolerable touch voltage

B.2 QRA applied to EN50522

Section 8.4 provided detail of a 'generic earthing design process' that incorporates QRA. The following figure, produced by the JWG, shows how QRA could be integrated into the design procedure within EN50522 [6].

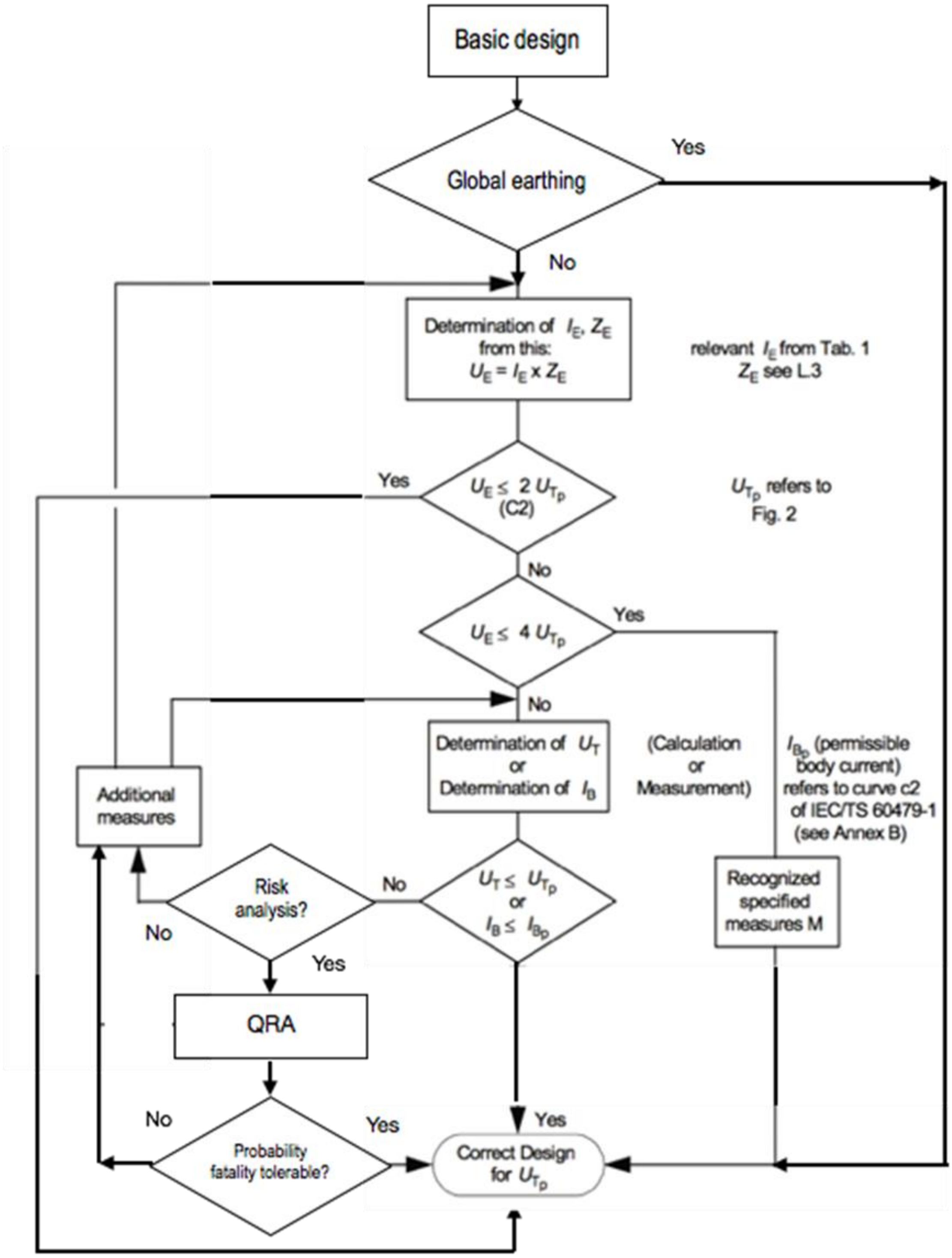


Figure B.4: A recommended revision to the EN50522 design process incorporating QRA

The main difference between the two flowcharts is that the EN50522 process includes a number of simplified steps:

- Global earthing - if a substation is located within a 'global earthing system' then the maximum touch voltage will be, by definition, less than the tolerable touch voltage.
- Safe touch and step voltage assumptions - where it is assumed that the maximum touch voltage will be less than 50% of the EPR of a substation, and

- 'Specified mitigation measures' - a range of mitigation measures are specified by which a designer may manage unacceptable touch voltage conditions.

While the use of simplifications is a normal part of most design processes, it is always the responsiblility of a designer to check that the case under investigation meets the boundary conditions/assumptions governing the use of the simplifications. If the assumptions or boundary conditions are known or easily checked then it is the responsibility of the designer to use first principles approach to the design. Such a fundamental approach has been taken in the generic design process provided in Chapter 8.

Appendix C – Transmission Case Study Details

C.1 Data for Transmission Substation - Overhead Case Study

This case study considers the performance of the earthing associated with a HV transmission substation. By performance we mean the range of responses within the earthing system due to the spectrum of faults which can occur within, or along any of the transmission line assets terminating at, the substation.

C.1.1 System description

This case study centres on the earthing associated with a transmission substation, nominally 400kV/110kV, whose terminating lines are all of overhead construction. A description of the network configuration is provided in Figure C.1.1.

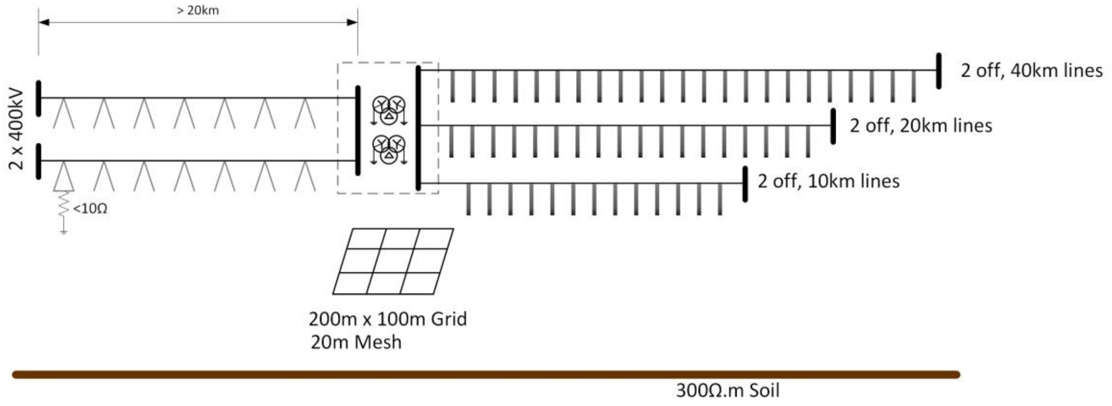


Figure C.1.1: Transmission substation earthing system

The substation general configuration is:

- Two incoming 400kV lines and six outgoing 110kV lines;
- The 400kV tower construction is described in Figure C.2;
  - ✓ average span lengths of 300m;
  - ✓ OPGW with Rac ($0.846\Omega/km$) and GMR(4.35mm)
- The 110kV pole construction is described in Figure C.3;
  - ✓ average span lengths of 150m;
  - ✓ an OHEW (ACSR-Apple) with Rac($0.861\Omega/km$) and GMR(2.6mm)
- Bus fault level 400kV of $\leq 40kA$;
- Bus fault level 110kV of $\leq 20kA$; and
- The transformers are tertiary winding auto-transformers.

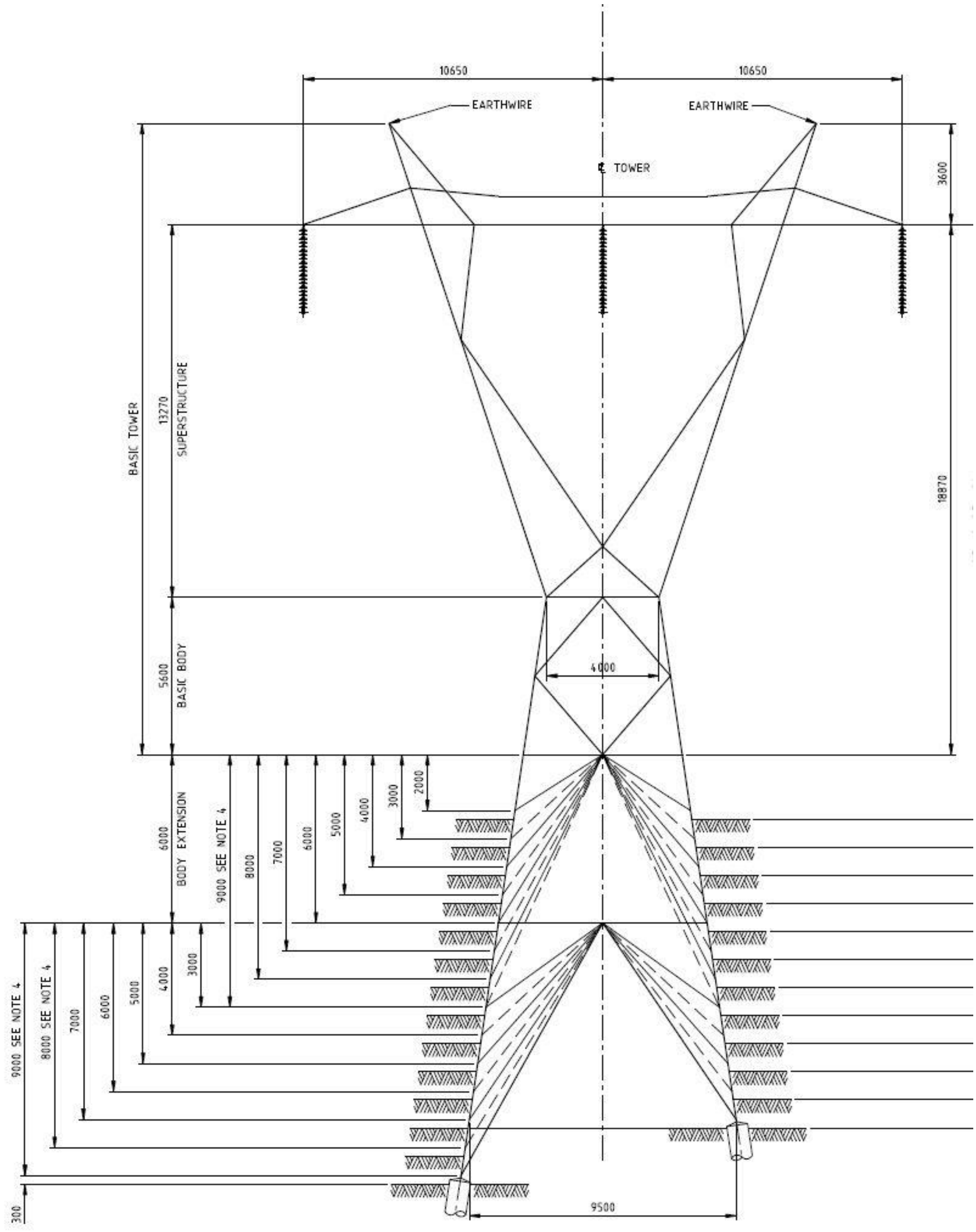


Figure C.1.2: 400kV tower configuration

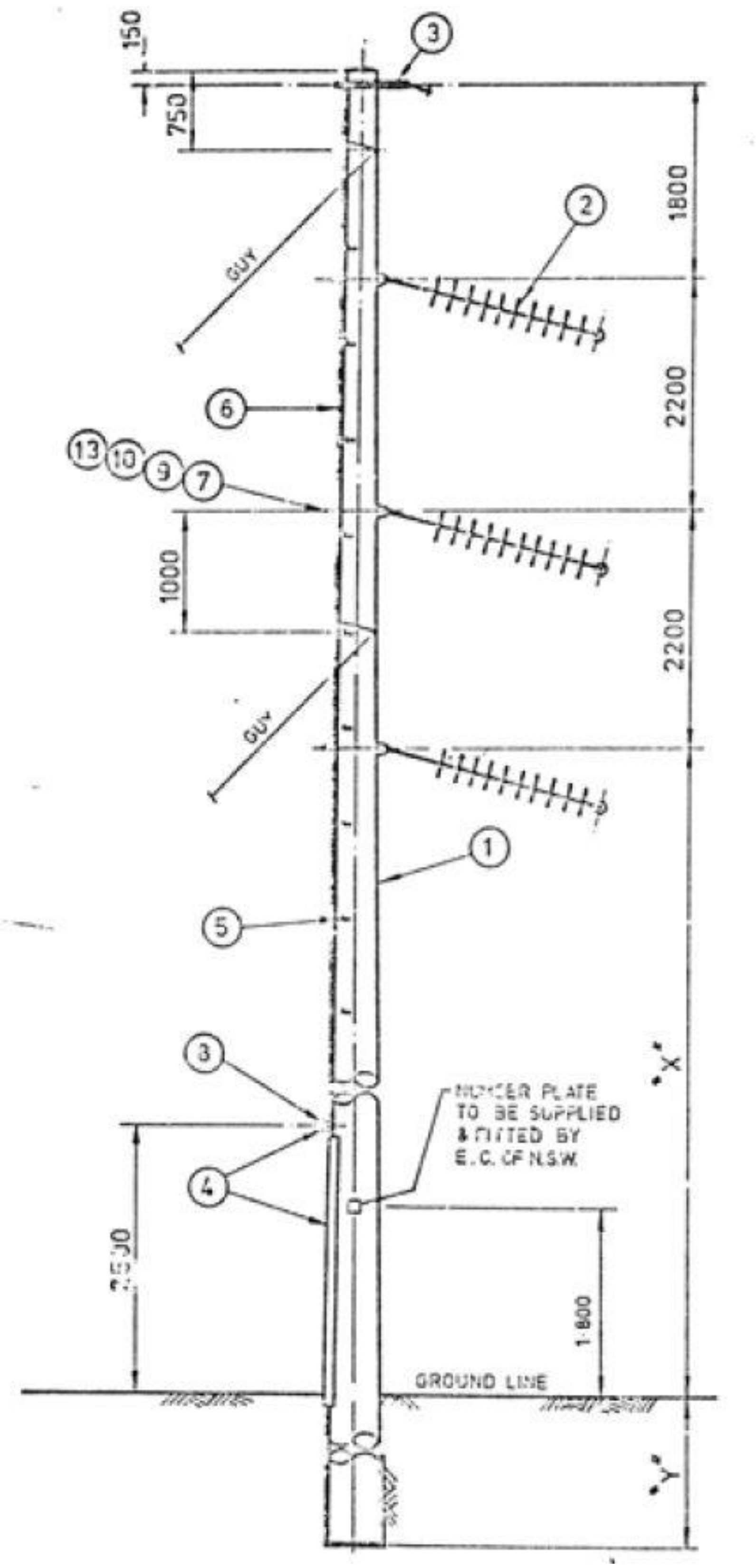


Figure C.1.3: 110kV pole configuration

C.1.2 Earthing system

The earthing system associated with the substation is described in Figure 9.2.1, and has the following salient points:

- All lines, both primary and secondary, are overhead;

- Each pole/tower and substation is bonded to each lines respective shieldwire/earthwire/OHEW;
- Grid is 200m by 100m with a 20m mesh;
- The soil is $300\Omega.\mathrm{m}$ across the study;
- The 400kV structures have an earth resistance of $< 10\Omega$;
- The 110kV structures have an earth resistance of $\leq 20\Omega$;
- The 110kV lines are all terminated by substations with earth grids of dimension 50m by 50m with 10m meshes; and
- The 110kV 'Neutral' Earthing options include:
  - ✓ Petersen Coils;
  - ✓ Resistance/reactance; and
  - ✓ Solid.

C.1.3 Protection

- 400kV ⇒ Unit/differential protection
- 110kV ⇒ Distance protection
  - ✓ Zone 1 ≤ 100 ms for 80% of the line.
  - ✓ Zone 2 ≤ 400 ms

C.1.4 System analysis

In this section the performance of the various elements of the earthing network are examined.

The first part of the analysis is to consider the conductive response of the various elements of the network. Conductive analysis considers the response of the network driven by the electric field, or V=IR. This can happen as the analysis is conducted at low frequency, so the electric response can be considered separately to the inductive or magnetic response.

In the second stage of the analysis the modelling is expanded to include the earthing associated with the 110kV & 400kV transmission lines, and faults on those lines. In reality all earthing elements will have some coupling to the fault current, but in this analysis only those elements which are parallel to the fault current will be considered. The inductive model uses the results of the conductive model, specifically those elements not considered parallel that share a common node can be combined to simplify the analysis.

C.1.5 Conductive analysis

We start by examining the response of the substation earth grid in isolation by subjecting it to 1kA of current[9]. By calculating the EPR of the grid and the soil potential surrounding the earth grid the internal and external hazard levels can be described. The hazards generated around the substation can then be defined for any fault as soon as the portion of the fault current passing through the substation earth grid is known.

The substation has an earth grid with dimensions of 200 x 100m with a 20m mesh buried in $300\Omega.\mathrm{m}$ soil. The grid has a calculated resistance, R_g, of 1.0Ω. The surface soil potential profile around the grid per kA is shown in Figure C.4. The surface soil potential contours around the grid per kA of grid current are shown in Figure C.5. A soil potential profile across the diagonal of the grid is shown in Figure C.6.

[9] Equivalent to a high current per unit analysis.

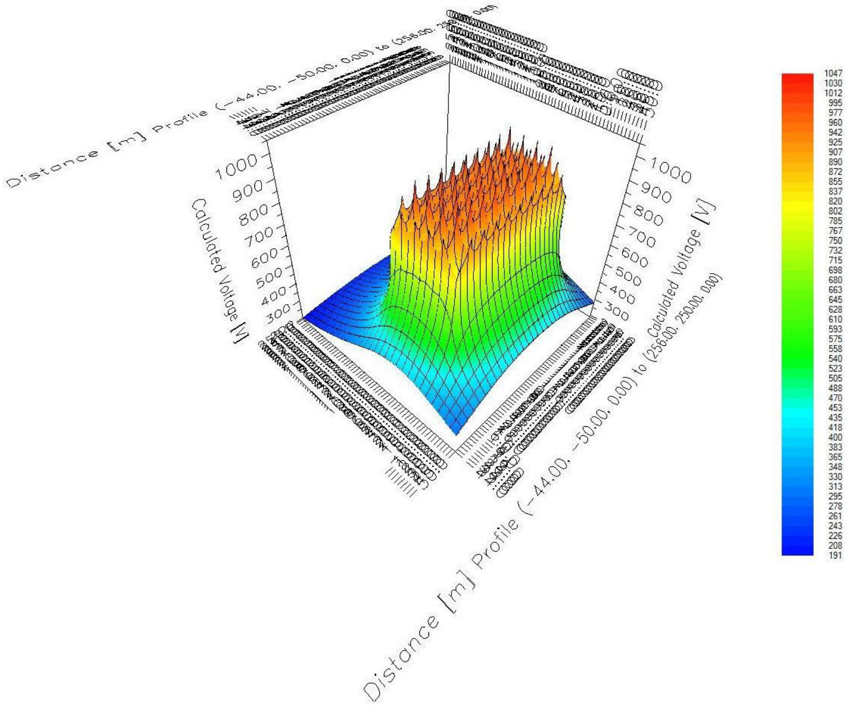


Figure C.1.4: Soil potential profile around substation (per kA)

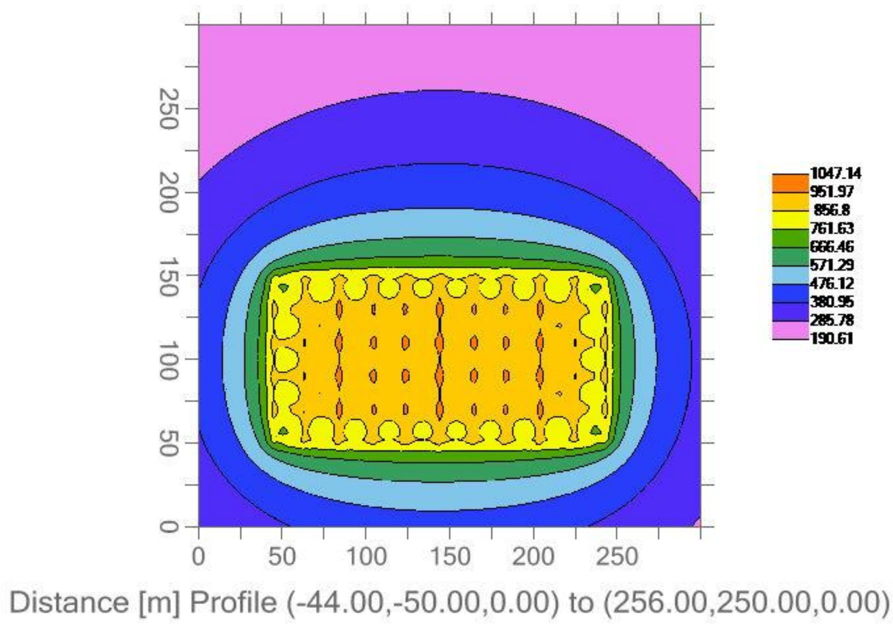


Figure C.1.5: Soil potential contours around substation (per kA)

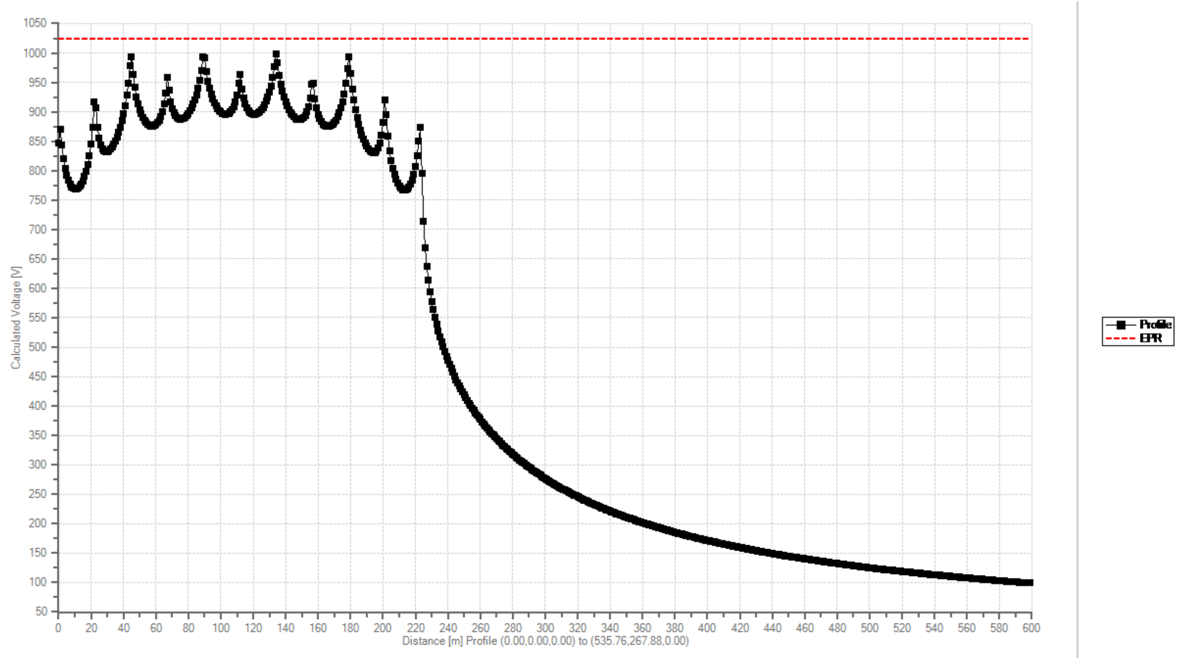


Figure C.1.6: Soil potential profile across substation grid (per kA)

C.1.6 Grid performance and hazard voltages with varying soil models

Table C.1.1: Case study a touch voltage analysis

Soil Resistivity (Ω m)		Resistance (Ω)	Touch Voltage (% EPR)			EPR (V)	
			1	2	3		
Upper	Lower		Mesh	Gate	Shower	400kV	110kV
300		1.0	25.9%	36.8%	51.9%	2801.1	1729.8
1000		3.4	25.8%	36.7%	51.9%	3101.5	1965.1
3000		10.2	25.7%	36.7%	51.9%	3108.9	2017.5
1000		1.7	43.8%	53.4%	33.4%	2904.6	1843.4
2000	300	2.6	54.4%	62.4%	23.5%	2954.5	1903.3
3000		3.5	59.6%	66.8%	18.8%	2973.3	1931.8
	1000	2.3	14.2%	23.7%	67.2%	3160.3	1946
300	2000	3.6	10.3%	18.3%	74.1%	3274.6	2014.5
	3000	4.7	8.6%	15.8%	77.4%	3319.8	2041.6

C.1.7 Broader earthing system performance

Next the contribution of the earthing associated with the 110kV & 400kV transmission lines to the substation earthing is considered. The conductive contribution is that impedance of a network where the network is not inductively coupled to the fault current. The analysis can be as simple as assuming the line is an 'infinite half line' [30], or each span in the line can be modelled. The earth grid of the terminating substation of the line being considered in this analysis is always assumed to be 1.0Ω. The earth grid impedance of the line's terminating substation has almost no impact on the conductive input impedance of the 110kV OHEW with a line length of 10km, so this value can almost be arbitrary for this consideration. The results are summarised in Table C.1.2. Note the input impedances for the 110kV lines are cited independent of their length for the above reason.

