PROBABILISTIC RISK ASSESSMENT OF ELECTRICAL SUBSTATIONS

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ABSTRACT

This thesis is concerned with the development of probabilistic risk assessment for substation earthing systems. A number of key parameters have been studied in detail which led to the development of a new approach that incorporates the recommendations of applicable standards and uses historical system fault data to take account of the probabilistic nature of load, protection systems and grid characteristics.
In this work, an in-depth appraisal of existing standards has led to the development of safety-limit surfaces that can be used to quantify the benefits/disadvantages of particular earthing standards. The investigation has revealed that there are substantial differences between the recommended values of tolerable voltages attributed to a combination of factors: (i) difference in assumed tolerable body current; (ii) differences in the parameters of the electrocution circuit; (iii) differences in the predicted touch voltage; and (iv) differences in the assumed worst-case shock location.
The electricity industry, like other industries, is looking to reduce risk to minimum feasible while maintaining costs of mitigation within acceptable limits. Therefore, a more rigorous and comprehensive procedure of probabilistic risk assessment of the earthing systems is required. In order to achieve this, a detailed analysis of all parameters was undertaken in this work using more representative accidental circuits and parameters extracted from historical system fault data, provided by the collaborating transmission companies. These parameters were modelled and integrated into the proposed probabilistic risk assessment process.
Work within this investigation on improving accuracy of calculation of heart fibrillation has led to the development of a probability surface of ventricular fibrillation and a computerised process that determines an accurate probability for a given body current and shock duration. This procedure takes into consideration the body current path and eliminates reading errors or assumptions that could result into conservative or optimistic conclusions.
The above fundamental investigations on parameters affecting the overall risk were implemented in a new computerised risk assessment procedure CRAFTS suitable for transmission systems. CRAFTS allows a probabilistic risk assessment of the system under investigation. The application integrates the recent developments in the latest standard IEC 60479-1 and the developed probability surface of ventricular fibrillation. A case study performed on a typical grid has shown that the developed program is very useful when applying sensitivity analysis of the various parameters of the system and accidental circuit.
The proposed full probabilistic risk assessment method incorporates the earthing system simulation results performed by specialised software, namely CDEGS, making it possible to simulate different electrocution scenarios throughout the substation instead of assuming a 'worst case scenario' and exposure to maximum possible voltages.
Overall, the research in this thesis, offers an integrated solution of probabilistic risk assessment of earthing systems in aid of sound cost/benefit analysis and decision making.

GLOSSARY OF TERMS

ACOP	Approved Code of Practice
ALARP	As Low As Reasonably Practicable
BS	British Standard
CB	Circuit Breaker
cdf	Cumultive Distribution Function
CENELEC	European Committee of Electrotechnical Standardization
CRAFTS	Cardiff Risk Assessment Facility for Transmission Systems
EA	Electricity Association
ENA	Energy Networks Association
EPR	Earth Potential Rise
GPR	Ground Potential Rise
HASAW	Health and Safety at Work
HAZID	Hazard Identification Analysis
HAZOP	Hazard and Operability Method
HIVES	High Voltage Energy Systems
HSE	Health and Safety Executive
HSW	Health and Safety at Work
IEC	Internantional Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
MHSWR	Management of Health and Safety at Work Regulations
NG	National Grid
OHL	Overhead Line
pdf	Probability Density Function
PHA	Preliminarily Hazard Analysis
PRA	Probabilistic Risk Analysis
PSA	Probabilistic Safety Analysis
QRA	Quantitative Risk Analysis
VF	Ventricular Fibrillation

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CHAPTER 1. INTRODUCTION

With the rapid advances in technology and the fast pacing development of the industrial world, there has been a huge increase in the number and size of large plants operating in various areas of engineering. As these plants increased in complexity and working force so did the public awareness of the risks associated with their operation.

Especially after key accidents such as Flixborough, Bhopal, Chernobyl and Piper Alpha, there has been an ever increasing need to minimise the risks associated with the operation of such plants while at the same time maximising the beneficial results of modern technology [1.1]. However, due to the hazardous nature of many processes, it is infeasible to eliminate risks totally. A balance, that would secure the benefits gained by the practice of the hazardous activity, while retaining the risk to acceptable levels, is desirable. As a result, government regulators have provided frameworks for industry, so that employers can assess the levels of risk of their operations and determine their acceptability.

The power industry is no exception to the rule. As in all industries, employees may be subject to different types of accidents ranging from trips and falls to fires and explosions. Also, due to the high operating voltages of the transmission and distribution systems, death from electrocution has always been a primary concern within the industry.