Table C.1.2: Transmission line earthing conductive input impedances

Line	Input Impedance [Ω]	Designation
110kV OHEW	$2.0\angle 22.2^o \Omega$	Z_{110}
400kV OPGW	$2.1\angle 23.1^o \Omega$	Z_{400}

The impedance of the substation earthing to use in the analysis conducted in the next Section, which includes consideration of inductive coupling, is determined by which lines are not considered parallel. In a first pass analysis one of the lines will be excluded as its performance will require induction be considered. These impedances, and how they are calculated, are summarised in Table C.1.3.

Table C.1.3: Substation earthing impedance for inductive analysis

Line Response Calculation	Substation Earth Grid	Calculation
Conductive Total[10]	$0.205\angle 18.0^o \Omega$	$\frac{Z_{110}}{6} \| \| \frac{Z_{400}}{2} \| \| R_g$
110kV	$0.217\angle 17.5^o \Omega$	$\frac{Z_{110}}{5} \| \| \frac{Z_{400}}{2} \| \| R_g$
400kV	$0.226\angle 17.3^o \Omega$	$\frac{Z_{110}}{6} \| \| Z_{400} \| \| R_g$

C.1.8 Line analysis - 110kV

As part of a conservative but effective process for analysing a line's earthing performance, and the impact that has on the supplying substation with regard earthing related hazards, it is assumed that:

- Any fault on the line is fed only by that line; and
- The other lines connected to the substation have no coupling to the fault.

On that basis the performance of the other lines can be reduced to their conductive input impedances and included in the impedance for the substation's earth grid as given by Table C.1.3 for the 110kV Line Response Calculation.

The power system described in Section C.1.1 includes $Y\nabla Y$ auto-transformers at the substation. This implies there is no break in the zero-sequence network at the substation so earth faults on the 110kV network transfer energy to the 400kV network. Whilst in practice this is beneficial in reducing the hazards at the substation for 110kV faults, it makes the example needlessly complicated. Consequently, it will be assumed that there is a break in the zero-sequence network at the substation. In practice the contribution to the overall earthing system performance of the 400kV network should be considered.

C.1.8.1 Fault Levels

Based on the stated 110kV bus fault level of 20kA we can assume a 110kV source impedance at the substation of $j3.2\Omega$. The fault levels along the line are described in Figure C.1.7. Of course, this changes if the fault can be supplied from both substations terminating the line, such as shown in Figure C.1.8. In producing Figure C.1.8 the source impedances at either end have been assumed to be identical, which is unlikely to be true.

[10] This is the impedance of the substation earthing system with all transmission line earthing connected but no inductive consideration.

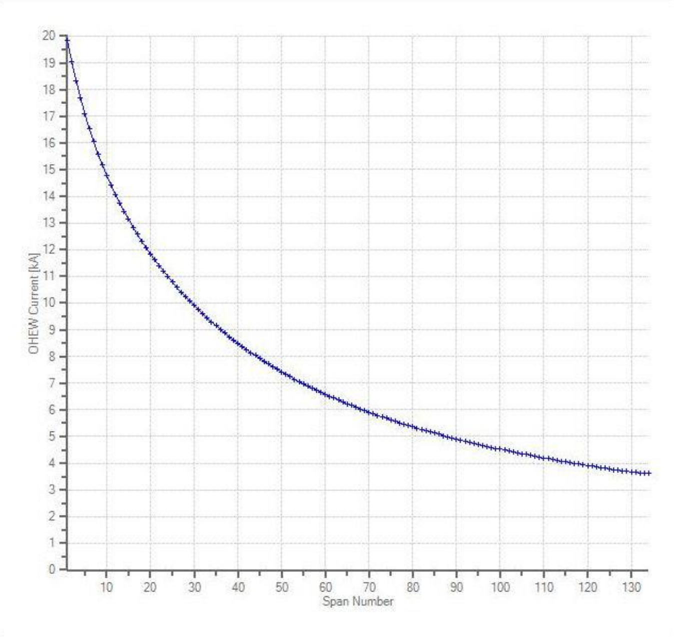


Figure C.1.7: 110kV line fault levels – single source

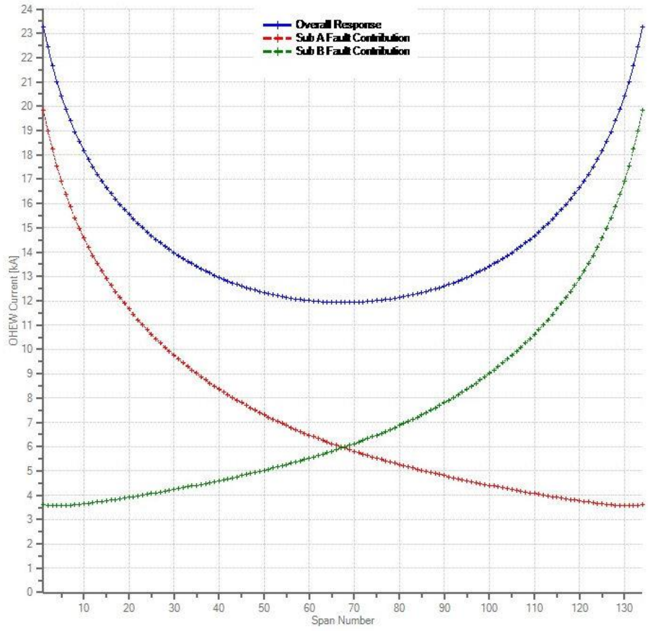


Figure C.1.8: 110kV line fault levels – dual source

C1.8.2 Earth Fault Response

For an earth fault at the end of a 10km line the EPR profile for each structure along the line is as shown in Figure C.1.9. Such analysis is completed using software, but the generic methods are outlined in [98] and [99].

An analysis which describes the maximum EPR for each structure for a set of faults impacting a line is called a MSEPR profile. Such a profile for a 10km 110kV line is described in Figure C.1.10.

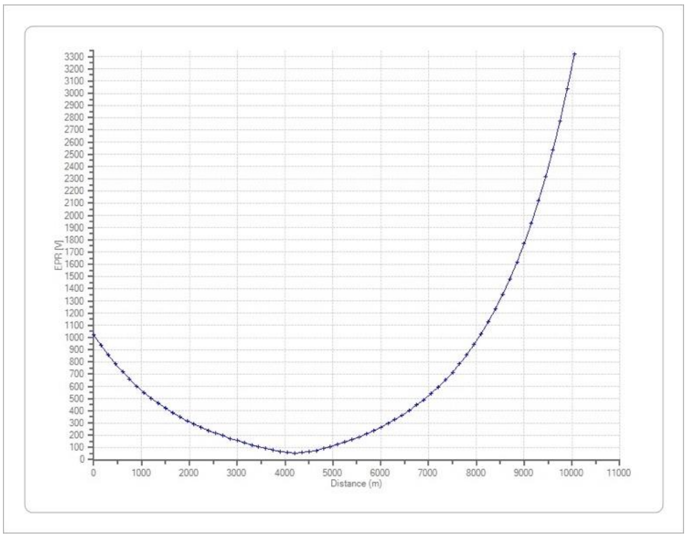


Figure C.1.9: Pole EPR assessment for 10km long 110kV line

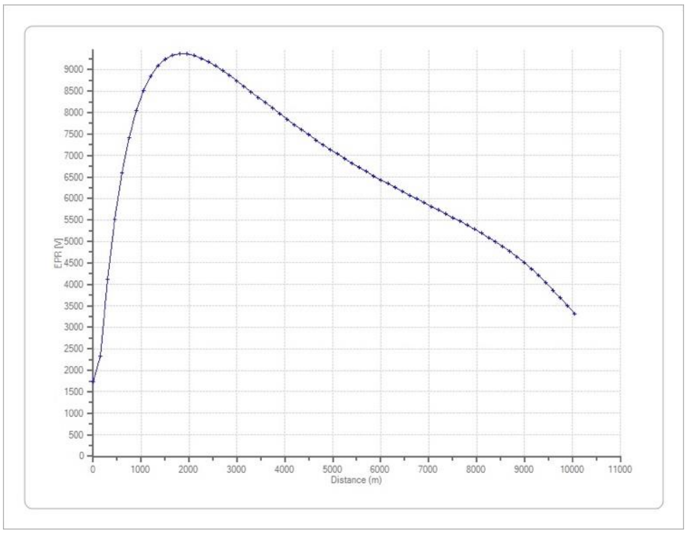


Figure C.1.10: MSEPR assessment of 10km long 110kV line

Alternatively, we can look at the EPR at a single location for every fault location on the line. Figure C.1.11 describes the EPR at the 400/110kV substation of interest based on faults along one of the 10km 110kV lines. Given a probability of a fault at each of those locations and the nature of hazards around the substation, including probability of exposure, a total risk for the substation due to faults on that line can be determined. By extension, repeating this process for every line will produce a more comprehensive risk profile for the substation.

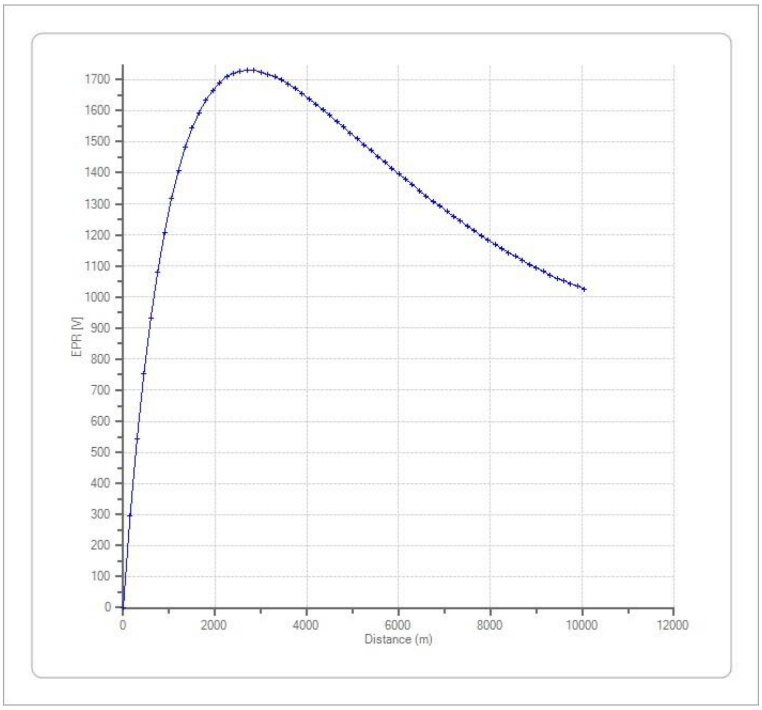


Figure C.1.11: Substation EPR assessment for all 110kV line faults

C.1.9 Line analysis - 400kV

The initial analysis of the 400kV network is based on one line being out of service.

C.1.9.1 Fault Levels

The stated 400kV bus fault level of greater than 40kA is a significant over estimation for the single line case. Consequently, it has been assumed that the actual fault level should be closer 20kA, based on the phase conductors being bundled conductor. This should result in a fault level approaching 40kA when the dual line case is considered.

The following analysis is based on the fault phase conductors being dual Mango conductors. Mango is an ACSR conductor (54/3.00, 7/3.00) with a GMR of 10.5mm and a Rac of $0.092\Omega/\mathrm{km}$. A dual Mango bundled conductor with a 350mm spacing has a GMR of 298.75mm and a Rac of $0.046\Omega/\mathrm{km}$. On this basis of a 400kV source impedance at the supplying substation bus of $j4.5\Omega$, the fault levels along the line are now as described in Figure C.1.12. The earthing system impedance at the supplying substation has been assumed to be 0.17Ω.

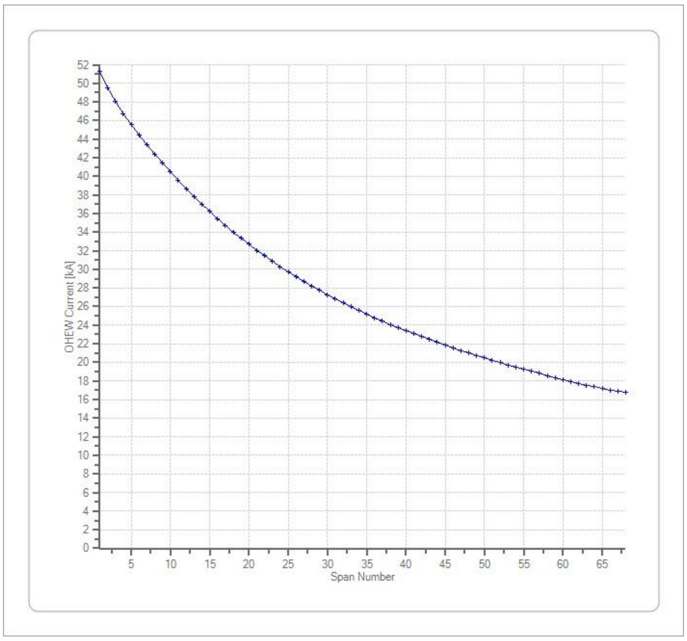


Figure C.1.12: 400kV line fault levels – single source

C.1.9.2 Earth Fault Response

For an earth fault at the end of the 20km long 400kV line the EPR for each structure along the line is as shown in Figure C.1.13.

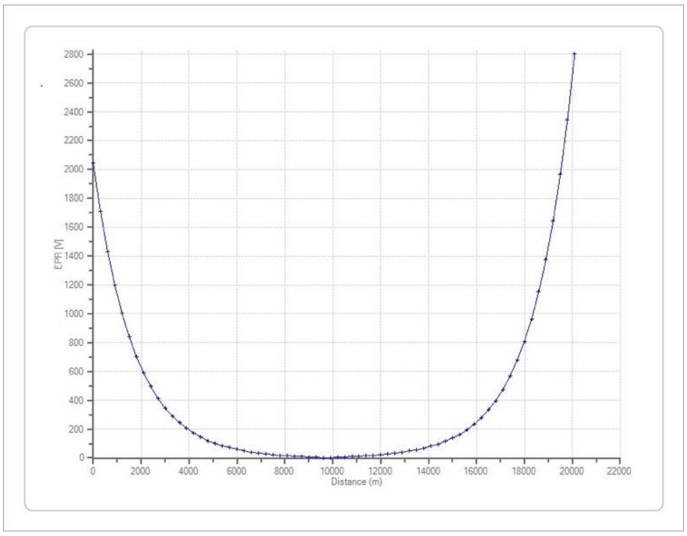


Figure C.1.13: Tower EPR assessment for 400kV line

The maximum EPR for each structure for any fault along the line is called a MSEPR profile. Such a profile for a 20km 400kV line is described in Figure C.1.14.

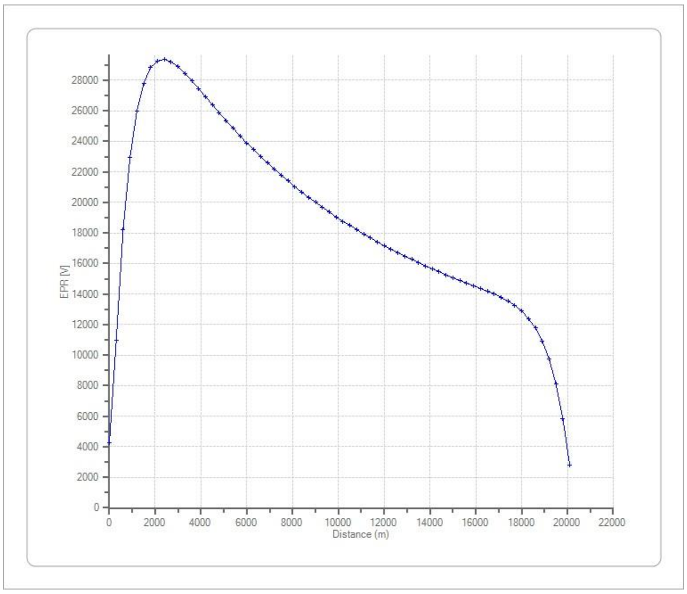


Figure C.1.14: MSEPR assessment for 400kV line

Alternatively, we can look at the EPR at a single location for every fault location on the line. Figure C.1.15 describes the EPR at the 400/110kV substation of interest based on faults along a 400kV line. Given a probability of a fault at each of those locations and the nature of hazards around the substation, including probability of exposure, a total risk for the substation due to faults on that line can be calculated. By extension, repeating this process for every line will produce a complete risk profile for the substation.

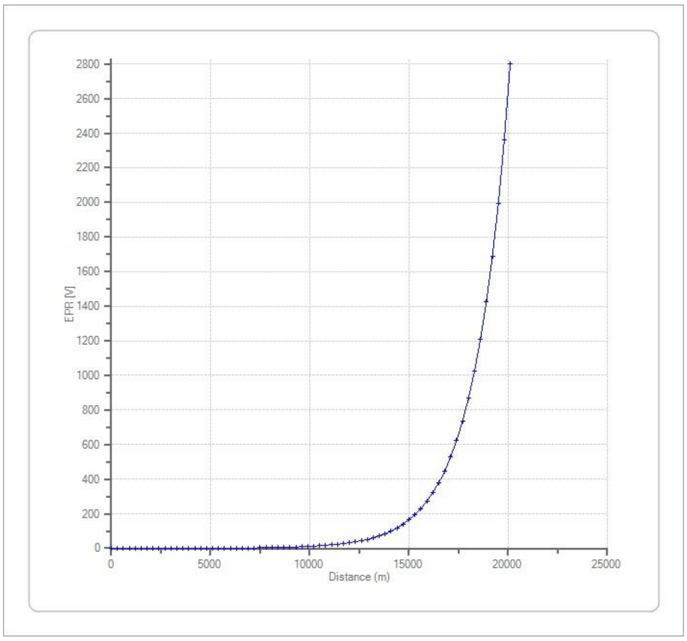
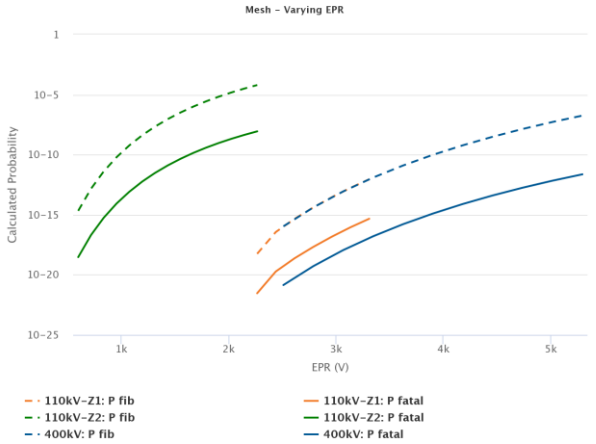


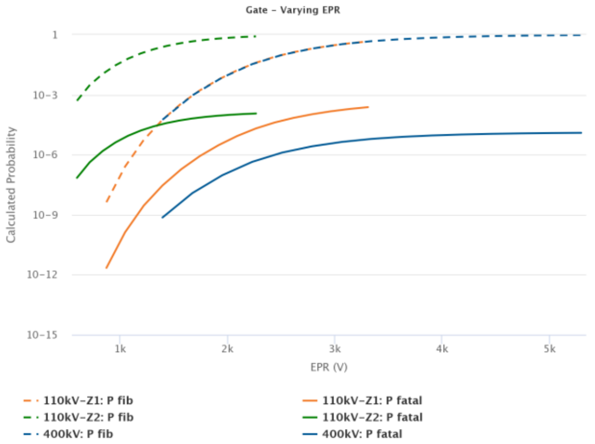
Figure C.1.15: Substation EPR assessment for all 400kV line faults

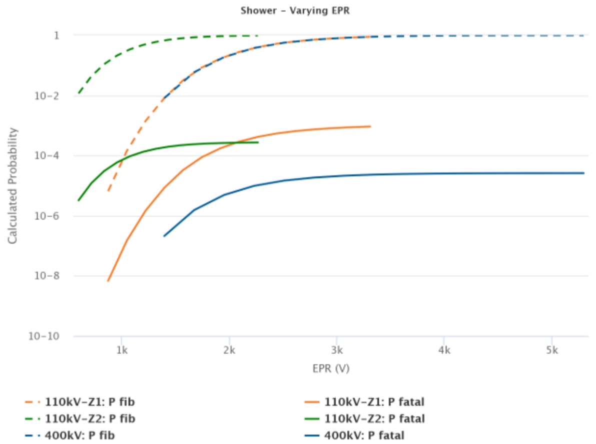
C.1.10 Risk analysis

The complete results of the risk analysis process are presented below for reference.

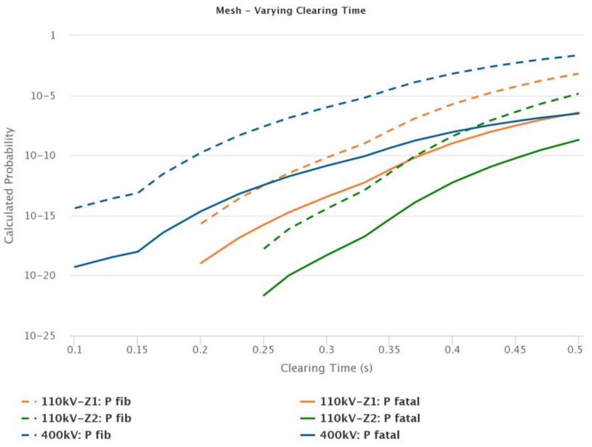
C.1.10.1 Varying EPR

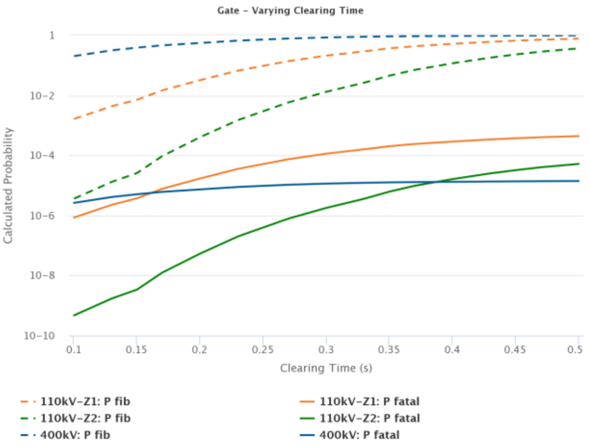


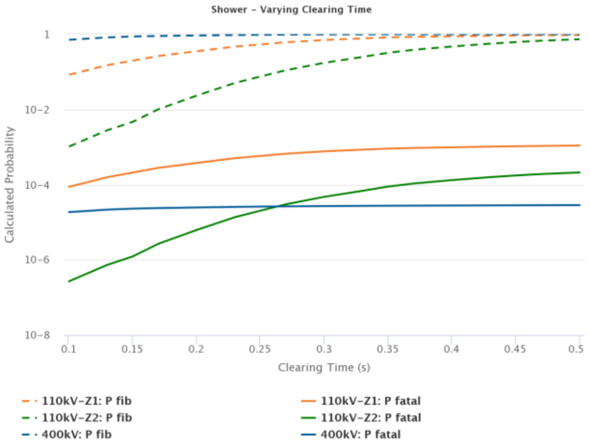




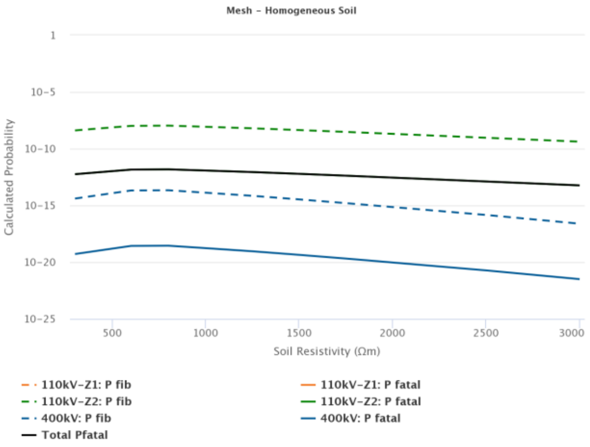
C.1.10.2 Varying Clearing Time

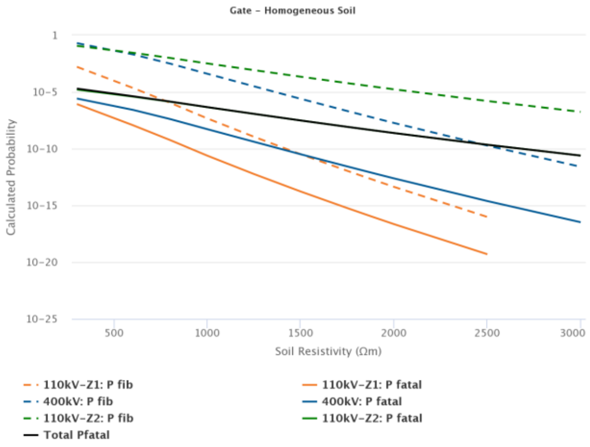


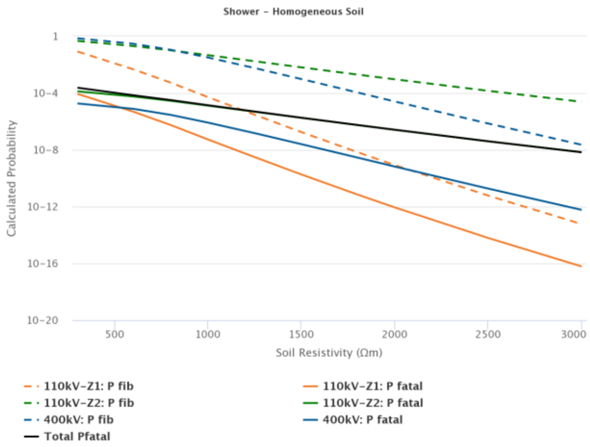




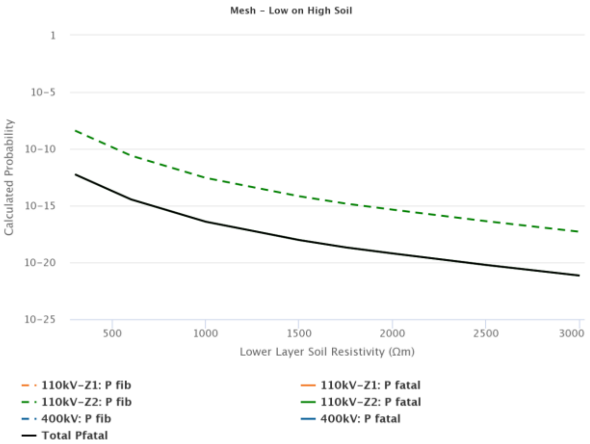
C.1.10.3 Varying Homogeneous Soil Models

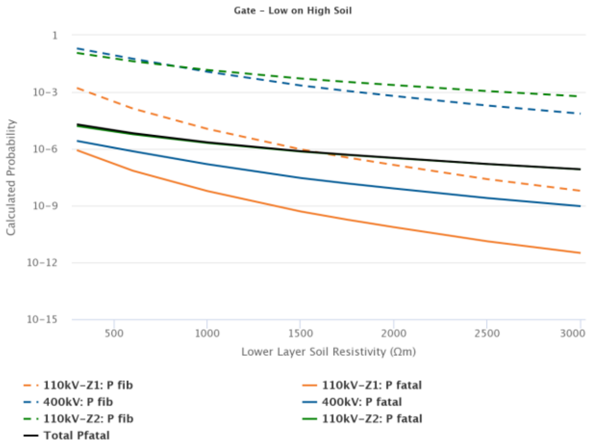


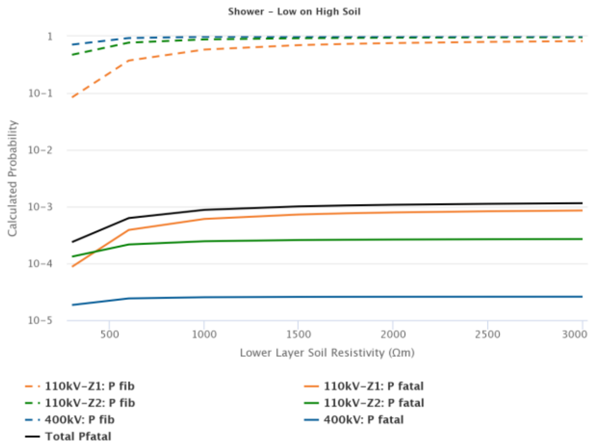




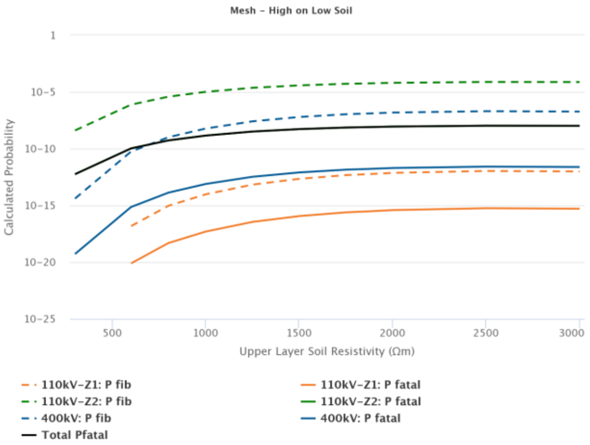
C.1.10.4 Varying Low-on-High Soil Models

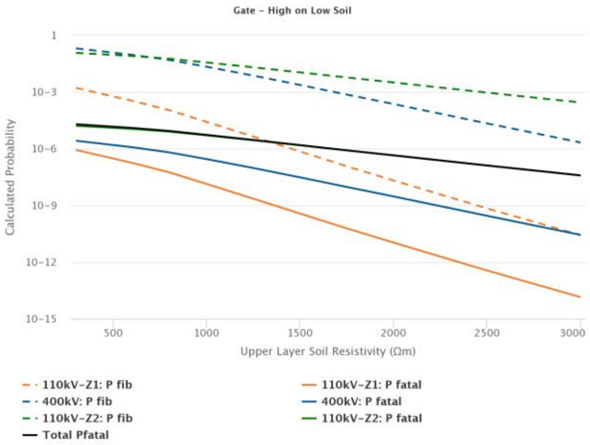


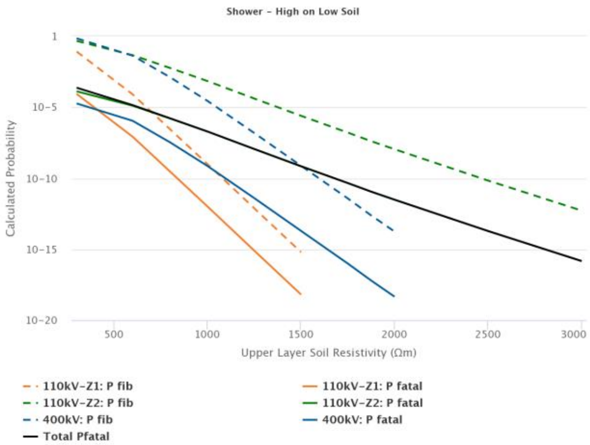




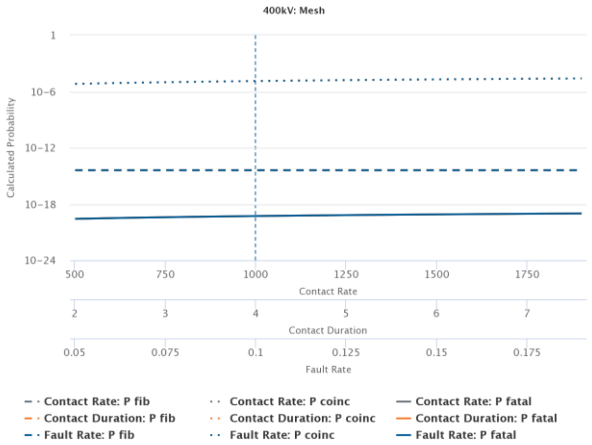
C.1.10.5 Varying High-on-Low Soil Models

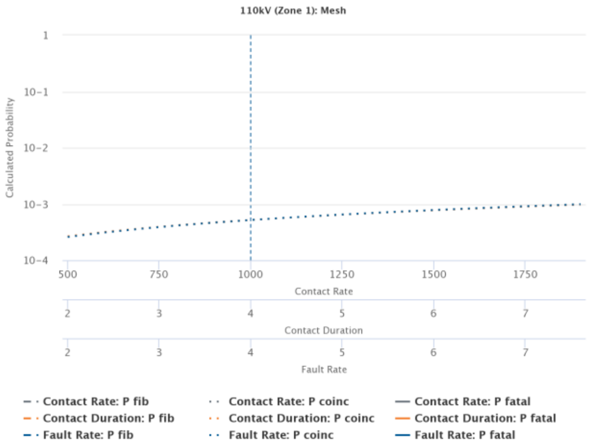


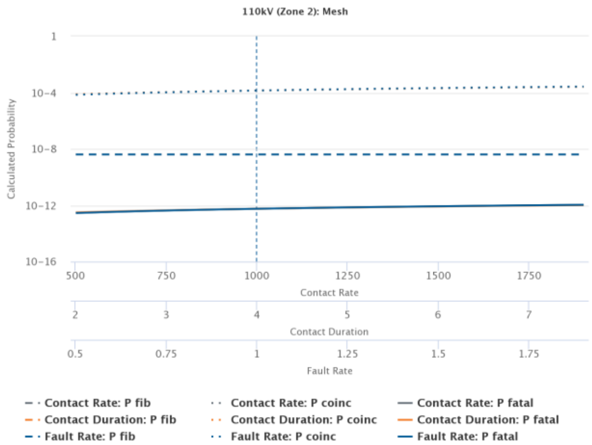




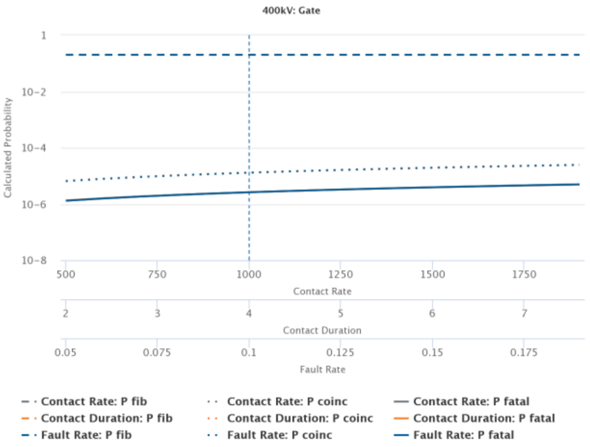
C.1.10.6 Varying Coincidence Factors Mesh Voltage Hazard

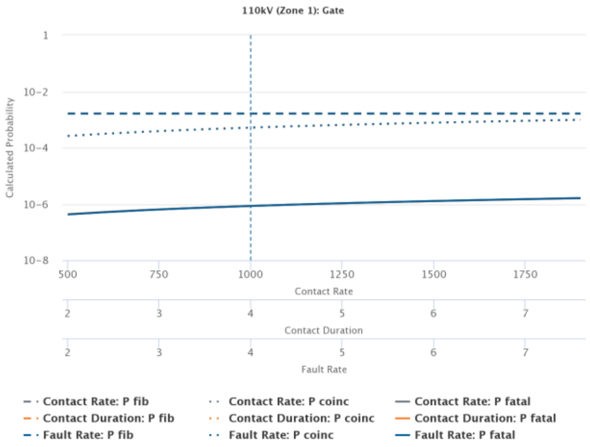


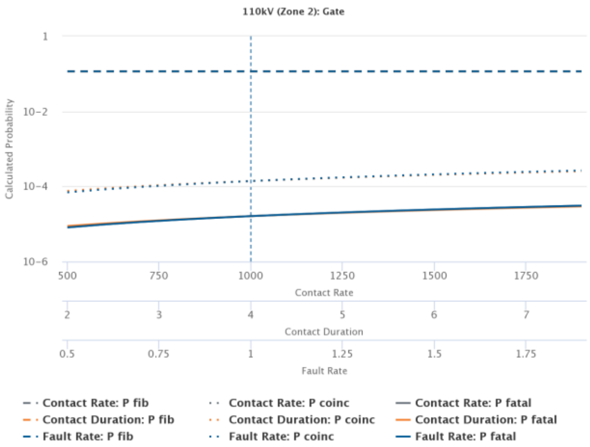




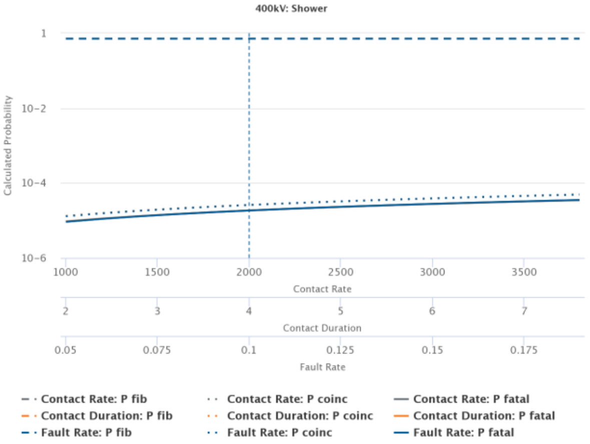
C.1.10.7 Varying Coincidence Factors Gate Touch Voltage Hazard

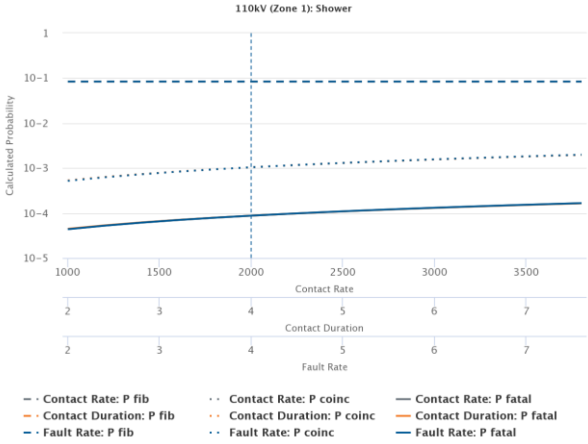


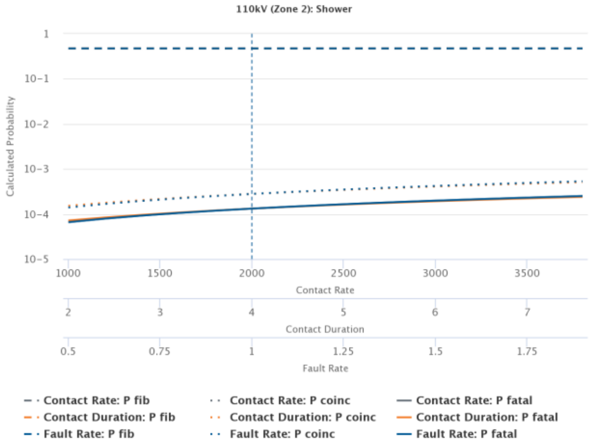




C.1.10.8 Varying Coincidence Factors Shower Touch Voltage Hazard







C.2 Data for Transmission Substation - Cable

This case study is an example of an inner-city substation, nominally 400/110kV with all connecting feeders of cable construction, which is presented to illuminate the method and specific results found for risk outcomes associated with normal or erroneous variations in input variables. The substation is supplied via three 400kV cables and supplies several 110kV circuits. The schematic is given in Figure C.2.1.

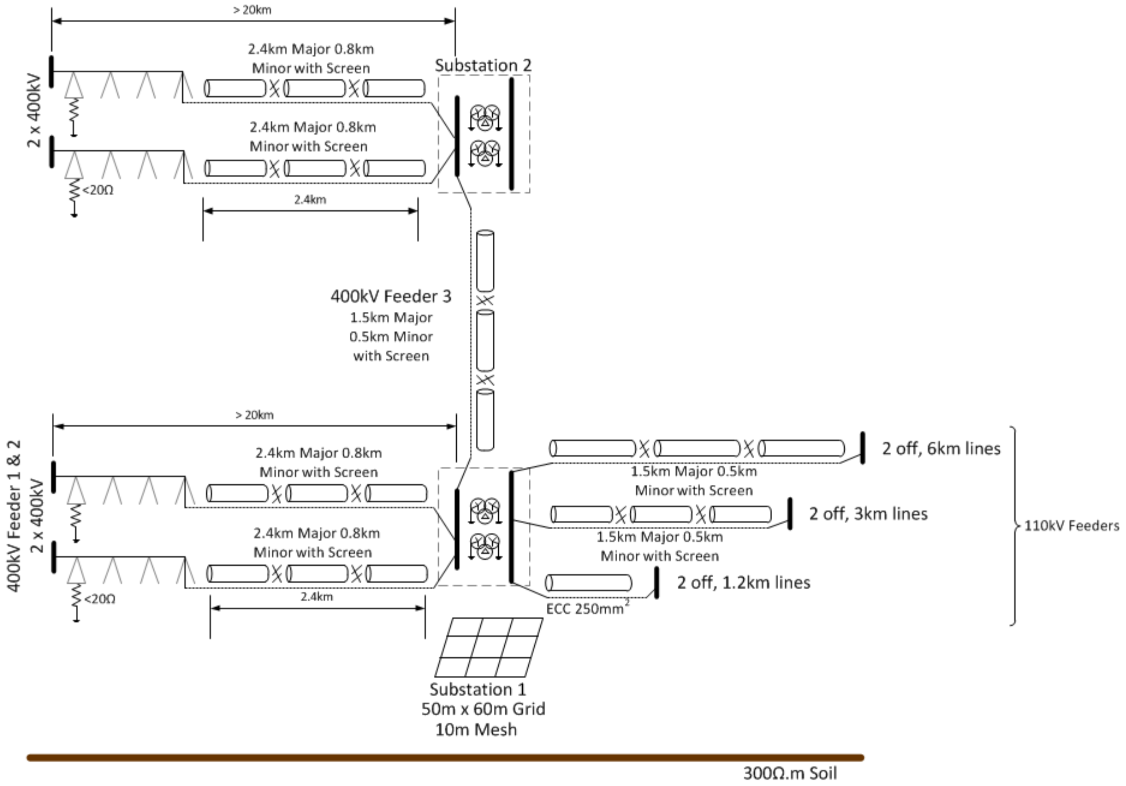


Figure C.2.1: Schematic of transmission substation - cable case study

C.2.1 System description

C.2.2 General configuration

The substation general configuration is:

- Three incoming 400kV lines and six outgoing 110kV lines;
- The 400kV tower construction is described in Figure C.1.2;
  - ✓ average span lengths of 300m;
  - ✓ OPGW with Rac ($0.846\Omega/\text{km}$) and GMR(4.35mm)
- The 400kV and 110kV cable construction is described in Figure C.2.2;
- The 400kV cable data is provided in Figure C.2.3;
- The 110kV cable data is provided in Figure C.2.4;
- 400kV feeder cables are 630mm^2, copper single core, aluminium sheath;
- 110kV feeder cables are 500mm^2, copper single core, aluminium sheath;

- Maximum earth fault level 400kV of 45kA[11];
- Maximum earth fault level 110kV of 40kA[12];
- The transformers are tertiary winding auto-transformers.