The 400/275 kV transmission system operated by National Grid consists of over 250 substations interconnected by 15000 km of overhead lines supported by more than 26,000 transmission towers. Another 500 km of underground cables are added creating a huge network. [1.2, 1.3]. According to National Grid, about 200 faults take place on their transmission system every year, of which 90% are classified as earth faults [1.2, 1.4]. Moreover, only 25% to 50% of these faults will result in significant current flow in the substation earth mat [1.5]. However, during these faults, the current magnitudes can range from 4 kA to 35 kA, depending on the level of generation, the system configuration and the type and location of the fault [1.6].

The distribution system, operating at voltages from 132 kV down to 6 kV, is far bigger compared to the transmission system. The total length of overhead line system is 180,000 km while the underground cables are approximately 133,000 km. There are about 5,000 substations operating in the range 132 kV down to 20 kV, and another 170,000 substations distributing power to the low voltage system [1.2, 1.7]. The distribution system because of its extent and greater susceptibility to short circuit events, suffers far more faults than the transmission system. The total number of faults occurring per annum are estimated to be 25,000, of which 70% involve connection to the earth [1.2, 1.8, 1.9]. Although the fault current magnitudes are lower than those on the transmission system, typically, ranging from 25 kA at 132 kV substations to 1-2 kA at 33/11 kV substations, the fault clearance times are much longer. While the main protection in the transmission system will usually clear a fault within the first 160 ms, in the distribution system, the fault clearance time may exceed 1 s [1.2].

When a proportion of the earth fault current flows through the earth path, as opposed to the earth wire, there will be a rise of potential of the earthing system with respect to remote earth. The generated potential differences across points at different locations inside or outside an installation (e.g. a substation), when bridged by humans may result in electrocution. Depending on the accidental circuit, these potential differences can be either touch, step or transferred voltages. [1.2, 1.10]

If the magnitude of these voltages and shock duration are high enough, it can result in severe burns, asphyxia or even heart fibrillation and death. Because of legal constraints, it is not easy to acquire statistical data and detailed accident description of deaths that occur. However, anecdotal evidence from electrical engineers reveals that regardless of the great advances in fault clearance times and earthing practice enforced by regulations and relevant standards, there is still a toll of human lives.

Over the past few years, there has been a vast improvement of the available earthing standards where mainly analytical solutions are provided to calculate the magnitude of the hazardous voltages and make an assessment of safety in any installation.

Since the magnitude of the step and touch voltages in a substation will depend on the location of the person, the shock scenario and the magnitude of fault current, it is common practice in various standards to make an assessment based on the maximum possible touch and step voltages and shock duration [1.2, 1.11-1.15]. However studies have shown that, due to different assumptions used for calculating the various parameters of a given earthing grid as well as the different accepted levels of allowable body current, there are substantial differences between the recommended values of tolerable voltages and, consequently, of the safety-limits that are applicable to an earth grid. The studies carried out by the author and other investigators [1.16-1.19] have established that the standards recommendations do not compare very well, resulting in either over-designing of the earthing system or, on the other hand, a compromise in safety.

1.1 Contributions of Present Work

During the course of the research programme the following contributions were achieved.

- Extensive survey of safety requirements to include government and private companies' practices and recommendations.

- Appraisal and comparison of national and international standards and their recommendations for calculation of safety voltages. The main differences are discussed and best practices are highlighted.
- Extension of the range of usability of IEC safety curves for allowable body current and body impedance through derivation of empirical equations and surface probabilities.
- Novel analysis of system fault data and its impact on risk assessment of earthing systems.
- Development of a new software program called Cardiff Risk Assessment Facility for Transmission Systems or "CRAFTS" to perform risk assessment of earthing systems in compliance with recommendations of national and international standards to allow engineers and asset managers to make informed decisions on earthing systems safety and mitigation of hazards on electricity networks.
- Development of advanced statistical and probabilistic procedure for the risk assessment of earthing systems.

1.2 Thesis Content

Over the past few years, the electrical industry worldwide has started recognising the probabilistic nature of the exposure to earth potential rise and of the effect of current on the human body. The internationally widely adopted standard IEC 479-1 [1.20], based on animal experiments, has provided curves of allowable body current against shock duration of different probability levels. Also, the body impedance was given as a function of the touch voltage for different confidence levels. Moreover, fault location, fault current magnitude, clearance time, soil resistivity, location of the person in time of shock as well as the current path are some of the parameters that show a statistical variation and can be included in the assessment process as such instead of single or "worst case scenario" values.