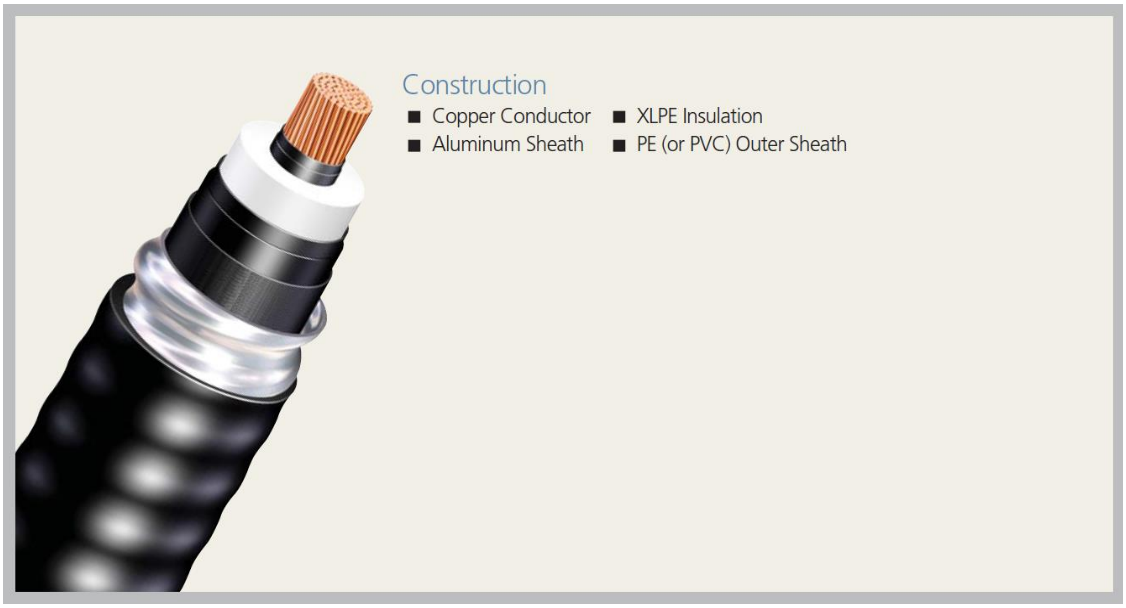


Figure C.2.2: 400kV and 110kV cable construction

Constructional Data (Nominal Values)

Conductor			Thickness of Conductor Screen Approx.	Thickness of Insulation	Thickness of Insulation Screen Approx.	Thickness of Aluminum Sheath	Thickness of Outer Sheath	Outer Diameter of Cable	Weight of Cable	Max. DC Conductor Resistance at 20°C	Capacitance
Cross-Sectional Area	Shape	Diameter									
mm²		mm	mm	mm	mm	mm	mm	mm	kg/m	Ω/km	μF/km
630	Compact Round Stranded	30.2	1.5	29.0	1.3	2.6	6	128	17.5	0.0283	0.14
800		34.0	1.5	29.0	1.3	2.7	6	132	19.6	0.0221	0.15
1000	Segment Stranded (Miliken)	38.7	1.5	29.0	1.3	2.8	6	138	22.5	0.0176	0.17
1200		41.8	1.5	29.0	1.3	2.8	6	141	24.6	0.0151	0.18
1600		48.1	1.5	29.0	1.3	3.0	6	150	29.9	0.0113	0.19
2000		54.3	1.5	29.0	1.3	3.1	6	157	34.7	0.0090	0.20
2500		63.0	1.5	29.0	1.3	3.3	6	167	42.0	0.0072	0.23
3000		69.0	1.5	29.0	1.3	3.3	6	174	46.7	0.0060	0.24

Figure C.2.3: 400kV cable data

[11] (the 3 data points to use for prob dist are 20, 45, 60)

[12] (the 3 data points to use for prob dist are 20, 40, 60)

Constructional Data (Nominal Values)

Conductor			Thickness of Conductor Screen Approx.	Thickness of Insulation	Thickness of Insulation Screen Approx.	Thickness of Aluminum Sheath	Thickness of Outer Sheath	Outer Diameter of Cable	Weight of Cable	Max. DC Conductor Resistance at 20°c	Capacitance
Cross-Sectional Area	Shape	Diameter									
mm²		mm	mm	mm	mm	mm	mm	mm	kg / m	Ω / km	μF / km
240		18.1	1.2	14.0	1.0	1.7	3.5	76	6.3	0.0754	0.17
300		20.4	1.2	14.0	1.0	1.8	3.5	78	7.0	0.0601	0.18
400	Compact Round Stranded	23.2	1.2	14.0	1.0	1.8	3.5	81	8.0	0.0470	0.20
500		26.3	1.2	14.0	1.0	1.9	4.0	86	9.3	0.0366	0.21
630		30.2	1.2	14.0	1.0	2.0	4.0	90	11.0	0.0283	0.23
800		34.0	1.2	14.0	1.0	2.0	4.0	94	12.9	0.0221	0.25
1000		38.7	1.2	14.0	1.0	2.1	4.0	99	15.4	0.0176	0.28
1200		41.8	1.2	14.0	1.0	2.2	4.5	104	17.7	0.0151	0.30
1600	Segment Stranded (Miliken)	48.1	1.2	14.0	1.0	2.4	4.5	111	22.1	0.0113	0.33
2000		54.3	1.2	14.0	1.0	2.5	4.5	118	26.5	0.0090	0.36
2500		63.0	1.2	14.0	1.0	2.6	4.5	128	33.0	0.0072	0.40

Figure C.2.4: 110kV cable data

C.2.3 Earthing system

The earthing system associated with the substation is described in Figure C.2.1 (referred to as Substation 1), and has the following salient points:

- All lines entering the substation, both primary and secondary, are cable;
- Each substation is bonded to the screen of a balanced and cross bonded cable, where applicable;
- Each substation is bonded to the ECC of a feeder cable, where applicable;
- Grid is 50m by 60m with a 10m mesh;
- The soil is initially 300Ω.m across the study. Later other resistivities are considered;
- The 400kV structures and cable major sections have an earth resistance of ≤ 20Ω;
- 400kV Feeders 1 and 2 source substations earthing system impedances are 1Ω;
- 400kV Substation 2 source substations earthing system impedance is 1Ω ;
- 400kV Substation 2 earth grid is 2.6Ω;
- 400kV feeder average overhead line span length of 300m;
- 110kV feeder terminating substations are 1Ω ;
- The 110kV cable major sections have an earth resistance of ≤ 20Ω;
- The 110kV ‘Neutral’ Earthing possiibilities include:
  - ✓ Petersen Coils;
  - ✓ Resistance/reactance to less than 20kA; and
  - ✓ Solid.

C.2.4 Protection

- 400kV ⇒ Unit/differential protection 100ms
- 110kV ⇒ Distance protection Zone 1 < 100ms for 80% of the line.
- Zone 2 < 400ms

C.2.5 System analysis

In this section the performance of the various elements of the earthing network are examined.

The first part of the analysis is to consider the conductive response of the various elements of the network. In the second stage of the analysis the modelling is expanded to include the earthing associated with the 110kV & 400kV transmission lines, and faults on those lines. The analysis conducted in this case study is essentially the same as that conducted in Section C.1 except that the magnetic coupling of underground power cables is somewhat stronger. This case study allows that difference in performance between the two networks to be demonstrated and the consequential difference in risk to be quantified.

C.2.6 Conductive analysis

In this case the installation is housed inside a building so the earth grid size is significantly smaller than the previous case. The 50 × 60m grid with 10m mesh in 300Ω.m soil has a calculated resistance of 2.6Ω. The soil potential profile around the grid per kA is shown in Figure C.2.5. The soil potential contours around the grid per kA of earth current are shown in Figure C.2.6. A soil potential profile across the diagonal of the grid is shown in Figure C.2.7. For reference purposes the analysis and graphs have been produced using AVC[13].

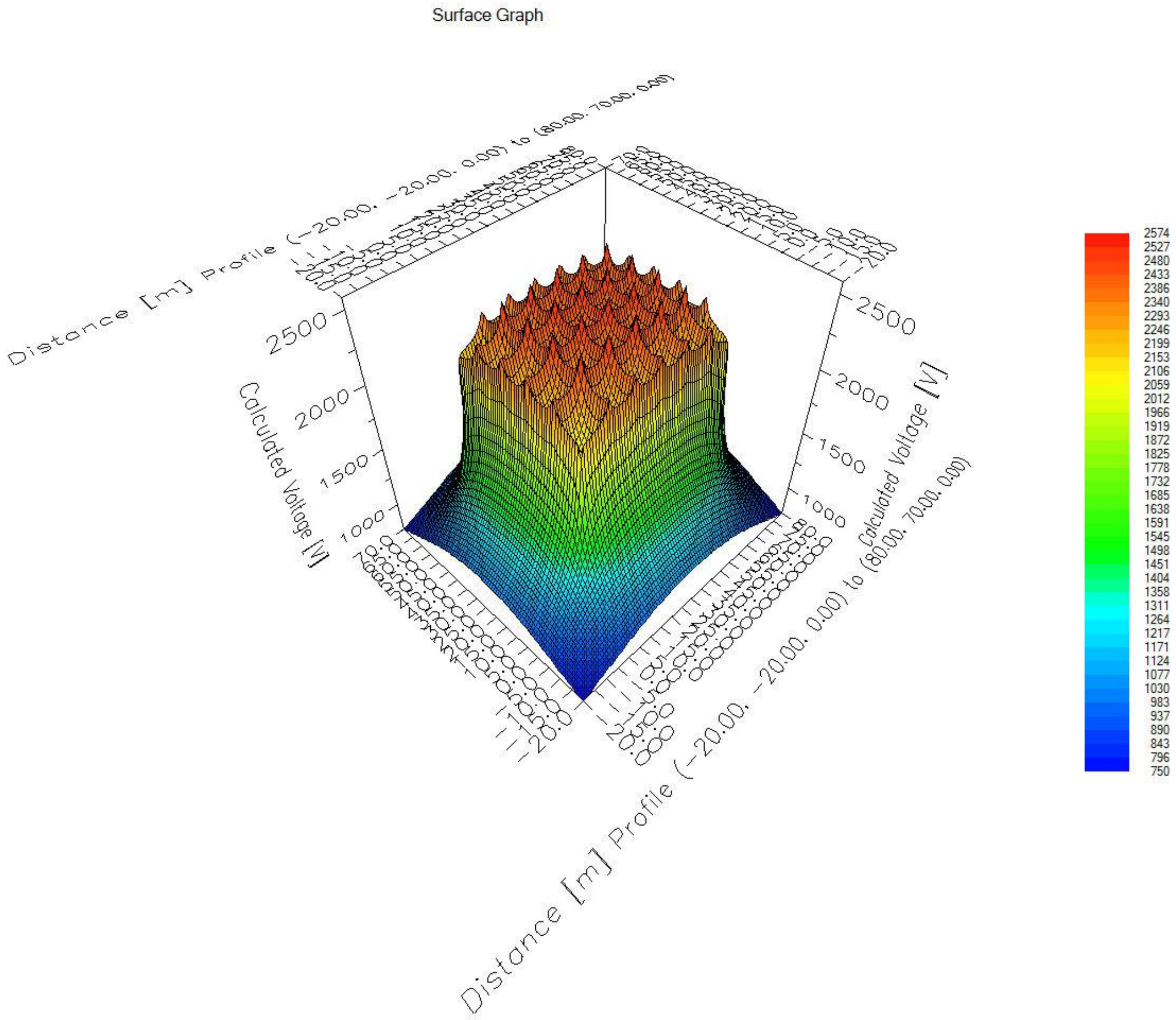


Figure C.2.5: Substation 1 soil potential profile per kA

[13] Software used by Safearth Consulting, originally developed when the group was part of Shortland Electricity/Energy Australia.

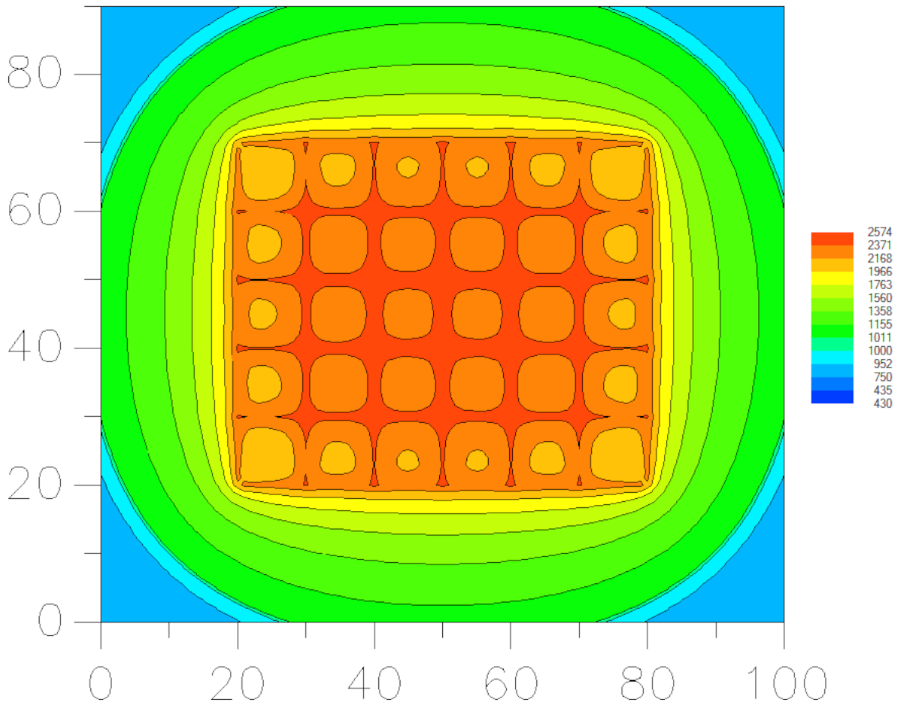


Figure C.2.6: Substation 1 soil potential contours per kA

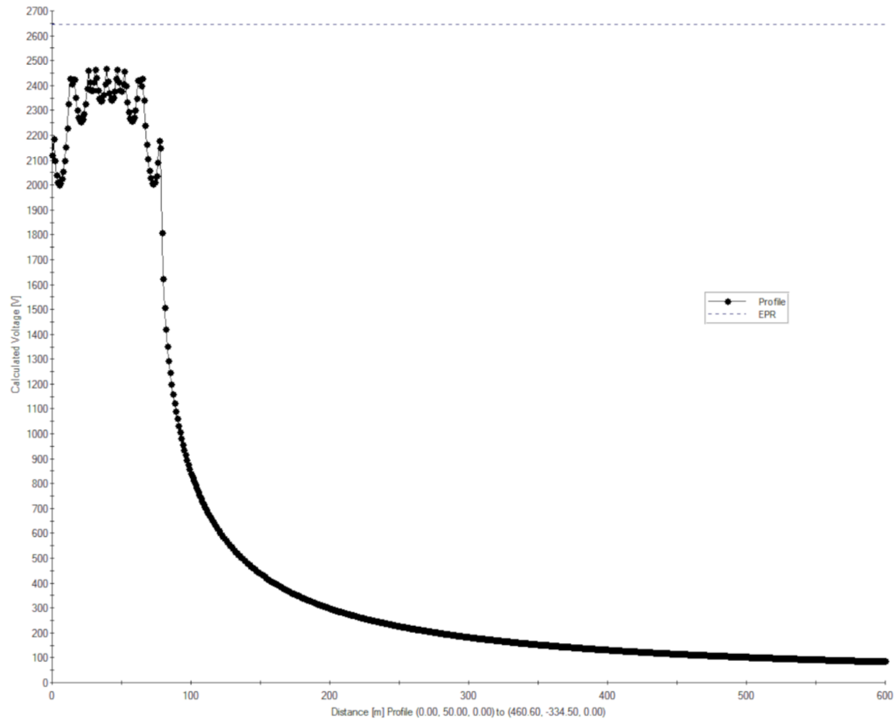


Figure C.2.7: Substation 1 soil potential profile per kA – across grid

Next the contribution of the earthing associated with the 110kV and 400kV transmission lines to the substation earthing is considered. The conductive performance is the impedance of an earthing system where the auxiliary paths, such as an OPGW, cable screen or ECC, are not inductively coupled to the fault current. The results are summarised in Table C.2.1.

Table C.2.1: Transmission line earthing conductive input impedances

Line	Input Impedance [Ω]	Designation
110kV	$1.5\angle 37^o\Omega$	Z_{110}
400kV Feeder 1 &2	$3.0\angle 32.1^o\Omega$	Z_{400A}
400kV Feeder 3	$2.2\angle 54^o\Omega$	Z_{400B}

The impedance of the substation earthing to use in the analysis was introduced in Section C.1.6 and Section C.1.7, which includes consideration of inductive coupling, is determined by which lines are not considered parallel. In a first pass analysis one of the lines will be excluded as its performance will require induction be considered. These impedances, and how they are calculated, are summarised in Table C.2.2.

Table C.2.2: Substation earthing impedance for inductive analysis

Line Response Calculation	Substation Earth Grid	Calculation
No induction[14]	$0.19\angle 35^o\Omega$	$\frac{Z_{110}}{6}\vert\vert\frac{Z_{400}}{2}\vert\vert R_g$
110kV	$0.21\angle 35^o\Omega$	$\frac{Z_{110}}{5}\vert\vert\frac{Z_{400}}{2}\vert\vert R_g$
400kV	$0.226\angle 17.3^o\Omega$	$\frac{Z_{110}}{6}\vert\vert Z_{400}\vert\vert R_g$

C.2.7 Single line analysis - 110kV

A conservative but effective method to analyse a line's earthing performance, and the impact on the supplying substation with regard to earthing related hazards, is to assume that any fault on the line is fed only by that line and the other lines connected to the substation have no coupling to the fault. On that basis the performance of the other lines can be reduced to the conductive performance as given by [30].

The system described in Section C.1 includes Y∇Y auto-transformers. This implies there is no break in the zero-sequence network at the substation so earth faults on the 110kV network transfer energy to the 400kV network. Whilst in practice this is beneficial in reducing the hazards at the substation for 110kV faults, it makes the example unnecessarily complicated. Consequently, it will be assumed that there is a break in the zero-sequence network at the substation. In practice the contribution of the 400kV network should be considered.

C.2.7.1 Fault Levels

Based on the stated 110kV bus fault level of 20kA we can assume a 110kV source impedance at the substation of j3.2Ω. The fault levels along the line are now as described in Figure C.2.8. Of course, this changes if the fault can be supplied from both substations terminating the line, such as shown in Figure C.2.9. In producing Figure C.2.9 the source impedances at either end have been assumed to be identical, which is unlikely to be true.

14 This is the impedance of the substation earthing system with all transmission line earthing connected but no inductive consideration.

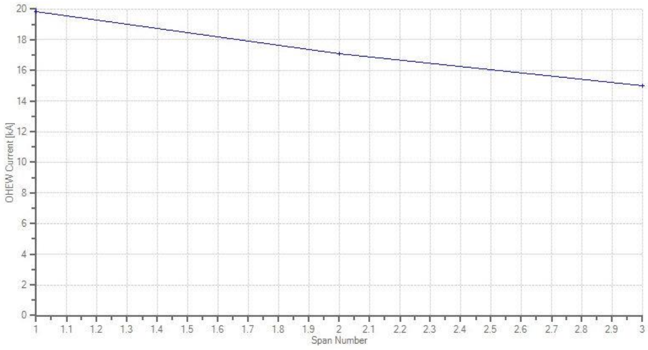


Figure C.2.8: Substation 1 fault levels one 3km long 110kV feeder – single source

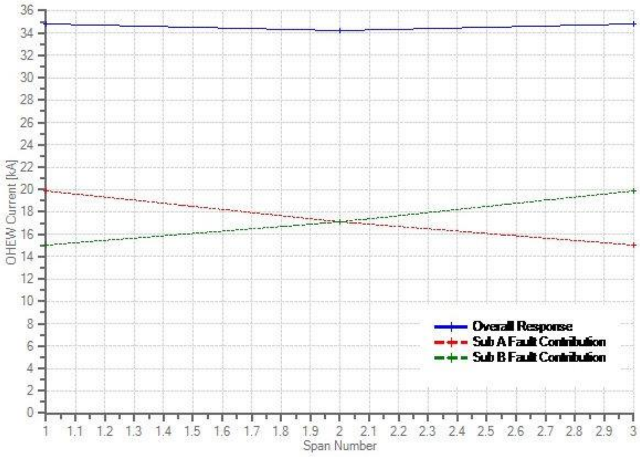


Figure C.2.9: Substation 1 fault levels one 3km long 110kV feeder – dual source

What Figure C.2.8 & Figure C.2.9 show is that whilst the 110kV bus fault levels are consistent between the two cases, the underground cable networks do not decay nearly as quickly due to the lower loop impedance presented to earth faults by the metallic screens of the cables.

C.2.7.2 Line Earth Fault Response

For a single source earth fault at the end of a 3km 110kV line the EPR profile for each structure along the line is as shown in Figure C.2.10.

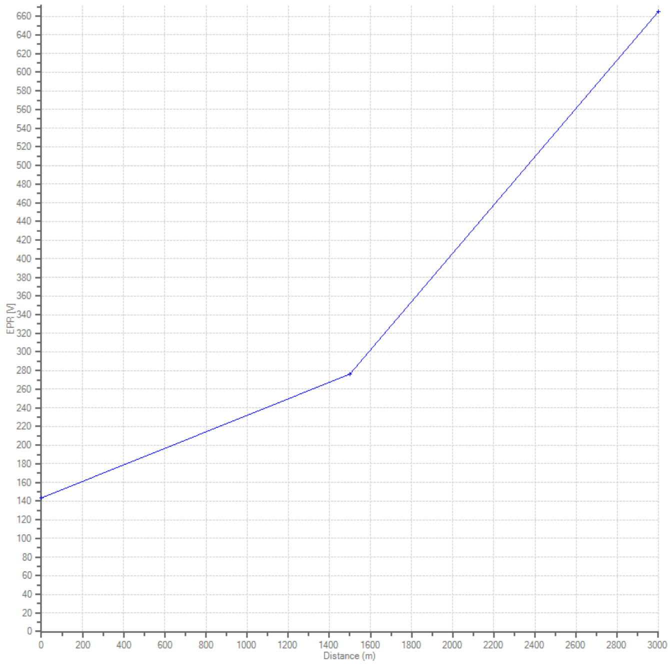


Figure C.2.10: Line EPR assessment for 110kV line

The Maximum Structure EPR for any fault along the line is called a MSEPR profile. Such a profile for a 3km 110kV line is described in Figure C.2.11.