It is shown that a standard may have safety and/or cost implications compared with the alternative standards, and harmonisation of earthing systems design standards require the inclusion of probabilistic parameters that may lead to a less subjective approach to design. Therefore, the contents of this thesis are summarised to:

- The development of safety-limit surfaces for various earthing standards. (Chapter 3)
- The development of probabilistic safety criteria based on the IEC 479-1 curves that can be integrated in the already applied risk assessment processes and also to a fully probabilistic method. (Chapter 4)
- The investigation of each of the various parameters that reflect the probabilistic nature of load, protection system and grid characteristics and their modelling based on historical data provided by the cooperating transmission company (National Grid). (Chapter 5)
- The implementation of the process, to a stand-alone software package "CRAFTS". (Chapter 6)
- A novel approach to probabilistic risk assessment of electrical substations based on the developed criteria that takes into consideration the probabilistic nature of all the contributing parameters. (Chapter 7)
- A case study where the suggested methodology is applied to an existing substation. (Chapter 7)

CHAPTER 2. RISK ASSESSMENT: A REVIEW

The term *risk* appeared in the English language in the 17th century and, etymologically, it comes from the Italian *"risco"* or *"rischio"* which means danger. It is derived from the Latin word *"risicare"* which actually means navigating a ship close to dangerous cliffs, and it is believed that the word originates from the Greek word *"riza"* which means both root and cliff [2.1].

2.1 Introduction

As mentioned before, reassuring safety and, therefore, assessing risk in any work environment has become a major issue in modern industry. Various approaches towards risk evaluation and quantification have been developed, and the ultimate purpose of this thesis is to contribute towards developing a comprehensive process of probabilistic risk assessment of power systems. Initially though, it is essential to investigate the regulatory framework upon which any risk assessment is based. It is important to comprehend what is expected from the risk assessment process, which are the fundamental principles that should be followed and the targets to be achieved. Therefore, the first part of this chapter reviews the relevant legislation that covers this area as well as to the general approaches to risk assessment.

Then, the focus is turned to risk assessment of power systems. In particular, the effects of current on the human body including electrocution hazards that exist from the high voltage installations are described.

In the next section, we examine the available approaches of risk assessment of power systems as well as the common practice that is followed in the UK in particular. The tolerability of risk is also discussed and how the acceptable levels of risk are defined in order to make justified decisions and determine the appropriate action. Finally, the different approaches for risk mitigation are listed and then followed by a brief discussion of their effect.

2.2 Health & Safety Legislative Framework

The initial piece of legislation covering Occupational Health and Safety in Great Britain is the Health and Safety at Work Act 1974, also referred to as HASAW or HSW [2.2], and later on, in 1978, the Health and Safety Work (Northern Ireland) Order for Northern Ireland was also released [2.3].

According to the legislation, there are five separate classes of persons that general duties apply to:

- Employers
- Employees
- Manufacturers and suppliers of industrial products
- The self-employed
- Occupiers of buildings in which persons work, other than one's own employees

The main duty of an employer is to ensure the health, safety and welfare at work of all his employees, as far as it is reasonably practicable [2.4]. The HSW act outlines in more detail the duties of employers and aims to:

1. Provide and maintain the plant or any system of work, safe and without any risks.
2. Make the necessary arrangements to ensure the safety and the absence of health risks when using, handling, storing and transporting articles and equipment.
3. When necessary, provide information, instruction, training and supervision in order to maintain safety.
4. Maintain safety in all places of work under the employer's control including entrance and egress.

5. Finally, provide adequate facilities and arrangements for employees' welfare.

Management of Health and Safety at Work Regulations (MHSWR) [2.5], initially published in 1992 and later revised in 1999, is the most significant regulation in current health and safety legislation [2.4] where Regulation 3 on "Risk Assessment" states that: Every employer shall make a suitable and sufficient assessment of:

1. The risks to the health and safety of his employees to which they are exposed whilst at work.
2. The risks to the health and safety of persons not in his employment arising out of or in connection with the conduct by him or his undertaking [2.5].

The responsibility of employers to undertake a "suitable and sufficient risk assessment" is regarded as the cornerstone of all modern protective legislation [2.4]. In a nutshell, under these principal legal requirements, employers are responsible for ensuring the safety and health of their employees and also the public if they are at risk from their working activities.

The Health and Safety Executive (HSE) published "Reducing risks, protecting people" initially in 1999 and later a revision in 2001; a document [2.6] which discusses the overall framework for decision making in order to "ensure consistency and coherence across the full range of risks" under the Health and Safety at Work Act 1974 (MHSWR) [2.6, 2.7]. The developments that influenced the decision making approach, the principles behind the tolerability limits of risks and also the role of risk assessment are discussed. Risk assessment is described as a "tool necessary to inform our decisions by helping us to understand further the nature and degree of risk and extrapolating, from available data, our experience of harm, or for representing a large amount of scientific information and judgment as an estimate of the risks" [2.6]. This statement has been the basis for the development of rigorous and analytical risk assessment procedures and shows the way towards quantification of risk. In the following section the main principles of risk assessment are outlined together with a list of some important definitions.