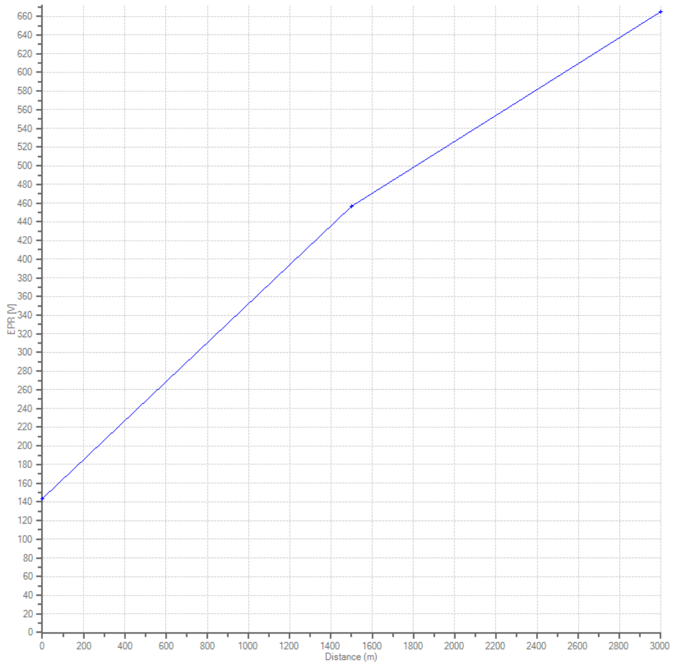


Figure C.2.11: MSEPR assessment for 110kV line

Alternatively, we can look at the EPR at a single location for every fault location on the line. Figure C.2.12 describes the EPR at the 400/110kV substation of interest based on faults along a 3km 110kV line. Given the probability of a fault at each of these locations and the nature of hazards around the substation, including probability of exposure, a total risk for the substation due to faults on that line can be calculated. By extension, repeating this process for every line will produce a complete risk profile for the substation.

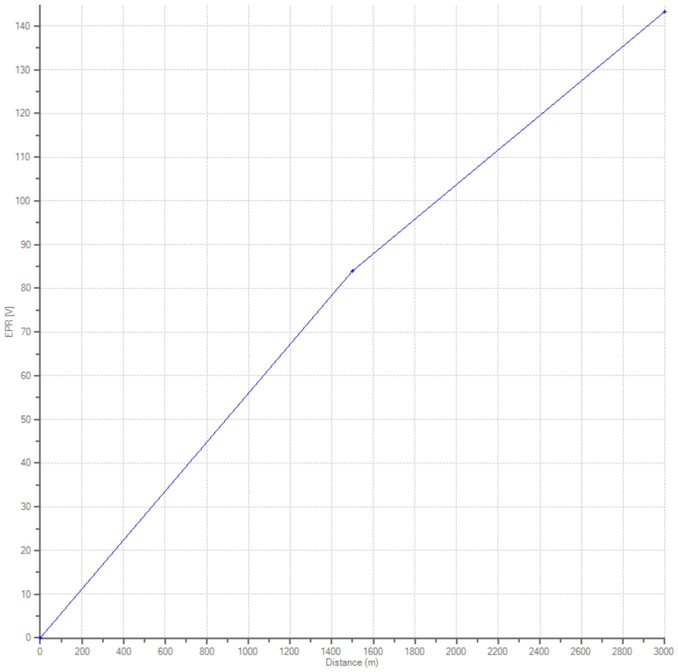


Figure C.2.12: Substation 1 EPR assessment for all 110kV line faults

C.2.8 Single line analysis - 400kV

The initial analysis of the 400kV network is based on one line being in service.

C.2.8.1 Fault Levels

The stated 400kV bus fault level of <45kA is an over estimation for the single line case. Consequently, it has been assumed that the actual fault level should be closer 15kA. This should result in a fault level approaching 45kA when the multiple line case is considered.

On the basis of a 400kV source impedance at the supplying substation bus of j4.5Ω, the fault levels along the line are now as described in Figure C.2.13.

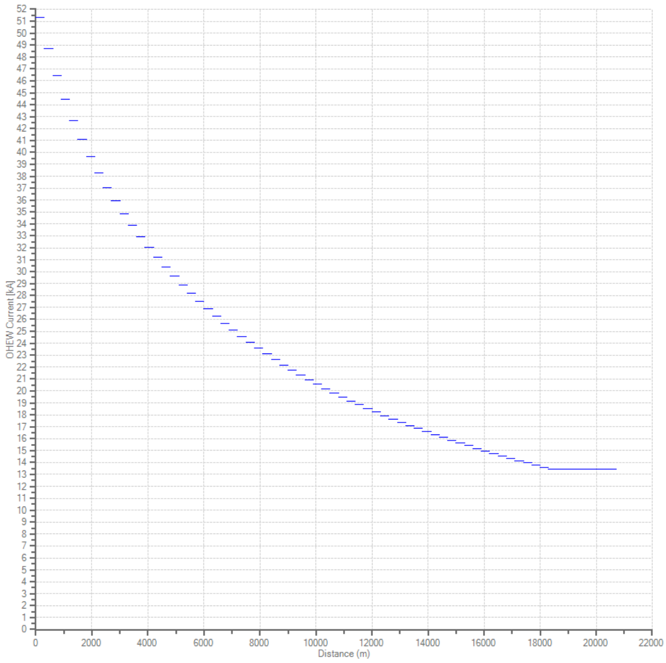


Figure C.2.13: 400kV line fault levels

C.2.8.2 Line Earth Fault Response

For an earth fault at the end of the 20km 400kV Feeder 1 the EPR profile for each structure along the line is as shown in Figure C.2.14.

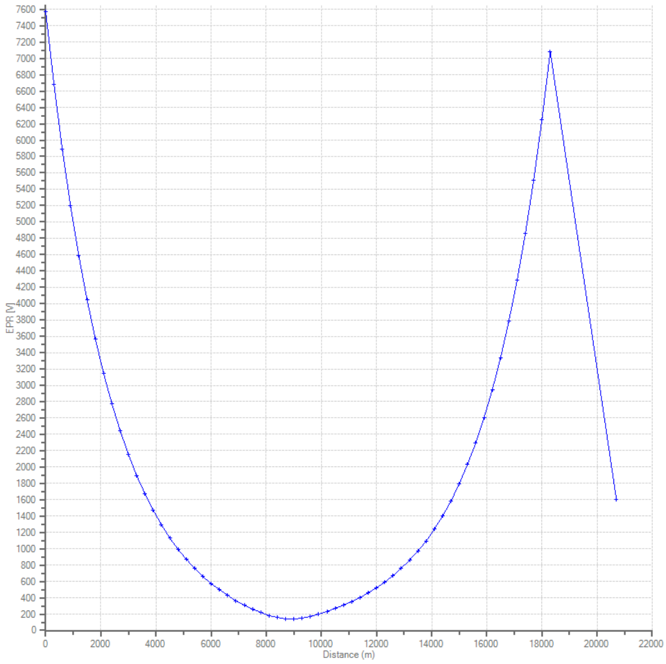


Figure C.2.14: Structure EPR assessment for 400kV fault at end of line

The maximum structure EPR for any fault along the line is called a MSEPR profile. Such a profile for a 20km 400kV line is described in Figure C.2.15.

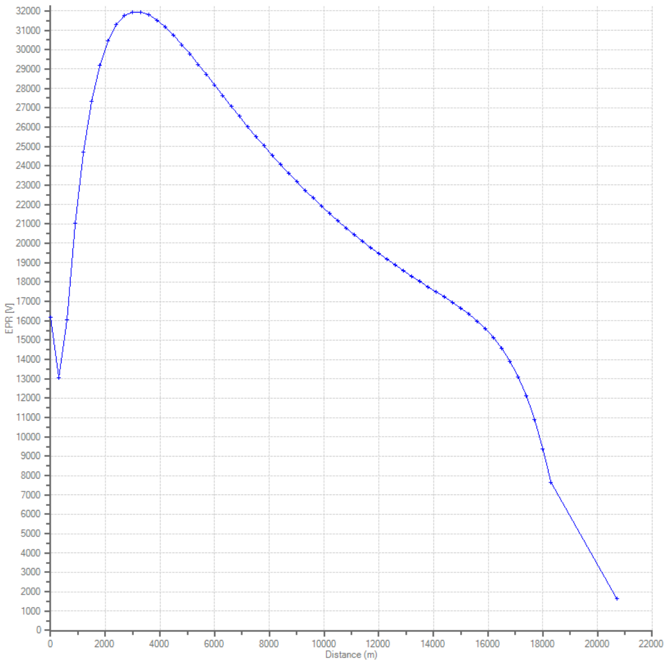


Figure C.2.15: MSEPR assessment for 400kV line faults

Alternatively, we can look at the EPR at a single location for every fault location on the line. Figure C.2.16 describes the EPR at the 400/110kV substation of interest based on faults along the 400kV line. Given the probability of a fault at each of these locations and the nature of hazards around the substation, including probability of exposure, a total risk for the substation due to faults on that line can be calculated. By extension, repeating this process for every line will produce a complete risk profile for the substation.

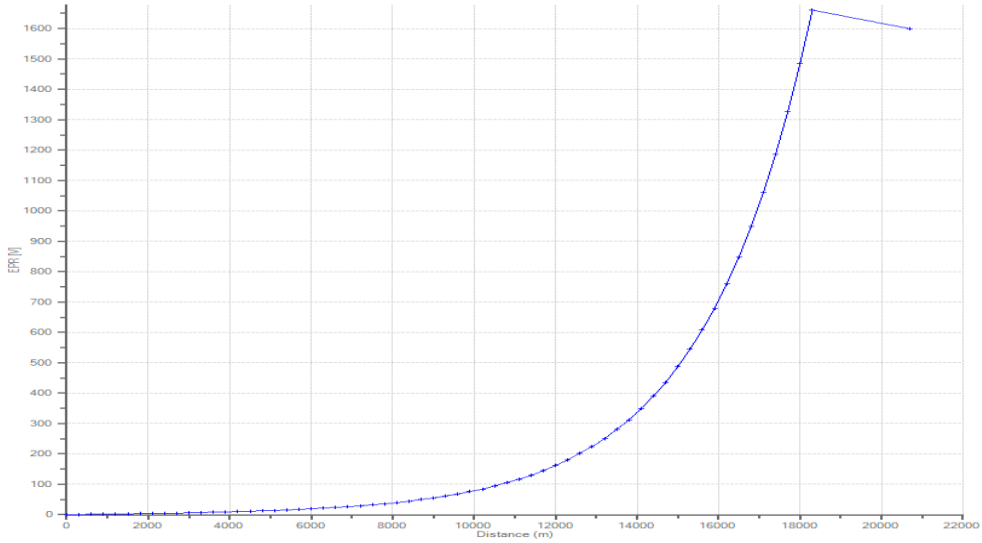


Figure C.2.16: EPR assessment at substation 2 for line faults on 400kV feeder 1

C.2.9 Hazard analysis

Further analysis has been completed to determine the variance in touch voltage hazards due to changes in soil resistivity. Referring to Table C.2.9, touch voltages have been calculated for the following three 400kV and 110kV scenarios[15]:

- Mesh: The maximum mesh voltage calculated for Substation 1.
- Gate: Touch voltage from an open gate 3m from the edge of the Substation 1 earth grid.
- Shower: House touch voltage, assuming the house pipes/neutral are remotely earthed and the individual's feet are positioned 10m from the edge of the Substation 1 earth grid. This case includes TN & TT system (unless the TT system has no conductive transfer beyond the individual premise via plumbing, fences or concrete reinforcing for example). Alternatively this touch voltage is the transfer out via neutral interconnections to places where the soil has dropped away (TN only).

Table C.2.3: Case study B touch voltage analysis

Soil Resistivity (Ωm)		**Resistance (Ω)**	**Touch Voltage (% EPR)**			**EPR (V)**	
Upper	*Lower*		*1 Mesh*	*2 Gate*	*3 Shower*	*400kV*	*110kV*
300		2.6	25%	39%	42%	1662	143
1000		8.8	25%	76%	42%	1689	155
3000		26.5	25%	43%	42%	1666	162
1000	300	5.3	37%	59%	25%	1670	153
2000	300	8.9	43%	67%	17%	1665	158
3000	300	12.4	46%	70%	14%	1659	161
300	1000	5.0	15%	29%	59%	1709	147
300	*2000*	7.0	11%	23%	67%	1724	149
300	3000	8.4	9%	20%	71%	1730	149

[15] There are potentially thousands of touch voltage hazards for any asset but for the purpose of this case study we consider a small number of scenarios, recognising that they represent more than one location in each case.

C.2.10 Comparison of hazards between case studies

Comparing the results of the hazard analyses for the two cases, which are summarised in Table C.1.1 and Table C.2.3, the reader can make the following observations:

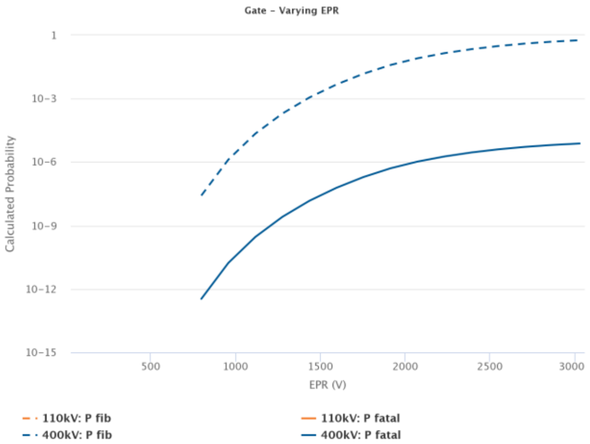
- The resistance of the earth grid for Case B is consistently 2.6× the value of that calculated for Case A. This is because the resistance is dependent on the soil resistivity, which is consistent across the cases considered, and the area of the earth grid. This should not be confused with the impedance of the earthing system to a fault at any location which is also dependent on the performance of the earthing network to that location.
- The EPRs calculated for Case B are consistently lower than Case A. This is due to the better performance of the earthing associated with underground cables. The mixed overhead/underground 400kV network is consistently better by about 50%, whereas the dominantly underground 110kV network has EPRs of only 10% of the equivalent cases in Case Study B.
- The touch voltages as percentages of EPR are essentially equivalent between the case studies. This is because touch voltages are dominantly dependent on the soil resistivity structure. There is some discrepancy due to the relative sizes of the earth grids.
- The touch voltages in absolute terms are much lower for Case Study B. The touch voltages produced on the 400kV network for Case B are about 50% of that found for Case A. The 110kV touch voltages for Case B are only about 10% of that predicted for case Study A. This is consistent with the EPRs calculated for the two cases.

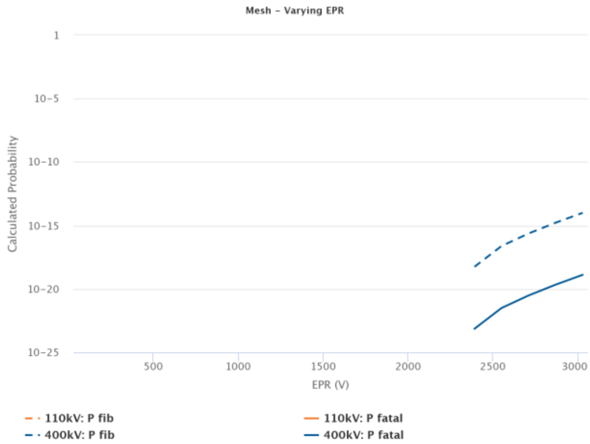
In summary, the hazards posed by the network considered in Case Study A, despite the significantly larger earth grid for the substation in that case, are significantly larger than the hazards presented for the equivalent scenarios in case Study B.

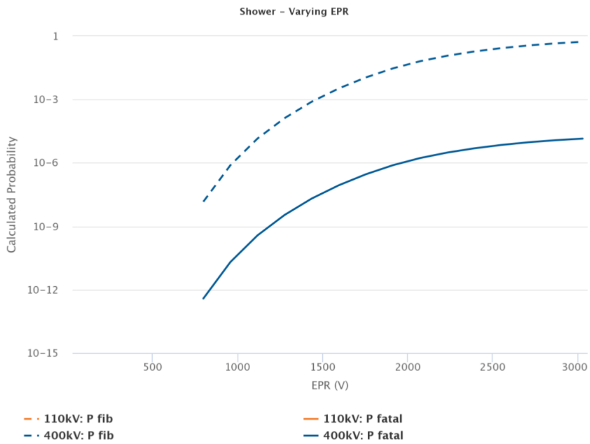
C.2.11 Risk analysis

The complete results of the risk analysis process are presented below for reference.

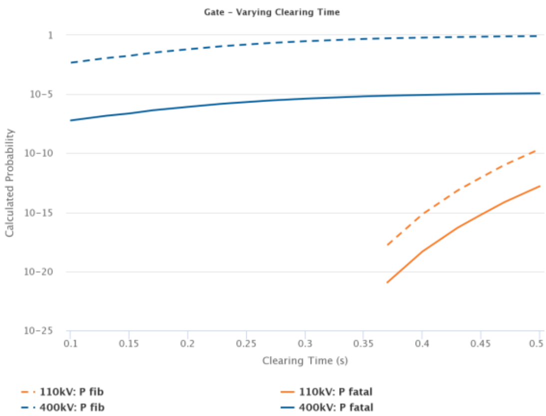
C.2.11.1 Varying EPR

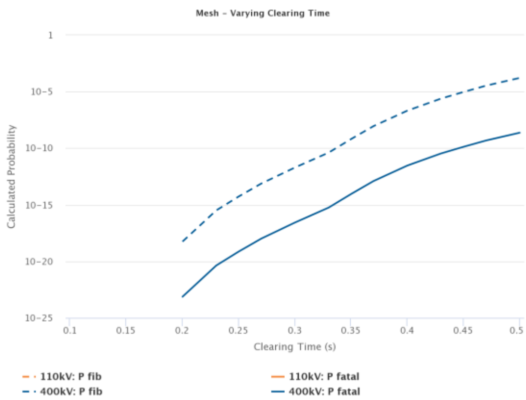


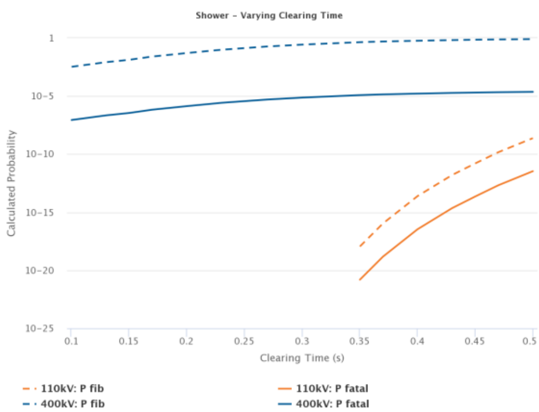




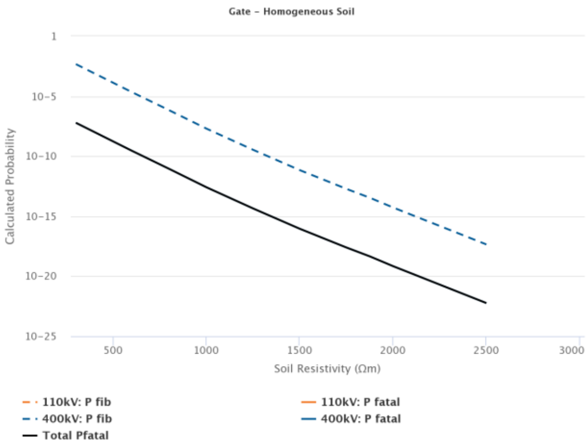
C.2.11.2 Varying Clearing Time

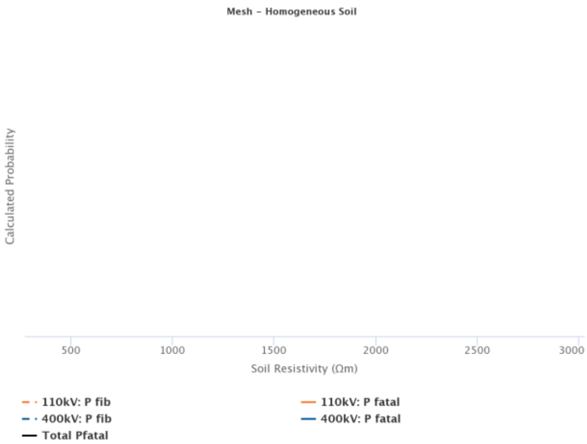


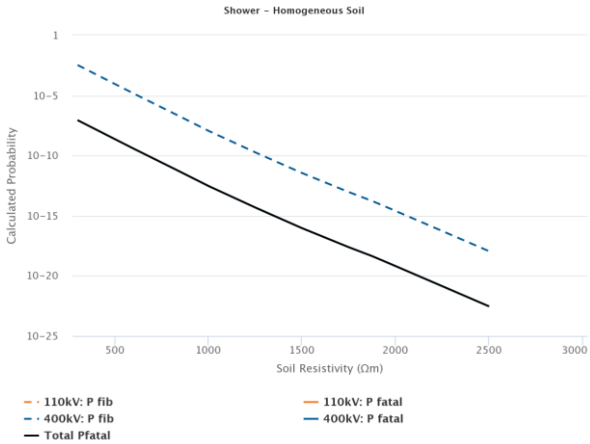




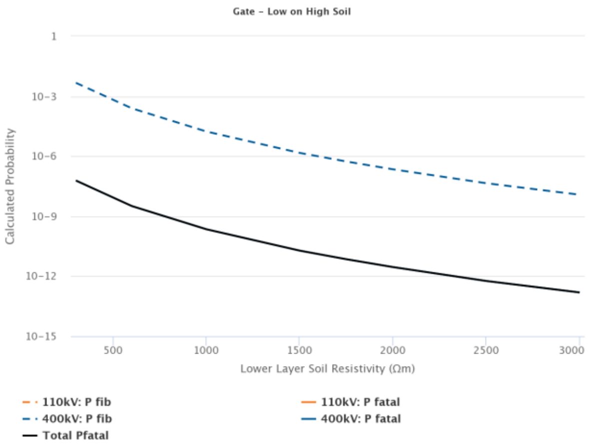
C.2.11.3 Varying Homogeneous Soil Models

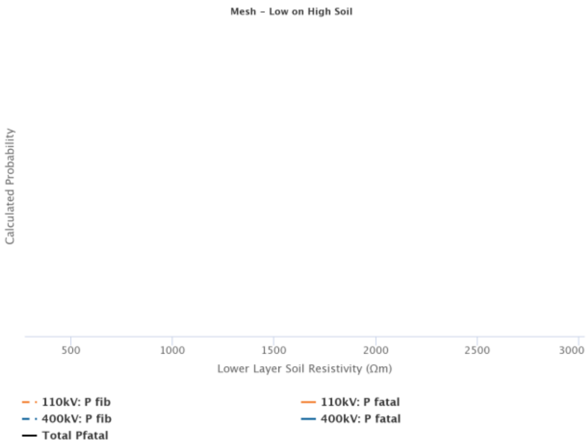


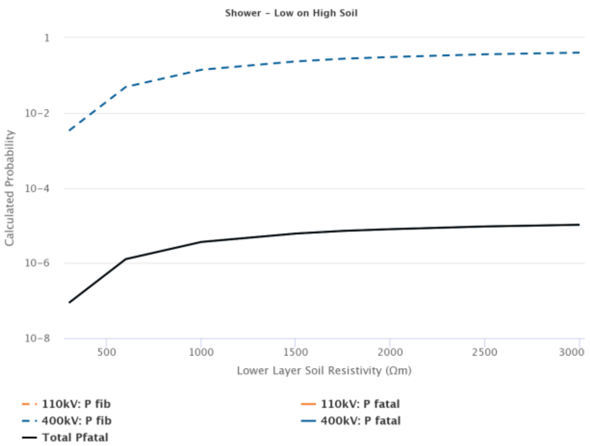




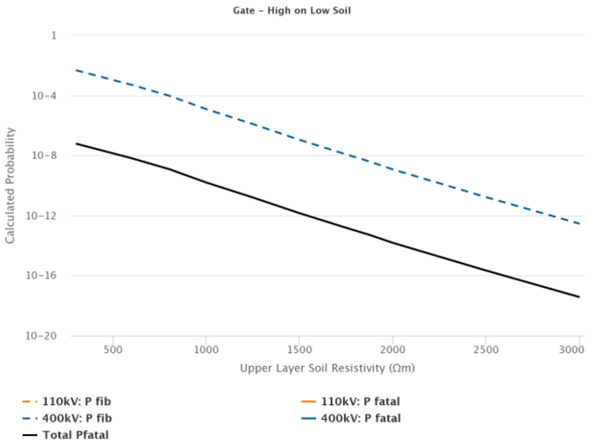
C.2.11.4 Varying Low-on-High Soil Models

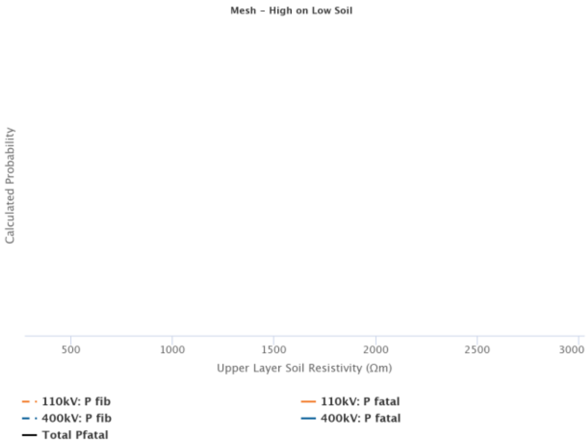


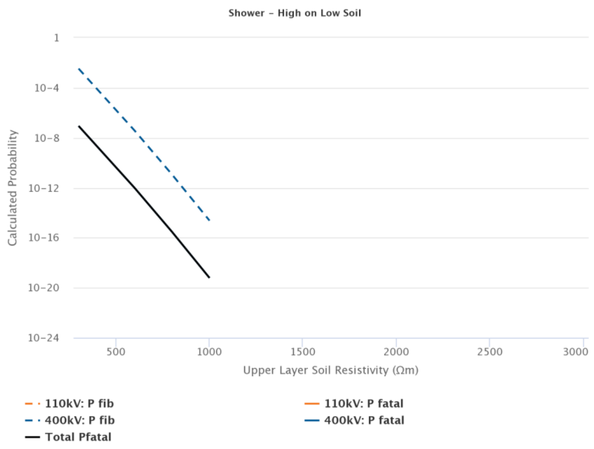




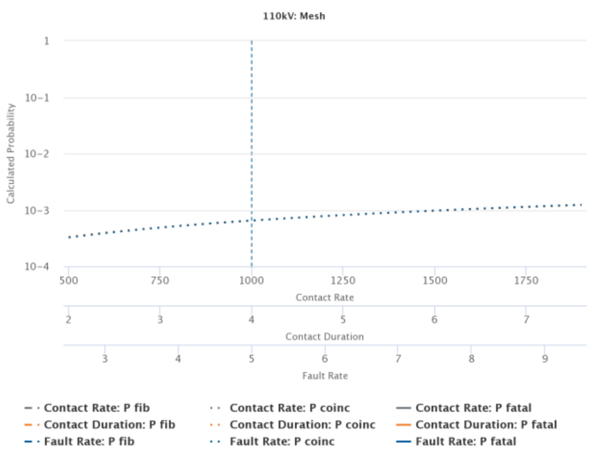
C.2.11.5 Varying High-on-Low Soil Models

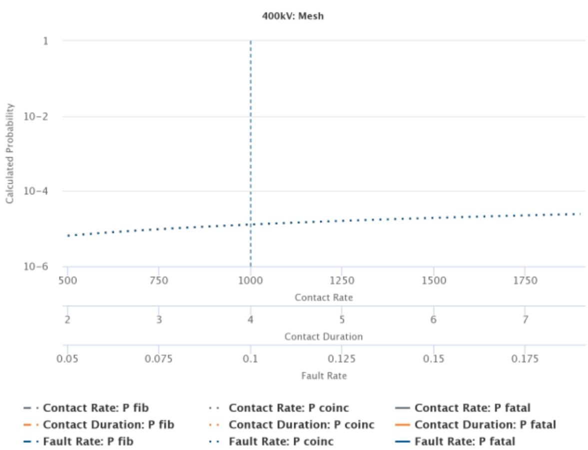




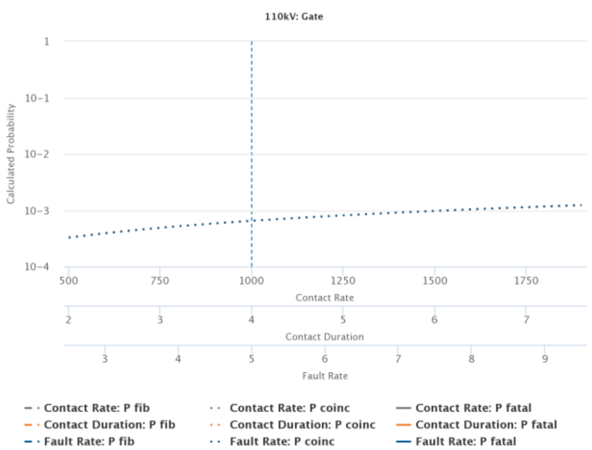


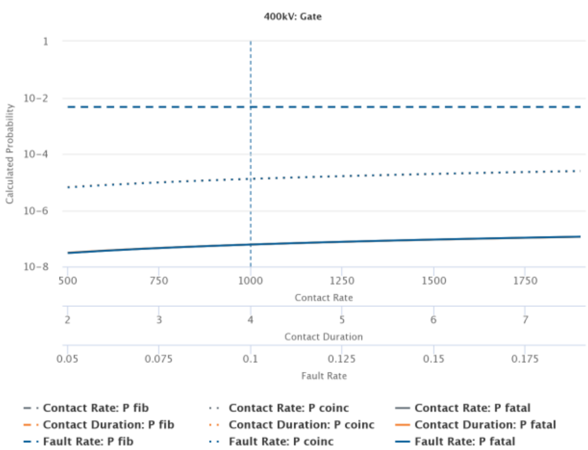
C.2.11.6 Varying Coincidence Factors Mesh Voltage Hazard



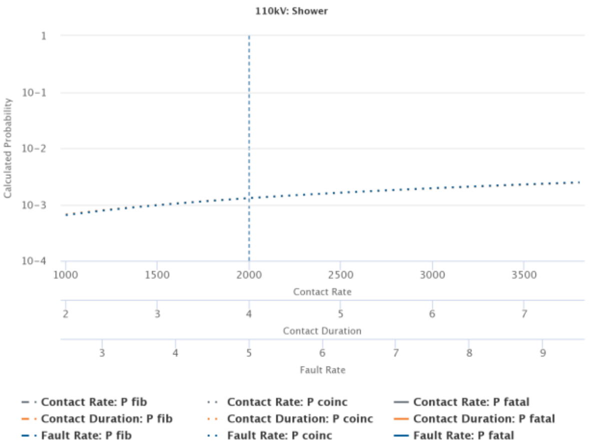


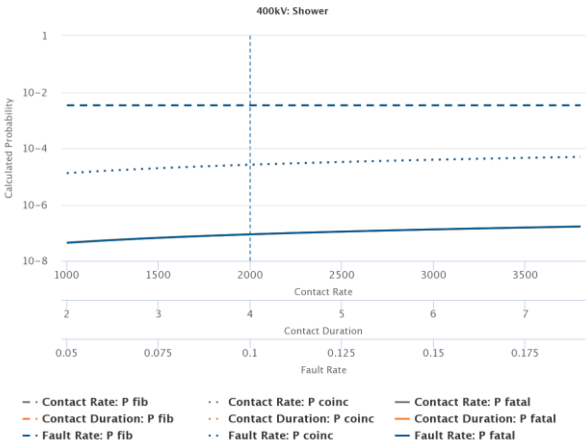
C.2.11.7 Varying Coincidence Factors Gate Touch Voltage Hazard





C.2.11.8 Varying Coincidence Factors Shower Touch Voltage Hazard





Appendix D – Distribution Case Study Details

This appendix describes additional examples of risk of fatality calculation focused on distribution network operation. The risk of fatality for all neutral point connections is evaluated to enable a comparison and sensitivity analysis of the resultant risks.

D.1 Distribution Case Study Network Topology and Parameters

The hazard created by an MV earth fault at a distribution transformer station (DTS) is selected to represent the process of risk probability calculation associated with the MV and LV distribution networks. As described in section 9.2, the DTS is placed at a distance '*l*' on a radial feeder supplied from a high/medium voltage (HV/MV) substation. The configuration of the network used in this case study is presented in Figure D.1.1 and its characteristic parameters are described in detail in this section.

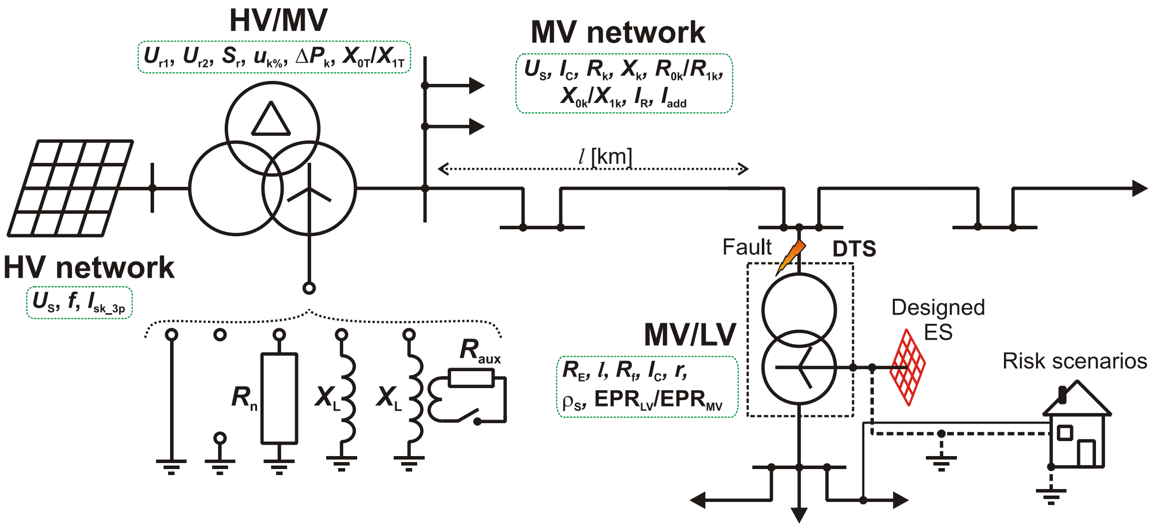


Figure D.1.1: Simplified scheme of distribution network for demonstration of individual risk probability calculation - case study

The network configuration and characteristic parameters are chosen to reflect the operating conditions seen in the majority of distribution networks. Several of the key aspects included in the model are discussed in the following:

Neutral point connection of HV/MV transformers: Five configurations are included in the analysis: solidly earthed, isolated, compensated (resonant earthed), compensated with auxiliary resistor and earthed through a resistor. The neutral point connection configuration has a significant impact on the level of earth fault current and clearing time, therefore will directly impact the risk of fibrillation for a person exposed to a touch voltage.

MV and LV earthing system (ES) interconnection: The MV and LV earthing systems may be interconnected or remain separated by a certain distance through the ground. A separated or segregated system will have a higher MV EPR, but the potential to which the LV neutral is lifted is usually lower. If the MV and LV earthing systems are interconnected the overall resistance is lower, and therefore the EPR is reduced, however, the voltage on the interconnected LV neutral is now the same as that on the MV earthing system. For the basic case study an interconnected MV/LV earthing system is used as shown in Figure D.1.2.

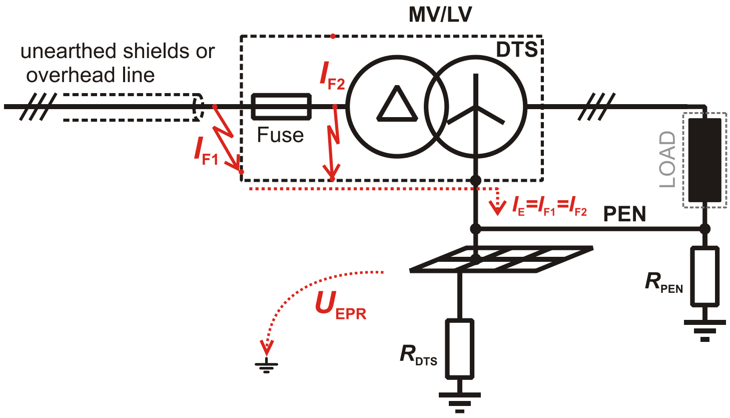


Figure D.1.2: Basic configuration of the earthing system of selected distribution transformer station

MV line type and earthing configuration: The incoming and outgoing lines from the DTS may be overhead lines or underground cables, and they may or may not have an earthing interconnection to the exposed conductive parts to the ES (e.g. shields or earth conductor interconnection and presence of accidental earthing conductors). The impact of these differences is represented by the fault current reduction factor '*r*', which is 1 for basic state of the case study (i.e. no shields and earth conductors connected to the ES - Figure D.1.2).

The following values of characteristic parameters of the network showed in Figure D.1.2 are used in the base case analysis:

a) HV network

U_s = 110 kV - nominal voltage of the network

f = 50 Hz - system frequency

I_{k_3p} = 15 kA - initial symmetrical short-circuit current given by HV network

b) Supply transformer HV/MV

U_{r1} = 110 kV, U_{r2} 22kV - rated voltage of the transformer on the HV and MV side respectively

S_r = 40 MVA - rated apparent power of the transformer

$u_{k\%}$ = 10 % - short-circuit voltage at rated current in percentage

ΔP_k = 0,09 MW - the total active power loss of the transformer in the windings at rated current

X_{0T}/X_{1T} = 1,5 - ratio of zero/positive sequence reactance of the transformer

c) MV network

U_s = 22 kV - nominal voltage of the network

Ic = 200 A - capacitive current of the network (non-solidly earthed network)

R_k = 0,224 Ω/km, X_k = 0,287 Ω/km - the line resistance and reactance per km

R_{0k}/R_{1k} = 1 and X_{0k}/X_{1k} = 1 - ratio of zero/positive sequence of the line resistance and reactance

I_R = 1000 A - rated current of nodal resistor

I_{aux} = 20 A - rated current of auxiliary resistor related to MV side

Feeder protection: Definite time over-current feeder protection is considered for the case study, its tripping time setting is showed in Figure 9.5.1 and Table D.4.1.

d) Distribution transformer station MV/LV

R_E (calculated base on ρ_s) - total earthing resistance of the earthing system affected by the earth fault

l = 20 km - distance of the ES from supply substation

R_f = 5 Ω - the earth fault resistance respecting all resistances in fault loop except resistance R_E, i.e. earth fault resistance, resistance of supply substation earthing system etc.

r = 1 - reduction factor (impact of LV earthing system is excluded, it is respected by variable EPR_{LV}/EPR_{MV}), ρ_s = 100 Ωm - soil resistivity

EPR_{LV}/EPR_{MV} = 1 - ratio of transferred potential EPR from MV to LV earthing system, value 1 is for case of interconnected MV/LV earthing system. For separated MV/LV earthing systems, this ratio depends on mutual impedance (distance) of MV and LV earthing systems (example where EPR_{LV}/EPR_{MV} = 0,25 is shown in Figure D.1.3). This parameter can also represent the voltage drop caused in LV earthing system.

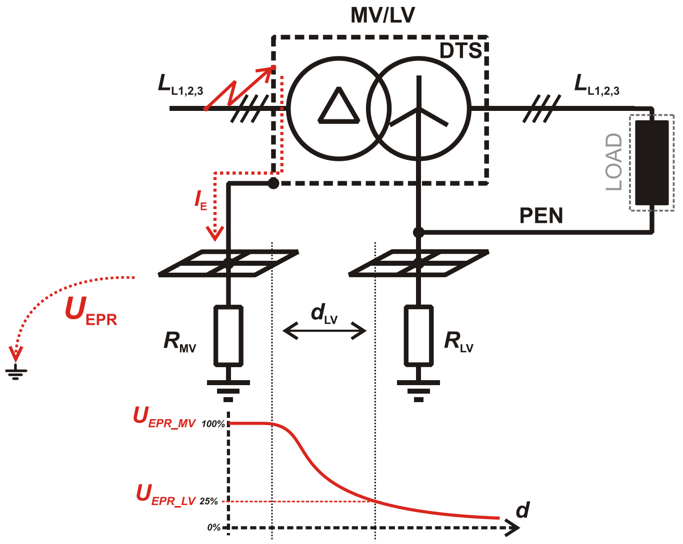


Figure D.1.3: Potential transfer from MV to LV earthing system

e) Evaluated earthing system

Design of evaluated earthing system of the DTS is shown in Figure D.1.4. Based on the analytical solution, the earthing resistance of such a DTS may be expressed by Equation D.1.

$$R_{DTS} = 0{,}04556 \cdot \rho_s. \qquad \text{Equation D.1}$$

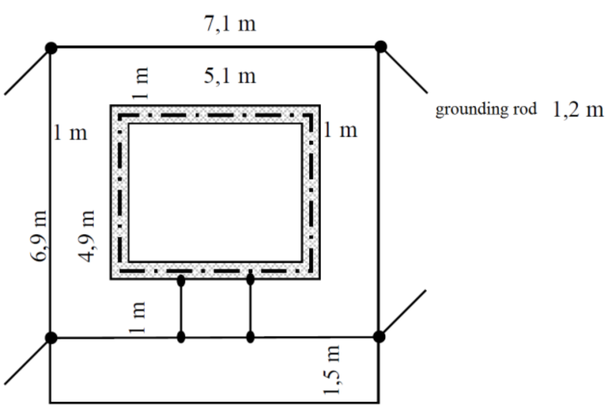


Figure D.1.4: Design of the earthing system of evaluated DTS

The earthing resistance of the LV earthing system is calculated as R_{PEN} = ρ_s/100 (R_{PEN} = 2 Ω for ρ_s < 200 Ωm). The total earthing resistance of the system, where the MV and LV earthing are interconnected can be calculated as $R_E = R_{DTS} // R_{PEN}$. Interconnected MV and LV earthing system is considered to be the basic case.

D.2 Hazard Scenarios Considered for Case Study

Once the potential on the MV or LV earthing systems has been determined, the next step is to identify locations where people could be exposed to potentially hazardous voltages. Six locations have been listed in Table D.2.1 as an example of where people could contact metalwork connected to the LV neutral conductor. Table D.2.1 also shows the key contact frequency and contact configuration parameters:

- the contact frequency p_n (presence of a scenario) presence per a year,
- the expected duration of contact p_d, insulation layer (e.g. footwear, gloves),
- prospective touch voltage related to EPR of given ES in percentage $U_{T/EPR}$,
- contact surface size, skin moisture condition,
- body impedance probability, and
- current path (LHBF - left hand both feet and BHBF - both hands both feet).

IEC 60479-1 has been used to define the body impedance values. At this stage only a 50% body impedance characteristic has been used, rather than the full probability distribution.

Table D.2.1: Considered hazard scenarios

Respected Risk Scenarios		Footwear	$U_{T/EPR}$ [%]	p_n contact/ year	p_d [s] Duration	Surface Size	Surface Condition	Body Impedance probability	Current Path
a)	Shower	No	30	1000	4	Large	Wet	50%	LHBF
b)	Tap (backyard)	No	50	100	4	Large	Wet	50%	LHBF
c)	Kitchen sink	No	20	3000	4	Large	Wet	50%	LHBF
d)	Washing machine	No	30	300	4	Large	Dry	50%	BHBF
e)	Tool use (backyard)	Yes	40	100	4	Large	Dry	50%	BHBF
f)	Tool use (cement mixer)	Yes	80	10	4	Large	Wet	50%	BHBF

D.3 Fault Statistics for Case Study

An important factor included in the risk probability calculation are the fault statistics (i.e. information about type, duration and frequency of individual earth faults in the network). In case these data are unknown, the statistics of similar distribution networks may be used. It is necessary to distinguish the relevant earth faults that can lead to an increase in EPR on the evaluated ES from those faults which do not give rise to an EPR. Therefore, the statistics that categorize earth faults occurring on overhead lines, cable lines and at DTSs individually has to be used. The fault statistics presented in Table D.3.1 are only an example based upon information prepared for the area operated by one distribution system operator (DSO). The table collects data in a way to enable the calculation of risk probability as described below. The data are structured into categories with regards to the:

- type of earth fault,
- fault location (line, DTS) and
- the component that cleared the earth fault (feeder protection or fuse) (fault I_{F1} and I_{F2} in Figure D.2.1).

To increase the accuracy of the results, it would be possible to analyse the statistics for individual sections of distribution network, eventually for sections supplied by one HV/MV transformer.

Note: It is assumed for the study that all faults are cleared by upstream line protection rather than the fuse on the transformer primary.

Table D.3.1: Estimated fault frequency for the MV distribution network

Voltage level	Neutral point connection	Type of earth fault	Total number of line faults (faults/yr/line type)		**Total number of DTS faults (faults/yr)**		Range of network (cable /overhead) (km)	**Number of DTS (pcs.)**
			Cable	*Overhead*	***Protec.***	*Fuse*		
MV	compensated	L-N	5	120	**200**	x	500/50000	**25000**
		Cross L-L-N	2	6	**10**	x		
MV	resistor earthed	L-N	10	10	**16**	x	1300/3000	**2000**
		Cross L-L-N	0	0	**0**	x		
MV	Isolated	L-N	3	20	**20**	x	20/5000	**2500**
		Cross L-L-N	0	4	**1**	x		
MV	solidly earthed	L-N	4	20	**44**	x	1000/10000	**5500**
		L-L-N	2	6	**5**	x		
		Cross L-L-N	0	0	**0**	x		

D.4 Detailed Results of the Individual Fatality Risk Calculation

In the context of the case study, where the DTS is supplied only by an overhead line without an earth conductor or an unshielded cable line, the EPR can be energized only during an earth fault (L-N, L-L-N, cross L-L-N) in the area of earthing system of the DTS. Therefore only the fault frequency at the DTS is considered for the individual risk probability calculation (Table D.3.1, blue colored).