2.3 Risk Assessment

According to the Management of Health and Safety at Work Regulations (MHSWR) [2.5], all employers and self-employed people are required to assess the risks to anyone who might be affected from work activities, including members of the public. The risk assessment process consists basically of identifying the possible hazards and evaluating the extent of the risk taking into consideration all safety controls already in place. If risk levels are unacceptable, further measures are implemented and the system is reassessed to confirm compliance with regulations [2.4, 2.8].

2.3.1 Definitions

The Approved Code of Practice (ACOP) [2.8], a document, that accompanies Management of Health and Safety at Work Regulations (MHSWR) [2.5], provides the following definitions:

a) A *hazard* is something with the potential to cause harm (this can include substances or machines, methods of work and other aspects of work organisation).
b) *Risk* expresses the likelihood that the harm from a particular hazard is realised.
c) The *extent* of the risk covers the population which might be affected by a risk, i.e. the number of people who might be exposed and the consequences for them.

Therefore, risk refers not only to the likelihood that the harm will occur but also to the consequences [2.4].

Across health and safety bibliography, there are various definitions of risk assessment but the one accepted by the HSE is:

"Risk assessment is a multi-stage process used to determine the magnitude of a threat (risk) of loss, in its widest sense, to assist management decision making. An assessment should determine whether the risk is tolerable, taking into account existing control measures. If they are not adequate, the assessment should recommend more effective measures. Monitoring of these controls must take place" [2.9].

2.3.2 The Risk Assessment Process

To provide assistance to risk assessors, the HSE has also published a guide called "Five Steps to Risk Assessment" [2.10] which provides an outline of the risk assessment, and summarizes the process in the following simple steps.

1. Identify the hazards.
2. Decide who might be harmed and how.
3. Evaluate the risks and decide on precaution.
4. Record findings and implement them.
5. Review assessment and update if necessary.

This iterative process is described in further detail in the latest version of the British Standard BS 8800 which is a guide to occupational health and safety management systems. This publication offers guidance and recommendations on risk management issues. It shares common management system principles with the BS EN ISO 9000 on "Quality Management" [2.11] and is consistent with the aforementioned HSE publication on "The Management of Health and Safety at Work Regulations 1999". [2.5]. The guide provides a detailed description of the risk assessment process, and it is presented here in Figure 2.1.

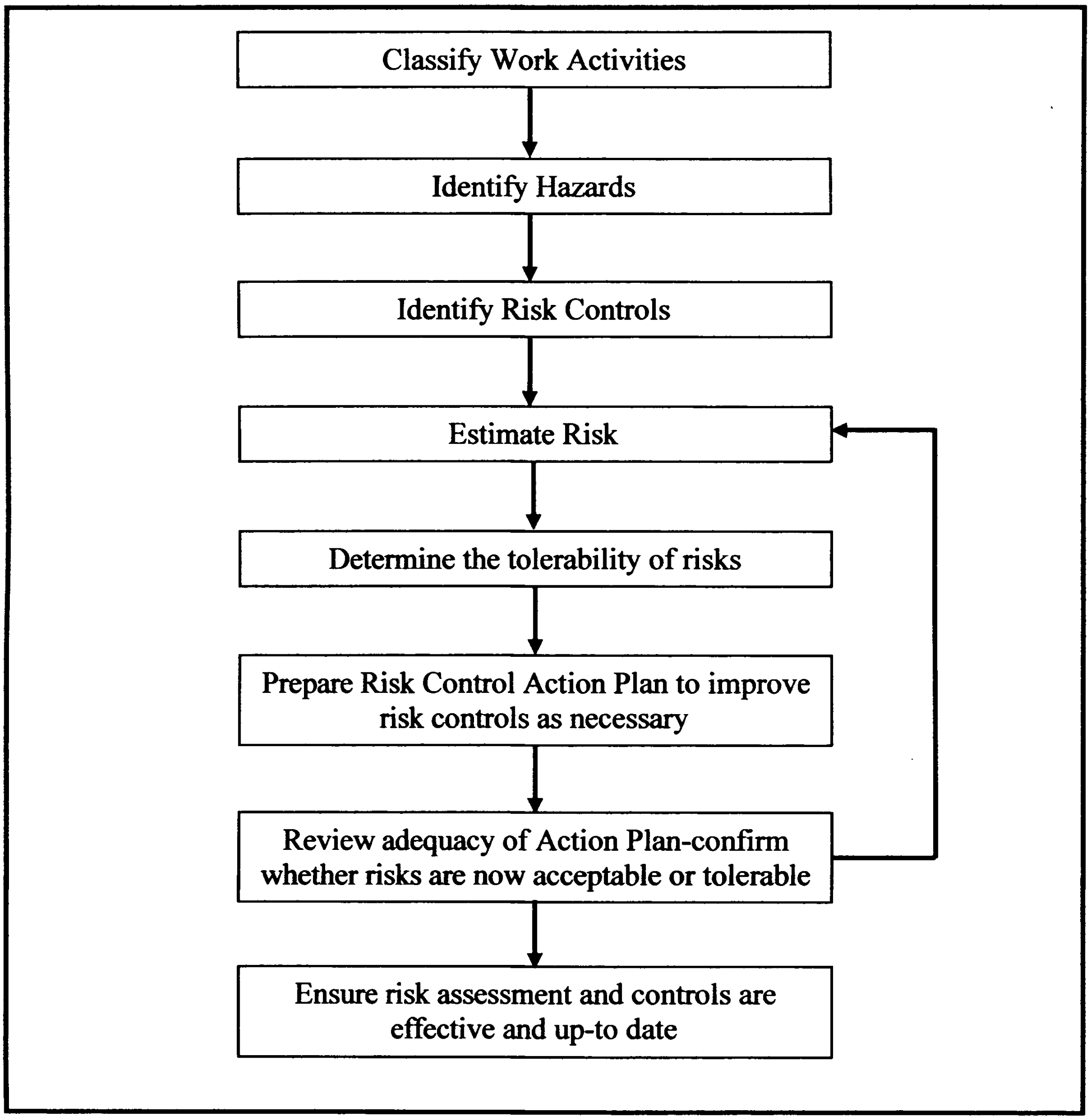


Figure 2.1: The process of risk assessment and control [2.11].

The classification of work activities is the initial stage of the process where all "rational and manageable" work activities should be included. It is essential to include apart from everyday activities, those infrequent tasks such as maintenance work or probable emergencies that may occur. These activities can be classified for example as:

- Activities that take place inside but also outside the premises under investigation.
- Tasks that are part of the everyday production process.

- Planned and reactive work.
- Phases of lifecycle of work equipment e.g. installation, normal operation, maintenance, repair etc.
- Tasks carried out by contractors.

Then, for each activity, information needs to be gathered concerning the nature of the task, the duration and frequency, the location, the number of people involved etc. It is necessary at this stage to identify if certain activities need to be assessed separately in order to ensure that all the parameters of the particular task are covered and assessed appropriately.

The second stage of the process deals with identifying the hazards. At this point, all possible sources need to be identified, and also who the stakeholders are and under what circumstances that hazard can materialize. Hazards of low harm potential do not need to be included in the process. In order to accommodate the identification of hazards, they are briefly classified as:

- Physical hazards where sources of electricity are included
- Chemical hazards
- Biological hazards
- Psychological hazards

At this point, it is necessary to identify whether the hazards could affect the public or perhaps the surrounding neighbourhood.

The next key step of the process is identifying the risk controls that may already be in place to mitigate the hazard or evaluating the effect of proposed possible measures.

The next phase of the process, that perhaps is the most difficult to deal with, is determining the risk. The risk of each hazard needs to be addressed with the appropriate qualitative, semi-quantitative or quantitative process that will be discussed later on.

Apart from the likelihood of a hazard materializing, its impact is also assessed and the consequences that it may bear. It is suggested that it may be useful at this stage to determine the risk also without taking into consideration the already applied risk controls. Such an approach assists in identifying the importance of the measures taken so far and may prevent from substituting or even cancelling controls with high mitigating impact.

Determining the tolerability of the risks is the process where it is decided whether a risk is acceptable or not and if legal requirements are met. Depending on the approach used to assess the risk, the results may be compared against different criteria.

The HSE document [2.6] that provides the framework of risk assessment also includes a valuable discussion on the principles behind the tolerability limits of risks. As will be seen in Section 2.7, these limits have been quantified and can be used to compare calculated risks and assist with the decision making process.

The next two steps deal with preparing an action plan to control all of the undesired risks which is then followed by a review of the adequacy of the action plan. Here, the risks are re-assessed taking into consideration the suggested mitigating measures, and then it is considered whether the risk is tolerable or acceptable by comparing against the appropriate criteria. If the results are not satisfactory, the process is repeated by re-estimating the risk and further action taken till the risk falls within the desired level. Finally, it is essential to keep reviewing the system on a regular basis seeking changes that may cause risk to increase and act accordingly to maintain safety [2.11].