Earth fault current magnitudes are calculated for various faults based on given neutral point connection and case study parameters according to practice (Section 6.1). The calculated current magnitudes for the various earth fault and clearing time values determined from the feeder protection are listed in Table D.4.1. The clearing time of the fuse is irrelevant for this case study because the frequency of faults cleared by fuse is zero (see Table D.3.1).

Note: Cross L-L-N fault type refers to a 'cross country' fault where the initial earth fault causes a second earth fault on another phase elsewhere on the system due to the displacement of the healthy phase voltages.

Table D.4.1: Table of earth fault currents magnitudes and clearing times

Neutral point connection	Type of fault	Fault current (A)	Clearing time (s)
			t_P
compensated	L-N	19,7	1200
	cross L-L-N	946	0,3
comp. + R_{aux} connected	L-N	39	1
	cross L-L-N	946	0,3
earthed through resistor	L-N	538	0,3
	cross L-L-N	946	0,3
Isolated	L-N	200	1
	cross L-L-N	946	0,3
solidly earthed	L-N	970	0,3
	L-L-N	676	0,3
	cross L-L-N	946	0,3

The particular results leading to the determination of the final value of individual risk probability P_{risk_tot} of all neutral point connections and considered risk scenarios are summarized in Table D.4.2. The considered risk scenarios are defined in Table D.2.1.

A detailed example of the calculation process is introduced below for the first row of the Table D.4.2 (L-N fault in compensated network and risk scenario ‘a’). Firstly, the potential rise of LV earthing system U_{EPR_LV} is calculated as follows:

$$U_{EPR\_LV} = R_E \cdot I_{F(L-N)} \cdot r \cdot (EPR_{LV} / EPR_{MV}) = 1{,}39 \cdot 19{,}7 \cdot 1 \cdot 1 = 27{,}3V \, , \qquad \text{Equation D.2}$$

where R_E is total earthing resistance of the system affected by the fault (Section 9.5.1), I_F is calculated fault current (Table D.4.1), r is reduction factor of the affected earthing system (Section 9.5.2), $EPR_{LV}/EPR\__{MV}$ is a level of transferred potential from MV to LV earthing system (Section 9.5.2).

The prospective touch voltage of the scenarios can be expressed as :

$$U_{vT} = U_{EPR\_LV} \cdot U_{T/EPR} = 27{,}3 \cdot 0{,}3 = 8{,}2V \, , \qquad \text{Equation D.3}$$

where $U_{T/EPR}$ is prospective touch voltage related to EPR of given ES (Table D.2.1).

Because the human body impedance is voltage dependent, generally an iterative routine is used to find the voltage across the human body as a part of the open circuit or prospective touch voltage U_{vT} for all scenarios with additional insulation layers. This means that an initial value of loaded touch voltage was taken as equal to the prospective touch voltage and was changed throughout each iterative step, to satisfy the Ohm´s law of series combination of human body impedance and impedance of an insulating layer.

The loaded touch voltage of hazard scenario ‘a’ is equal to the prospective touch voltage ($U_{load} = U_{vT}$) because no additional insulation layer is considered. Body current I_{HB} = 5,8 mA is calculated for 50 % body impedance, large size of surface, wet condition and current path left hand both feet in accordance with standard IEC 60479-1 (according to Table D.2.1). The next column of Table D.4.1 expresses the fault clearing time t_{fault} for the earth faults as presented in Table D.4.1. Column I_{HB} contains the resultant shock current through the human body for each prospective touch voltage, respective current path (Table D.2.1) and additional insulating layer. For this case study the insulating layer resistance was assumed to be 1000 Ω.

Table D.4.2: Detail results of the individual fatality probability calculation

Earth fault		U_{EPR_LV}	Risk scen.	U_{vT}	U_{load}	t_{fault}	I_{HB}	P_{Coinc}	P_{Fib}	P_{Risk}	P_{Risk_tot}
		[V]		[V]	[V]	[s]	[mA]	[-]	[-]	[-]	
Compensated	L-N	27,33	a)	8,20	8,20	1200	5,80	3,05E-04	4,17E-17	1,27E-20	4,24E-08
			b)	13,66	13,66		9,66	3,05E-05	1,13E-11	3,45E-16	
			c)	5,47	5,47		3,87	9,16E-04	2,87E-22	2,63E-25	
			d)	8,20	8,20		6,31	9,16E-05	2,41E-15	2,21E-19	
			e)	10,93	7,58		5,83	3,05E-05	4,17E-17	1,27E-21	
			f)	21,86	13,16		15,13	3,05E-06	1,12E-07	3,42E-13	
	Cross L-L-N	1314,68	a)	394,40	394,40	0,3	634,16	5,45E-08	3,61E-01	1,97E-08	
			b)	657,34	657,34		1296,07	5,45E-09	9,79E-01	5,34E-09	
			c)	262,94	262,94		350,62	1,64E-07	9,62E-03	1,57E-09	
			d)	394,40	394,40		1030,52	1,64E-08	8,97E-01	1,47E-08	
			e)	525,87	239,01		498,87	5,45E-09	1,22E-01	6,67E-10	
			f)	1051,74	414,07		1109,07	5,45E-10	9,35E-01	5,10E-10	
Aux. Resistor	L-N	53,74	a)	16,12	16,12	1	11,40	1,27E-06	3,32E-12	4,21E-18	1,23E-13
			b)	26,87	26,87		19,12	1,27E-07	2,85E-08	3,62E-15	
			c)	10,75	10,75		7,60	3,81E-06	6,24E-16	2,38E-21	
			d)	16,12	16,12		12,40	3,81E-07	1,56E-11	5,94E-18	
			e)	21,50	14,90		11,46	1,27E-07	3,32E-12	4,21E-19	
			f)	42,99	25,86		29,80	1,27E-08	9,39E-06	1,19E-13	
Earthed through	L-N	747,88	a)	224,36	224,36	0,3	281,49	1,09E-06	1,06E-03	1,16E-09	5,70E-08
			b)	373,94	373,94		585,39	1,09E-07	2,66E-01	2,90E-08	
			c)	149,58	149,58		164,13	3,27E-06	5,74E-07	1,88E-12	
			d)	224,36	224,36		457,42	3,27E-07	7,35E-02	2,40E-08	

			e)	299,15	148,08		262,71	1,09E-07	4,73E-04	5,16E-11	
			f)	598,31	265,74		578,34	1,09E-08	2,53E-01	2,76E-09	
	Cross L-L-N	1314,68	a)	394,40	394,40	0,3	634,16	0,00E+00	3,61E-01	0,00E+00	
			b)	657,34	657,34		1296,07	0,00E+00	9,79E-01	0,00E+00	
			c)	262,94	262,94		350,62	0,00E+00	9,62E-03	0,00E+00	
			d)	394,40	394,40		1030,52	0,00E+00	8,97E-01	0,00E+00	
			e)	525,87	239,01		498,87	0,00E+00	1,22E-01	0,00E+00	
			f)	1051,74	414,07		1109,07	0,00E+00	9,35E-01	0,00E+00	
Isolated	L-N	277,97	a)	83,39	83,39	1	72,46	1,27E-06	4,09E-02	5,19E-08	3,04E-07
			b)	138,99	138,99		146,20	1,27E-07	6,06E-01	7,69E-08	
			c)	55,59	55,59		43,64	3,81E-06	7,16E-04	2,72E-09	
			d)	83,39	83,39		110,45	3,81E-07	2,95E-01	1,12E-07	
			e)	111,19	66,53		77,68	1,27E-07	6,06E-02	7,68E-09	
			f)	222,38	116,89		183,42	1,27E-08	8,20E-01	1,04E-08	
	Cross L-L-N	1314,68	a)	394,40	394,40	0,3	634,16	5,45E-08	3,61E-01	1,97E-08	
			b)	657,34	657,34		1296,07	5,45E-09	9,79E-01	5,34E-09	
			c)	262,94	262,94		350,62	1,64E-07	9,62E-03	1,57E-09	
			d)	394,40	394,40		1030,52	1,64E-08	8,97E-01	1,47E-08	
			e)	525,87	239,01		498,87	5,45E-09	1,22E-01	6,67E-10	
			f)	1051,74	414,07		1109,07	5,45E-10	9,35E-01	5,10E-10	
Solidly Earthed	L-N	1347,83	a)	404,35	404,35	0,3	658,43	1,09E-06	4,08E-01	4,45E-07	9,47E-07
			b)	673,92	673,92		1333,12	1,09E-07	9,83E-01	1,07E-07	
			c)	269,57	269,57		363,16	3,27E-06	1,32E-02	4,33E-08	
			d)	404,35	404,35		1069,95	3,27E-07	9,18E-01	3,00E-07	
			e)	539,13	243,98		513,28	1,09E-07	1,44E-01	1,57E-08	
			f)	1078,27	422,01		1141,39	1,09E-08	9,46E-01	1,03E-08	
	Cross L-L-N	1314,68	a)	394,40	394,40	0,3	634,16	0,00E+00	3,61E-01	0,00E+00	
			b)	657,34	657,34		1296,07	0,00E+00	9,79E-01	0,00E+00	
			c)	262,94	262,94		350,62	0,00E+00	9,62E-03	0,00E+00	
			d)	394,40	394,40		1030,52	0,00E+00	8,97E-01	0,00E+00	
			e)	525,87	239,01		498,87	0,00E+00	1,22E-01	0,00E+00	
			f)	1051,74	414,07		1109,07	0,00E+00	9,35E-01	0,00E+00	
	L-L-N	939,21	a)	281,76	281,76	0,3	386,73	1,24E-07	2,20E-02	2,73E-09	
			b)	469,61	469,61		825,02	1,24E-08	7,00E-01	8,68E-09	
			c)	187,84	187,84		222,45	3,72E-07	5,72E-05	2,13E-11	
			d)	281,76	281,76		628,55	3,72E-08	3,49E-01	1,30E-08	
			e)	375,69	179,53		341,15	1,24E-08	7,60E-03	9,42E-11	
			f)	751,37	319,00		751,85	1,24E-09	5,83E-01	7,23E-10	

Note: Row 'Aux Resistor' presents partial steady state of an earth fault in a compensated network with auxiliary resistor at the moment that auxiliary resistor is connected (usually for 1s).

The coincidence probability for risk scenario 'a' is calculated as :

$$P_{\text{Coinc\_RS}} = \frac{f_n \cdot p_n \cdot (t_{\text{fault}} + p_d)}{365 \cdot 24 \cdot 60 \cdot 60} = \frac{(200/25000) \cdot 1000 \cdot (1200+4)}{365 \cdot 24 \cdot 60 \cdot 60} = 3{,}05 \cdot 10^{-4}, \qquad \text{Equation D.4}$$

where

f_n is number of earth faults per year, the fault frequency statistic is summarized for the case study in Table D.3.1

p_n is number of human presences per year and p_d is the typical human presence duration (seconds), both of these values are estimated for each risk scenario in Table D.4.2.

The probability of fibrillation P_{Fib_RS} is determined by Matlab routine based on method described in reference [1]. Then individual risk probability is calculated for each risk scenario as follows :

$$P_{\text{Risk\_RS}} = P_{\text{Fib\_RS}} \cdot P_{\text{Coinc\_RS}} = 3{,}05 \cdot 10^{-4} \cdot 4{,}17 \cdot 10^{-17} = 1{,}27 \cdot 10^{-20}$$ Equation D.5

and the final individual risk probability, respecting all risk scenarios in resonant earthed distribution network without auxiliary resistor, is given as sum of $P_{\text{Risk\_RS}}$

$$P_{\text{Risk}} = \sum_{n} P_{\text{Risk\_RS (n)}} = \underline{\underline{4{,}24 \cdot 10^{-8}}},$$ Equation D.6

where *n* is number of all respected risk scenarios and all faults in resonant earthed network (L-N, Cross L-L-N) .

Individual fatality risk probability results are summarised in Table D.4.3 for each of the risk scenarios and five neutral point connection configurations under the case study conditions. As Table D.4.3 shows, the intolerable risk boundary 10^{-6} isn't exceeded, therefore consideration of additional measures or redesign of ES isn't necessary. Only in the case of a solidly earthed system does the individual risk probability go very close to the intermediate risk boundary 10^{-6} There is a high possibility that small change of any input parameter of CS can cause an increase of individual risk probability what can move risk to intermediate risk region. Therefore sensitivity analyses of input parameters should be carried out.

Table D.4.3: Table of results of the individual risk probability for all respected neutral point connections

Scenario		Solidly Earthed	Isolated	Earth Resist	Compensated	Comp+R_{aux}
L-N	a)	4,45E-07	5,19E-08	1,16E-09	1,27E-20	4,22E-18
	b)	1,07E-07	7,69E-08	2,90E-08	3,45E-16	3,96E-15
	c)	4,33E-08	2,72E-09	1,88E-12	2,63E-25	2,38E-21
	d)	3,00E-07	1,12E-07	2,40E-08	2,21E-19	6,16E-18
	e)	1,57E-08	7,68E-09	5,16E-11	1,27E-21	4,22E-19
	f)	1,03E-08	1,04E-08	2,76E-09	3,42E-13	4,61E-13
Cross L-L-N	a)	0,00E+00	1,97E-08	0,00E+00	1,97E-08	1,97E-08
	b)	0,00E+00	5,34E-09	0,00E+00	5,34E-09	5,34E-09
	c)	0,00E+00	1,57E-09	0,00E+00	1,57E-09	1,57E-09
	d)	0,00E+00	1,47E-08	0,00E+00	1,47E-08	1,47E-08
	e)	0,00E+00	6,67E-10	0,00E+00	6,67E-10	6,67E-10
	f)	0,00E+00	5,10E-10	0,00E+00	5,10E-10	5,10E-10
L-L-N	a)	2,73E-09	0	0	0	0
	b)	8,68E-09	0	0	0	0
	c)	2,13E-11	0	0	0	0
	d)	1,30E-08	0	0	0	0
	e)	9,42E-11	0	0	0	0
	f)	7,23E-10	0	0	0	0
P_{risk}		**9,47E-07**	**3,04E-07**	**5,70E-08**	**4,24E-08**	**4,24E-08**

Note: 'Comp.+R_{aux}' is a resonant earthed network equipped with an auxiliary resistor which may be switched in parallel to enable the earth fault current to be increased. This case is given by sum of risk probability of compensated network and state when auxiliary resistor is connected (Aux. resistor in Table D.4.2).

D.5 Sensitivity Analyses of Case Study Parameters

The process of calculating shock risk highlights the significance of a number of variable parameters that have previously been ignored in safety assessments. Therefore sensitivity analysis representing impact of the errors of relevant input variables on resulting value of the individual fatality probability is performed. Sensitivity of calculated individual fatality probability to differences in the input variables is carried out for each type of neutral point connection individually and it is depicted in the figures below. The following variables were included in the sensitivity analyses:

Variation of relative values defined in CS scenarios and fault statistics :

f_n - relative value of fault frequency related to values in Table D.4.2

p_n - relative number of human presences per year related to values in Table D.4.1

p_d - relative human presence duration related to values in Table D.4.1

$U_{T/EPR}$ - relative prospective touch voltage related to values in Table D.4.1

R_E - relative value of earthing system resistance related to basic value of the case study for ρ_s = 100 Ωm

Each variable varies from 50 % up to 150 % and the resulting individual fatality probability is presented in percentage related to basic value of case study (Table D.4.3). Note that for this particular case study data set the response of variables f_n and p_n is the same for all cases (resulting from Equation D.4).

Variation of value of case study characteristic parameters.

t_{clear} - clearing time, vary from 33 % up to 500 % of basic values listed in Table D.4.1

d_{feeder} - fault distance, vary from 0,5 km up to 50 km

r - reduction factor, vary from 0,1 to 1

ρ_s - soil resistivity, vary from 100 Ωm to 5000 Ωm

R_f - fault resistance, vary from 0 Ω to 20 Ω

EPR_{LV}/EPR_{MV} - ratio of transferred potential EPR from MV to LV earthing system, vary from 50 % to 100 %

D.5.1 Analysis of isolated distribution network

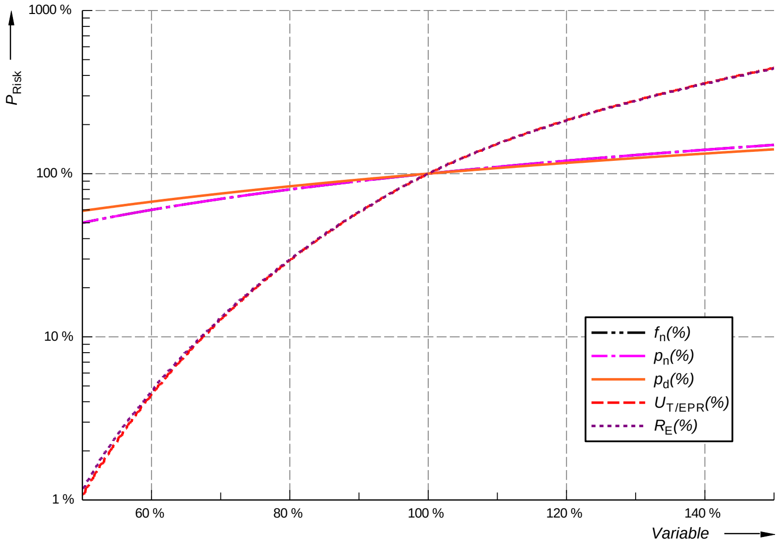


Figure D.5.1: Relative sensitivity analyse of CS scenario variables for isolated network

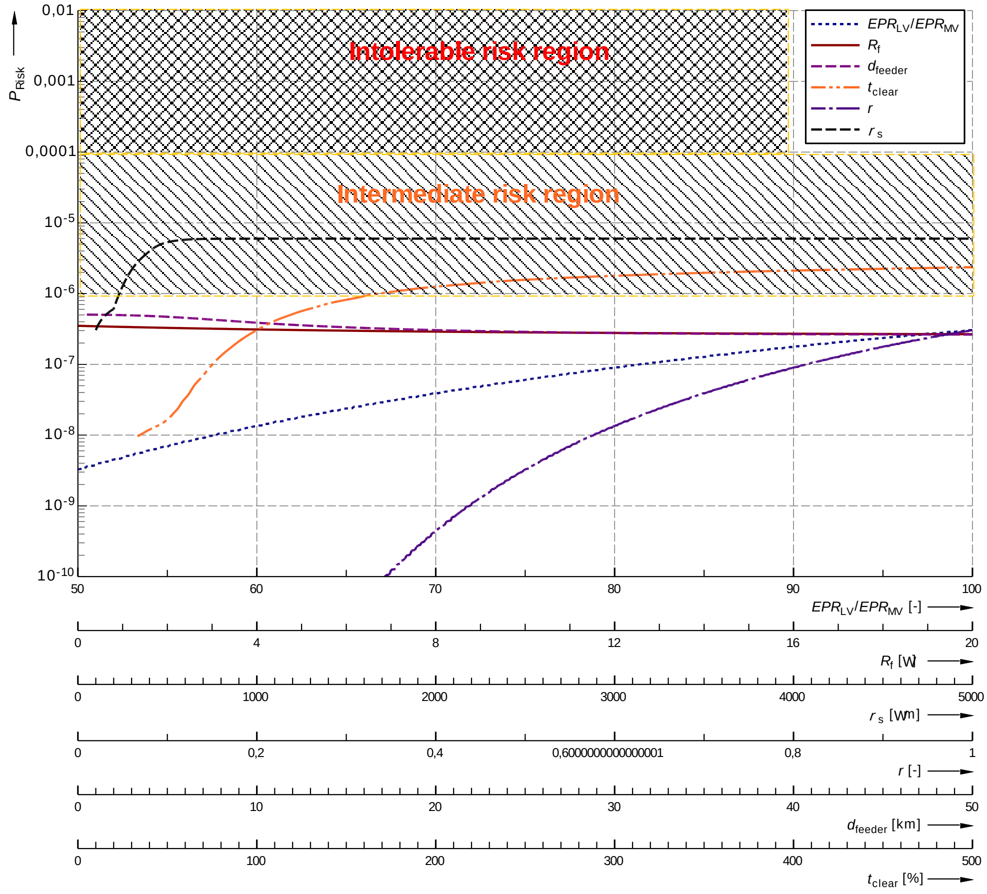


Figure D.5.2: Sensitivity analyse of the case study parameters for isolated network

Description of the P_{risk} sensitivity to variables:

Soil resistivity - The significant gradient of the risk probability is in the range of soil resistivity 100 - 600 Ωm. In case that soil resistivity exceeds 600 Ωm, the risk probability converges on total coincidence probability $5{,}97 \cdot 10^{-6}$ (the probability of fibrillation of respected scenarios nears to 100 % value for soil resistivity over 600 Ωm). The first bump (100 - 200 Ωm) is caused by simplified approach of total earthing resistance calculation where the earthing resistance of LV earthing system is calculated as $R_{PEN} = \rho_s/100$ for $\rho_s > 200$ Ωm and $R_{PEN} = 2$ Ω for $\rho_s < 200$.

Clearing time - The pattern of clearing time curve results from calculated fault current levels and respected tripping times of the scenario. In this case, the risk probability converges to the coincidence probability of L-L-N fault which is calculated for maximal value of clearing time (500 % in case presented in Figure C4) - it means that probability of fibrillation caused by Cross L-L-N nears to 100 % in case that real clearing time will be double or higher than respected (Table D.4.1).

Fault resistance and fault distance - The impact of this variables to P_{risk} is insignificant. The length of the line to fault is given by network topology and increasing of fault resistance reduces P_{risk}.

NOTE: Gradient of these curves is not so high as in case of other neutral point connections, because earth fault current calculation in isolated network doesn't respect fault resistance and fault distance The earth fault is calculated as 10 % of network capacitive current in this case.

Reduction factor - The gradient of the reduction factor is substantial in case, that value lower than 1is used for case study. It is necessary to respect influence on P_{risk} caused by increasing of this value during the life-time of the earthing system.

Potential transfer EPR_{LV}/EPR_{MV} - The impact of the ratio of potential transfer from MV to LV earthing system to risk probability is the same as in case of reduction factor.

Summary:

The highest gradient of P_{risk} can be seen in case of change of soil resistivity and clearing time. Deviation of both this variables can significantly affect the real risk probability as it is shown in Figure D.5.2. The risk probability enters to intermediate risk region when soil resistivity reaches value 230 Ωm and clearing time 170 % value of preset tripping time (e.g. due to change of protection settings).