2.3.3 Qualitative Risk Assessment

Qualitative methods are usually adopted not only for the assessment of an operating system but also in the early stages of design and installation when decision making is necessary for the selection of equipment and final system configuration. Through these studies, all the potential hazards occurring either from equipment or from operating procedures that can critically affect safety are identified and ranked. These methods can lead to significant risk mitigation but also can provide valuable input to quantitative studies. A few of the methods, which find great use in industry and plant studies, are Hazard Identification Analysis (HAZID), Checklists or "What if" method, Hazard and Operability method (HAZOP) and Preliminarily Hazard Analysis (PHA) [2.12]. A detailed discussion of the benefits and utility of different techniques of risk assessment employed by the industry can be found in previous project work of the author [2.13]. Qualitative answers are often sufficient for making good decisions about the allocation of resources for safety improvements. However, as managers seek quantitative cost/benefit information upon which to base their decisions, they are increasingly turning their attention to the use of Probabilistic Risk Assessment (PRA).

2.3.4 Probabilistic Risk Assessment

Probabilistic Risk Assessment (PRA), also called Quantitative Risk Analysis (QRA) or Probabilistic Safety Analysis (PSA), is the process that aims to quantify the risk that is caused by high technology installations.

Many sectors worldwide employ quantitative risk assessment methods, including transport, construction, energy, chemical processing, aerospace, the military, and even to project planning and financial management. In many of these areas of industry, PRA techniques have become essential to the decision making. Especially because of the benefit that PRA allows in categorising and assessing risks with enough precision to enable consistent application by different assessors at different times, quantitative techniques in several sectors have been adopted as part of the regulatory framework by relevant authorities.

Generally, even for those areas that PRA is not a standard practice, there is a constant increase in the application of these methodologies either for validating claims for safety or for providing numerical evidence showing the need for further improvement. [2.12, 2.14-2.16].

Because of this trend and the wide acceptability of PRA, over the past few years, quantitative techniques and tools that apply these techniques have grown in sophistication. However, the risk analysis essentially provides answers to the following three questions:

- What can happen?
- How likely is it to happen?
- Given that it occurs, what are the consequences?

The identification of the possible hazards, the quantification of the likelihood that the hazard materializes and, finally, the severity of the consequences are the parameters that define risk [2.14].

For each sector, there is great variation in the goals, size, complexity and techniques of probabilistic risk analysis. Descriptions of the various techniques as well as a discussion of their applicability in different areas are also included in the author's previous work [2.13]. At this point, risk assessment in power systems is focused on and the main practices followed in the sector nowadays as well as the challenges faced by the electrical industry will be presented.

2.4 Risk Assessment in Power Systems

Under the current legislation of Health and Safety at Work etc Act 1974 (HASAW) [2.7] and the Management of Health and Safety at Work Regulations (MHSWR) [2.5], transmission and distribution companies must ensure safety for their employees and the public. Power plants, as any other type of plant impose various hazards (falls, trips, fire, exposure to harmful substances etc), and qualitative and quantitative assessments take place to control those risks. Specifically, due to the high voltages operating in these systems, electrical safety is a prime concern and is managed independently.

2.4.1 Effects of Current on Human Body

Electrocution of the human body can result in various consequences ranging from burns to asphyxia and ventricular fibrillation depending on current magnitude and shock duration [2.17]. However, the primary cause of death following electrocution is considered to be ventricular fibrillation. Based on animal experiments, this heart condition is used to deduce threshold currents for given shock durations or estimate the probability of death from an electric shock. Next, follows a more detailed analysis of the effects of alternating current as well as a description of the induced heart condition of ventricular fibrillation.

2.4.2 Effects of sinusoidal alternating current

The international standard IEC 479-1 [2.17] on "Effects of current on human beings and livestock" provides a detailed description on the effects of sinusoidal alternating current passing through the human body for frequencies between 15 Hz to 100 Hz as well as the various current threshold values of these effects [2.17].

The lowest threshold of current, the threshold of perception is defined as the minimum value of touch current which causes any sensation for the person through which it is flowing. The magnitude of this body current threshold depends on various parameters, such as the body contact area with an electrode, the conditions of contact, and finally the physiological characteristics of the individual.

The threshold of reaction, or else the minimum value of touch current that causes involuntary muscular contraction is regarded to be 0.5 mA independent of time and depends on the same parameters as before.

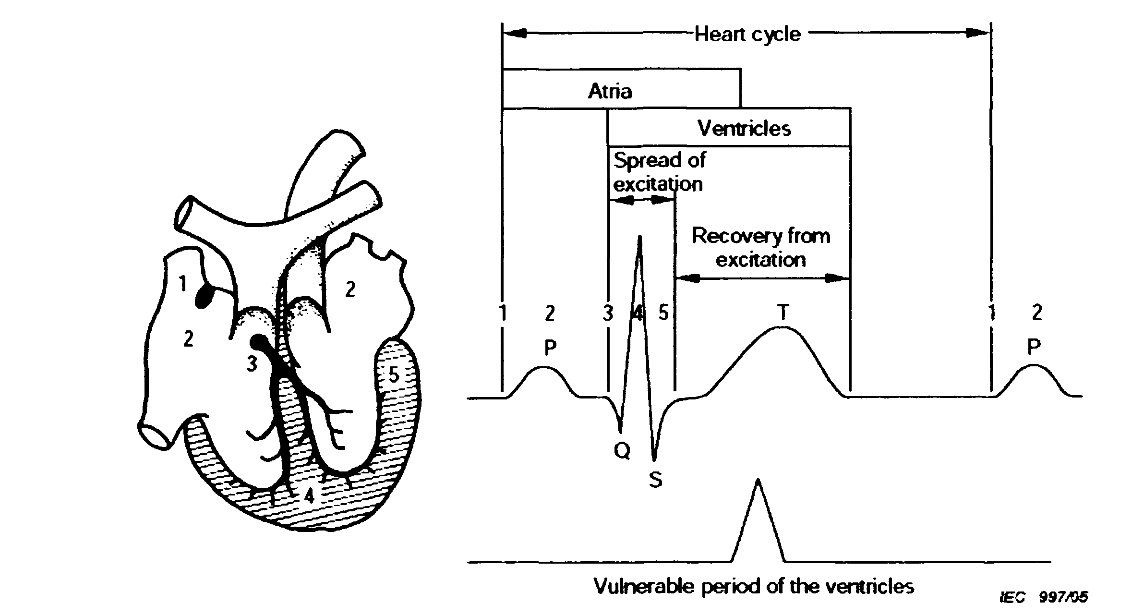
Immobilization is the effect of current on muscles or on associated nerves or parts of the brain, which causes the human body or part of the human body not to be able to move voluntarily. The magnitude of current that can cause immobilization depends on the volume of the muscles affected as well as the part of the brain and type of nerves affected by the current.

A very important threshold is the value of 'let-go' current since it is the maximum value of touch current at which a person holding live electrodes can let go of the electrodes. The value depends on various parameters such as the contact area, the shape and size of the electrodes and also on the physiological parameters of the individual. The threshold of let-go current for adult males is typically 10 mA while the value of 5 mA covers the whole population [2.17].

2.4.3 Ventricular Fibrillation

The threshold of ventricular fibrillation is the minimum value of current through the body which causes ventricular fibrillation. If this threshold is exceeded, it can be fatal because the blood flow stops, and no oxygen is being transported to the human body.

Ventricular fibrillation can occur only if the shock occurs within the heart's vulnerable period. The IEC 479-1 describes the vulnerable period as a comparatively small part of the cardiac cycle during which the heart fibres are in an inhomogeneous state of excitability and ventricular fibrillation occurs if they are excited by an electric current of sufficient magnitude. This period, as shown in Figure 2.2, corresponds to the first part of the T-wave in the electrocardiogram and lasts for approximately 10% of the heart cycle. Figure 2.3 shows the triggering of ventricular fibrillation when the electric shock falls within the vulnerable period [2.17]. Parameters that affect the threshold of ventricular fibrillation can be physiological such as anatomy of the body, state of cardiac function, etc.



NOTE The numbers designate the subsequent stages of propagation of the excitation.

Figure 2.2: Occurrence of vulnerable period of ventricles during the cardiac cycle [2.17].