D.5.2 Resonant earthed distribution network with auxiliary resistor

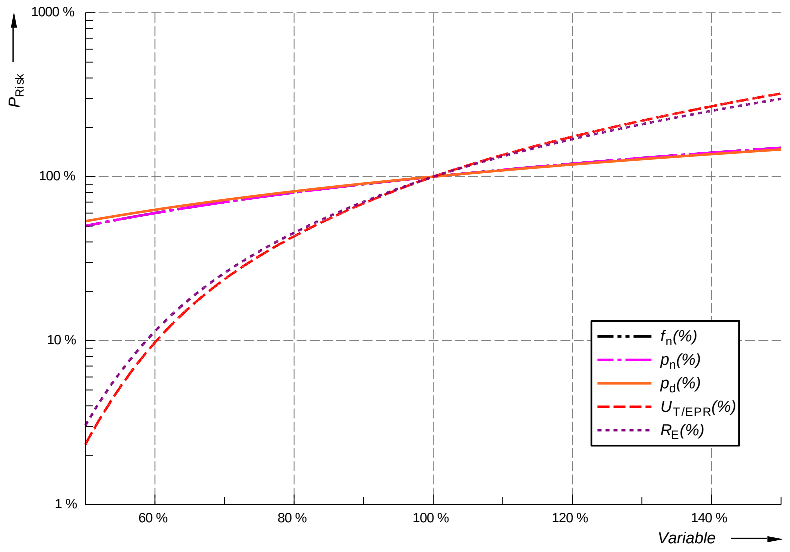


Figure D.5.3: Relative sensitivity analyse of CS scenario variables for resonant earthed network with auxiliary resistor

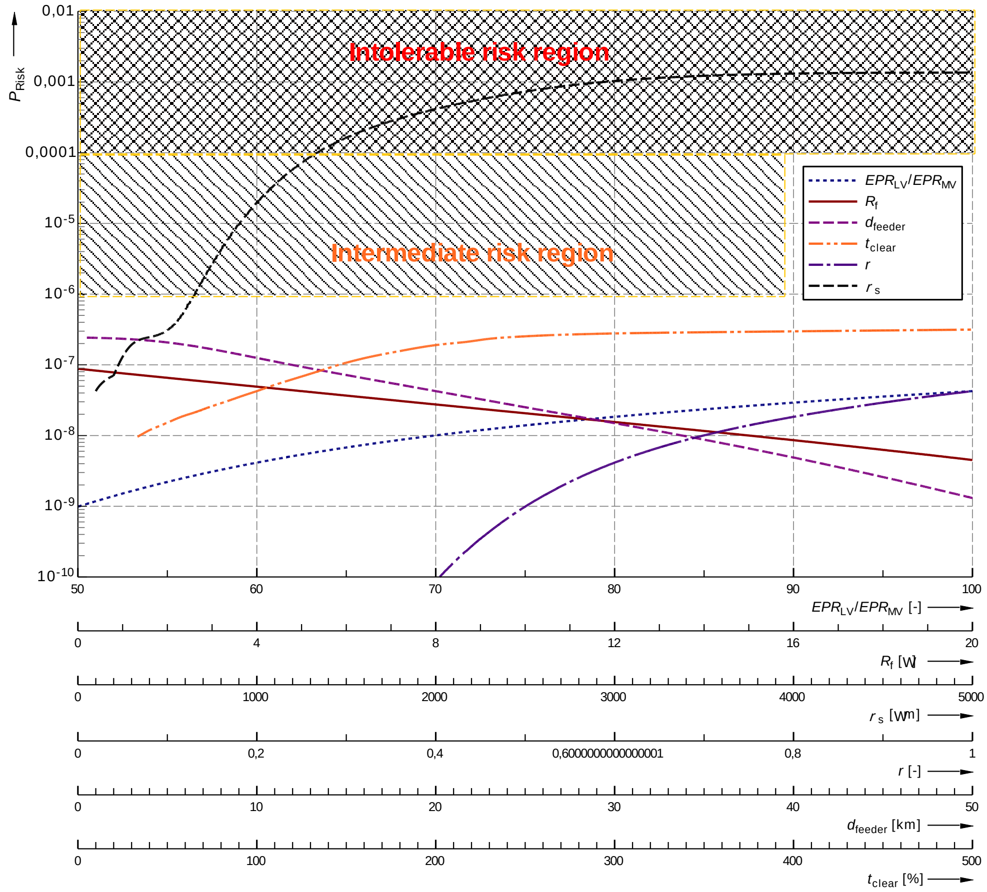


Figure D.5.4: Sensitivity analyse of the case study parameters for resonant earthed network with auxiliary resistor

Description of the P_{risk} sensitivity to variables:

Soil resistivity - The significant gradient of the risk probability is in the range of soil resistivity 100 - 1500 Ωm. The risk probability converges on total coincidence probability of the case study 1,38·10^{-3} in case that soil resistivity exceeds 3 kΩm (the probability of fibrillation is close to 100 %). The first bump of this curve (100 - 200 Ωm) is caused by simplified approach of total earthing resistance calculation where the earthing resistance of LV earthing system is calculated as $R_{PEN} = \rho_s/100$ for $\rho_s > 200$ Ωm and $R_{PEN} = 2$ Ω for $\rho_s < 200$ Ωm. The second bump (200 - 400 Ωm) respects saturation of risk probability related to Cross L-L-N faults (probability of fibrillation caused by L-L-N nears to 100 %) - the risk probability converges to coincidence probability of Cross L-L-N fault 2,46·10^{-7}.

Clearing time - The risk probability converges to the coincidence probability of Cross L-L-N fault 3,15·10^{-7} calculated for maximal considered value of clearing time (500 % in case presented in Figure D.5.4) - it means that probability of fibrillation caused by Cross L-L-N nears to 100 %, in case that real clearing time will be > 2,5 times of respected value (Table D.4.1).

Fault resistance and fault distance - The impact of this variables to P_{risk} is insignificant, because the length of the line to fault is given by network topology and increasing of fault resistance reduces P_{risk}.

Reduction factor - The gradient of the reduction factor is substantial especially in case, when value lower than 1is used for case study. It is necessary to respect influence on P_{risk} caused by increasing of this value during the life-time period of the earthing system.

Potential transfer EPR_{LV}/EPR_{MV} - The impact of the ratio of potential transfer from MV to LV earthing system to risk probability is the same as in case of reduction factor.

Summary:

The highest gradient of P_{risk} has curve of the soil resistivity and partly clearing time. Especially deviation of soil resistivity can significantly affect the real risk probability as it is shown in Figure D.5.4. The risk probability enters to intermediate risk region when soil resistivity reaches value 650 Ωm and when value 1300 Ωm is reached, the risk probability goes to intolerable risk region.

D.5.3 Resistor earthed distribution network

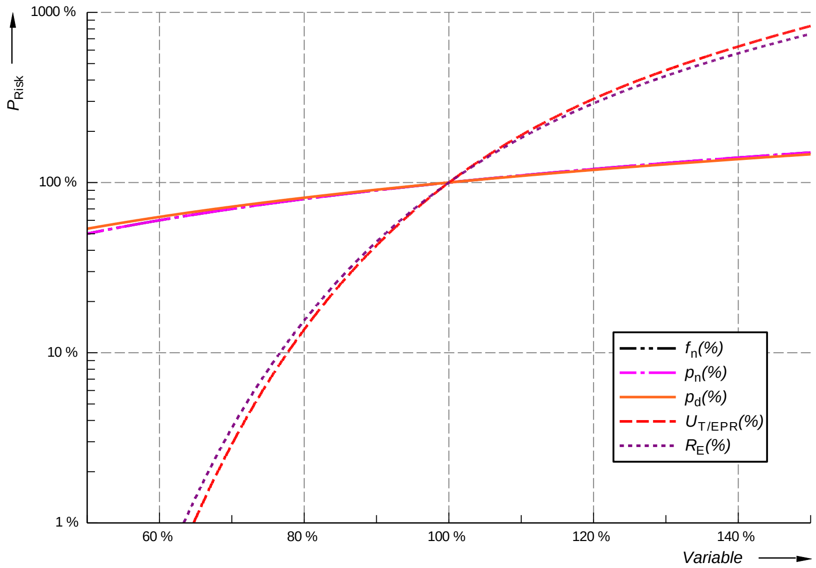


Figure D.5.5: Relative sensitivity analyse of CS scenario variables for resistor earthed network

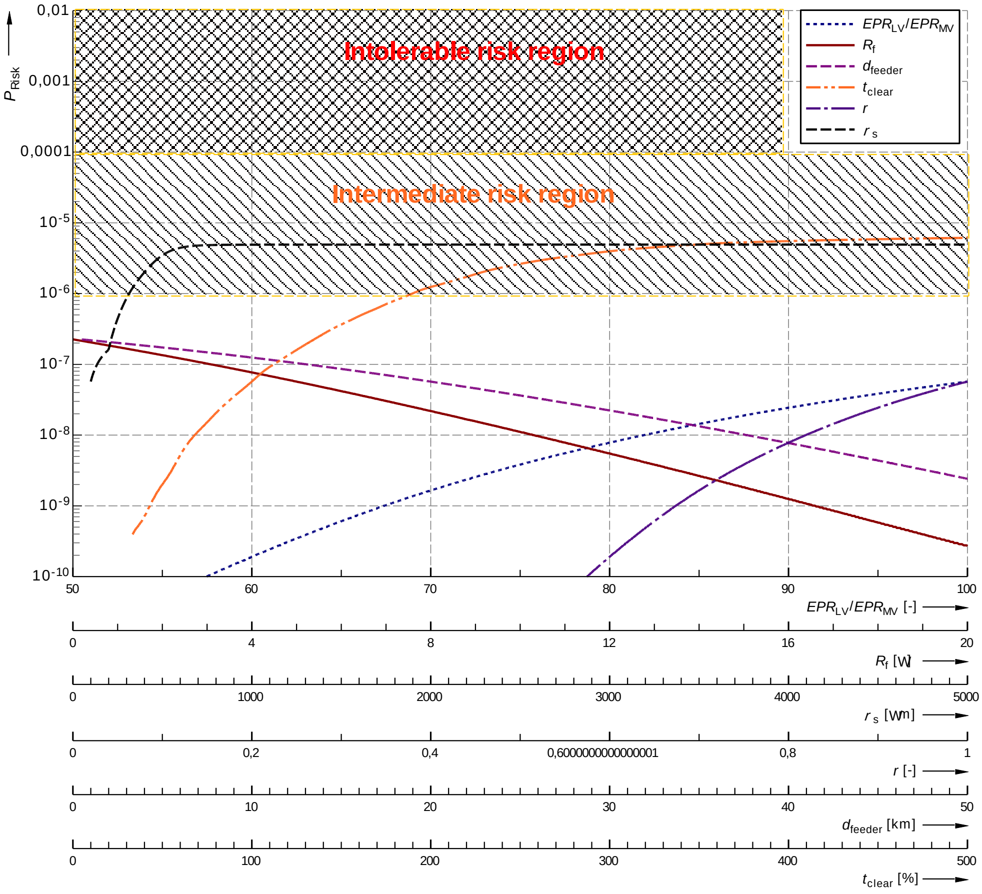


Figure D.5.6: Sensitivity analyse of the case study parameters for resistor earthed network

Description of the P_{risk} sensitivity to variables:

Soil resistivity - The significant gradient of the risk probability is in the range of soil resistivity 100 - 600 Ωm. The risk probability converges on total coincidence probability 4,92·10^{-6} in case that soil resistivity exceeds 600 Ωm (the probability of fibrillation is nearing to 100 %). The first bump of this curve (100 - 200 Ωm) is caused by simplified approach of total earthing resistance calculation where the earthing resistance of LV earthing system is calculated as R_{PEN} = ρ_S/100 for ρ_S > 200 Ωm and R_{PEN} = 2 Ω for ρ_S < 200 Ωm.

Clearing time - The risk probability converges to the coincidence probability of L-N fault 6,29·10^{-6} which is calculated with respect of maximal value of clearing time (500 % in case presented in Figure D.5.6) - it means that probability of fibrillation caused by L-N fault nears to 100 %, in case that real clearing time will be > 3 times of respected value (Table D.4.1).

Fault resistance and fault distance - The impact of this variables to P_{risk} is insignificant, because the length of the line to fault is given by network topology and increasing of fault resistance reduces P_{risk}. The gradient of these curves isn't also so steep as in case of soil resistivity or clearing time.

Reduction factor - The gradient of the reduction factor is substantial especially in case, that value lower than 1is used for case study. There is necessary respect influence on P_{risk} caused by increasing of this value during the life-time of the earthing system.

Potential transfer EPR$_{LV}$/EPR$_{MV}$ - The impact of the ratio of potential transfer from MV to LV earthing system to risk probability is the same as in case of reduction factor.

Summary:

The highest gradient of P_{risk} can be seen in case of change of soil resistivity and clearing time. Deviation of both this variables can significantly affect the real risk probability as it is shown in Figure D.5.6. The risk probability enters to intermediate risk region when soil resistivity reaches value 315 Ωm and clearing time 190 % value of preset tripping time (e.g. due to change of protection settings).

D.5.4 Solidly earthed distribution network

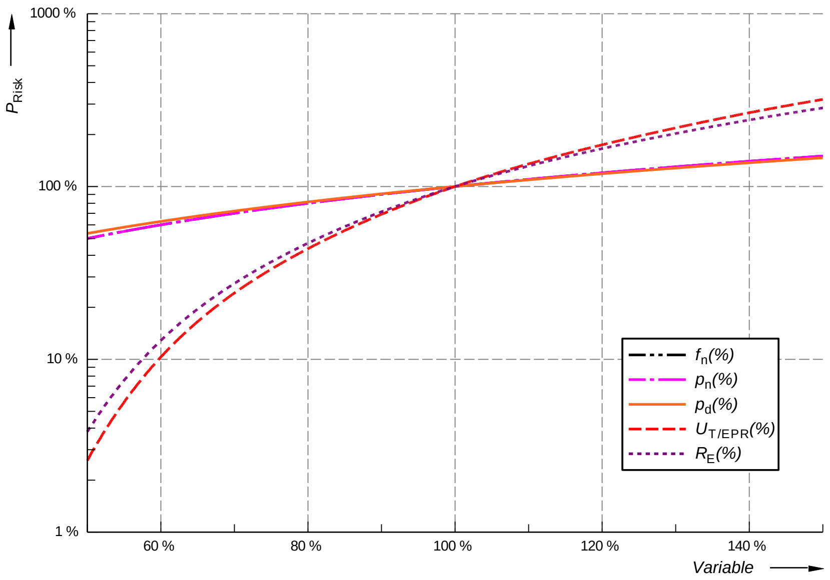


Figure D.5.7: Relative sensitivity analyse of CS scenario variables for solidly earthed network

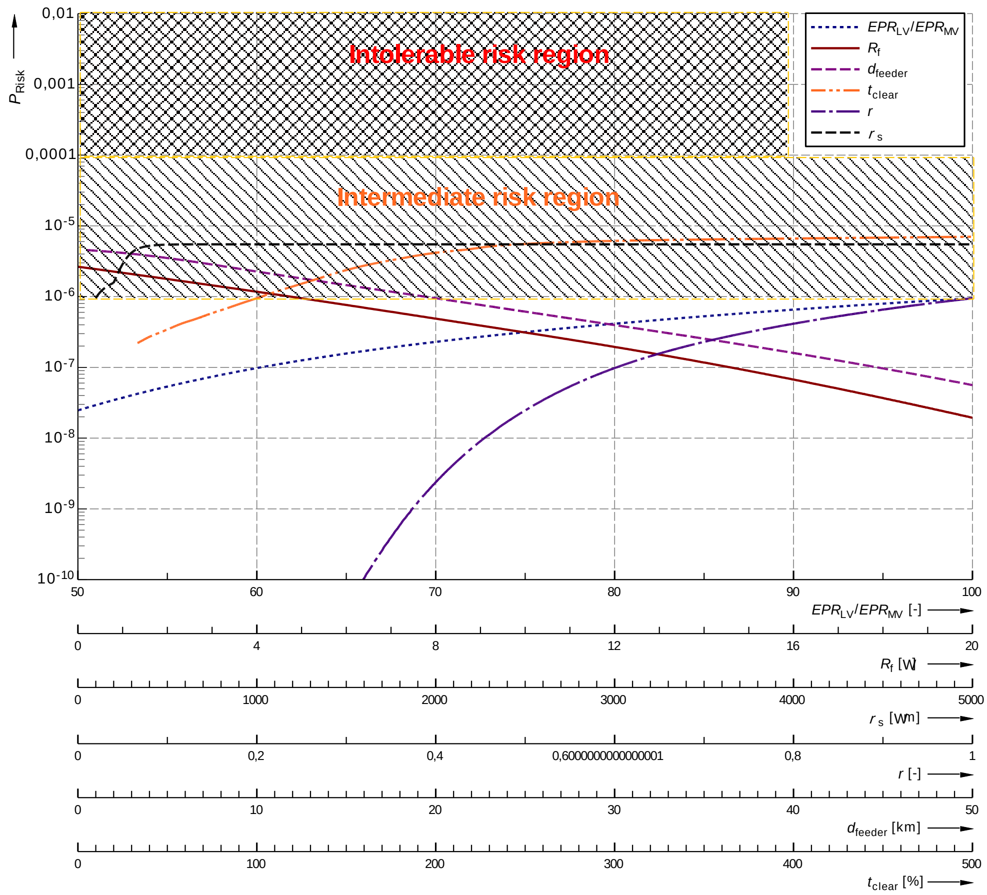


Figure D.5.8: Relative sensitivity analyse of variables defined in CS scenarios and fault statistics for solidly earthed network

Description of the P_{risk} sensitivity to variables:

Soil resistivity - The significant gradient of the risk probability is in the range of soil resistivity 100 - 350 Ωm. The risk probability converges on total coincidence probability $5,48 \cdot 10^{-6}$ in case that soil resistivity exceeds 350 Ωm (the probability of fibrillation is nearing to 100 %). The first bump of this curve (100 - 200 Ωm) is caused by simplified approach of total earthing resistance calculation where the earthing resistance of LV earthing system is calculated as $R_{PEN} = \rho_s/100$ for $\rho_s > 200$ Ωm and $R_{PEN} = 2$ Ω for $\rho_s < 200$ Ωm.

Clearing time - The risk probability converges to the total coincidence probability of L-N and L-L-N faults $7{,}01 \cdot 10^{-6}$ which is calculated with respect of maximal value of clearing time (500 % in case presented in Figure D.5.8) - it means that probability of fibrillation caused by L-N and L-L-N faults goes near to 100 %, in case that real clearing time will be > 2 times of respected value (Table D.4.1).

Fault resistance and fault distance - The impact of this variables to P_{risk} is insignificant, because the length of the line to fault is given by network topology and increasing of fault resistance reduces P_{risk}. The gradient of these curves isn't also so steep as in case of soil resistivity or clearing time.

Reduction factor - The gradient of the reduction factor is substantial especially in case, that value lower than 1is used for case study. There is necessary respect influence on P_{risk} caused by increasing of this value during the life-time of the earthing system.

Potential transfer EPR_{LV}/EPR_{MV} - The impact of the ratio of potential transfer from MV to LV earthing system to risk probability is the same as in case of reduction factor.

Summary:

The highest gradient of P_{risk} can be seen in case of change of soil resistivity and clearing time. Deviation of both this variables can significantly affect the real risk probability as it is shown in Figure D.5.9. The risk probability enters to intermediate risk region when soil resistivity reaches value 100 Ωm and clearing time 100 % value of preset tripping time (e.g. due to change of protection settings).

Appendix E – Derivation of the simplified coincidence probability formula

As described in Sections 4.4, 6.5 & 6.6, the risk based approach includes consideration of the probability of a coincidence of the presence of a person and an earth potential rise as well as the probabilistic nature of body impedances and fibrillation susceptibility. Also, the effect of a coincidence reduction factor (CRF) may be taken into account (see Section 6.6.3). If the stochastic distribution of the influencing parameters are known, the risk can be determined.

The risk of a fatality as given in terms of increased probability of fatality for an individual per year may be calculated by Equation 6.6.2 as a product of these 3 factors.

Following is a derivation of the simplified coincidence probability.

The general simplified stochastic derivation of the coincidence of the two possible overlapping, independent and rare events with:

- Event 1 e.g. an earth fault causing EPR
- Event 2 e.g. a contact situation of a person

over a certain time span of e.g. one year, is based on:

- Frequency of occurrence of each event (f_1, f_2), e.g. per year,

and on:

- Duration of each of those events (T_1, T_2).

There are two possible, mutually exclusive, sequences leading to such a coincidence:

- Sequence A) While event 1 is already on going, event 2 sets in randomly
- Sequence B) While event 2 is already on going, event 1 sets in randomly

Due to the rules of conditional probability, the frequency of sequence A is given by the product of the basic frequency of event 2 (f_2) and the probability ($p_{event\ 1}$) that event 1 is already on going:

$$f_A = f_2 \times p_{event\ 1} \qquad \text{Equation E.1}$$

The probability of event 1 is given by:

$$p_{event\ 1} = f_1 \times T_1 \qquad \text{Equation E.2}$$

resulting in

$$f_A = f_2 \times (f_1 \times T_1) \qquad \text{Equation E.3}$$

The same consideration applies for sequence B:

$$f_B = f_1 \times p_{event\ 2} = f_1 \times (f_2 \times T_2) \qquad \text{Equation E.4}$$

The superposition of two different, mutually exclusive events are

$$f_{coinc} = f_A + f_B = f_2 \times (f_1 \times T_1) + f_1 \times (f_2 \times T_2) = f_1 \times f_2 \times (T_1 + T_2) \qquad \text{Equation E.5}$$

These stochastic considerations are applied to earthing systems, regarding personal safety in case of an earth fault, the following designations are used.

Correspondences:

- Event 1 → earth fault causing EPR
- Event 2 → contact of the individual
- Hence the quantities of formula Equation E.5 become:
- f_1 → $f_{earth\ fault}$ … frequency of earth faults per year and e.g. substation
- T_1 → $T_{earth\ fault}$ … duration of the earth fault
- f_2 → $f_{contact}$ … frequency of contacts per year in the relevant location
- T_2 → $T_{contact}$ … duration of the contact

From this, the individual risk of coincidence (probability of coincidence) for an individual due to a particular electrical installation may be calculated (see Equation E.5).

For the individual risk of fatality assessment, the probability of heart fibrillation ($P_{fibrillation}$) and the so called coincidence reduction factor CRF (see Equation 6.6.2) are taken into account.

Guidance on determining the fibrillation probability is given in Section 6.5.

Remark 1: 'Earth fault situation' means e.g. single phase-to-earth or cross-country fault. The type of earth fault situation which has to be analysed depends on the network structure and the operators' experience.

Remark 2: 'Considered equipment' e.g. high voltage pylon, ring main unit – RMU, low voltage equipment galvanically connected to HV or MV equipment through a T-N system etc. The value for the above mentioned quantities can be taken from the operators' experience or from the tables in Section 6.