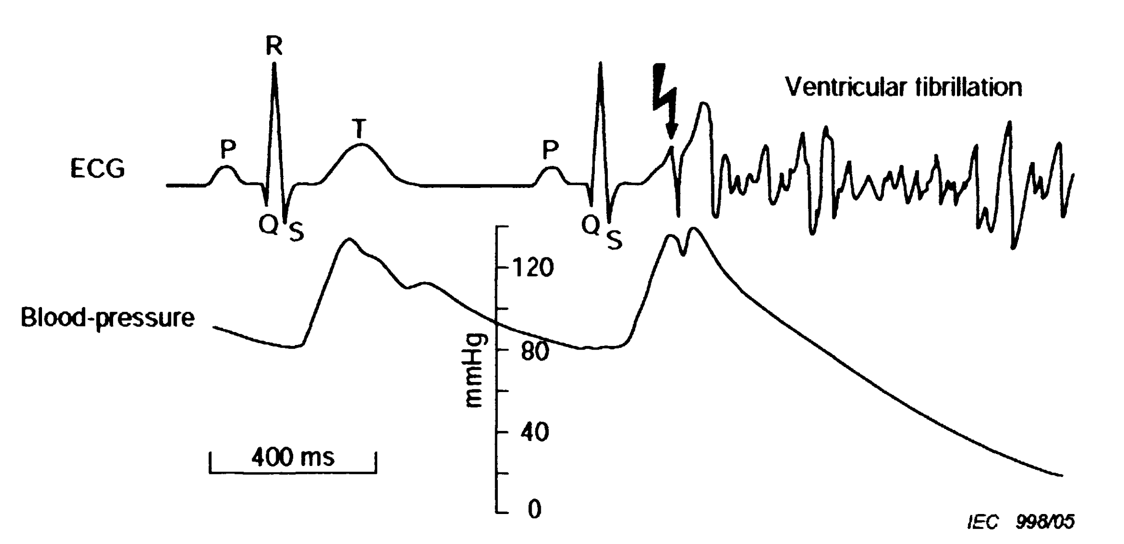


Figure 2.3: Triggering of ventricular fibrillation in vulnerable period-Effects on electro-cardiogram (ECG) and blood pressure [2.17].

Figure 2.4 shows zones of allowable body current against shock duration for a current path from left hand to both feet based on statistical results from animal experiments and human beings. Curve c_1 was empirically produced to show the current below which ventricular fibrillation is unlikely to occur.

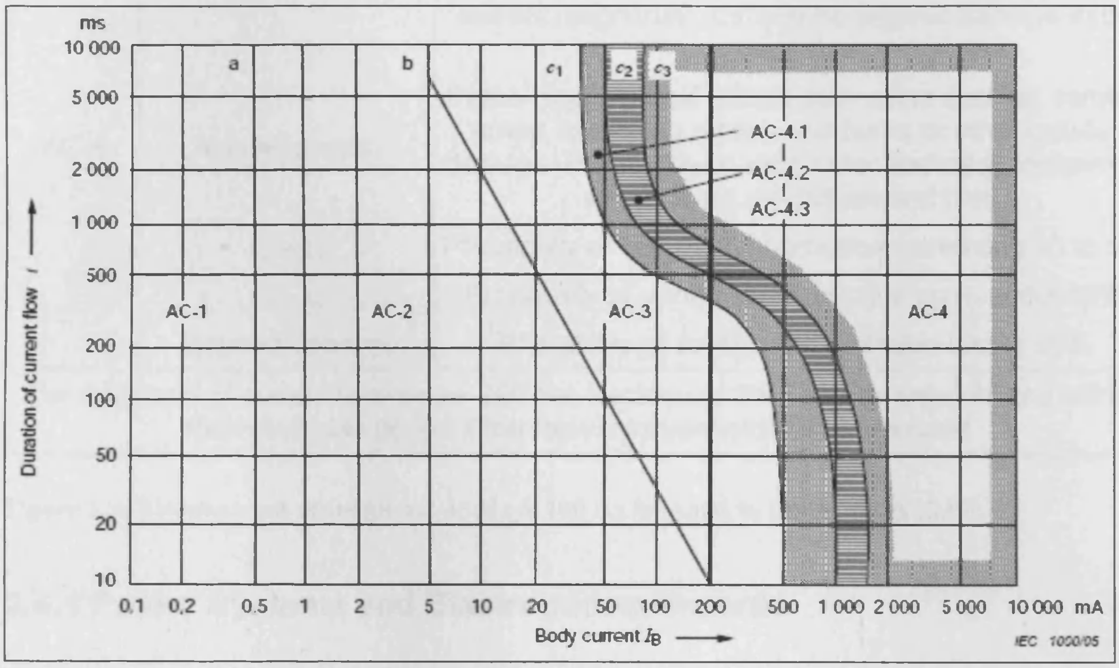


Figure 2.4: Conventional time/current zones of effects of a.c. current (15 Hz to 100 Hz) on persons for current path corresponding to left hand to feet [2.17].

A more detailed description of the time/current zones of the effects of a.c. current on persons is presented on Figure 2.5.

Zones	Boundaries	Physiological effects
AC-1	Up to 0.5 mA curve a	Perception possible but usually no 'startled' reaction
AC-2	0.5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of hearth function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	$c_1 - c_2$	Probability of ventricular fibrillation increasing up to 5%
	$c_2 - c_3$	Probability of ventricular fibrillation up to about 50%
	Beyond curve c_3	Probability of ventricular fibrillation above 50%
For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed.		

Figure 2.5: Time/current zones for a.c. 15 Hz to 100 Hz for hand to feet pathway [2.17].

2.4.4 Power Systems and Electrocution Hazards

It is sometimes and wrongly assumed that when a conductor is earthed, then it is safe to touch [2.18]. When the insulation of a high voltage conductor to earth fails, the fault current, or a part of it, flows through the earth mat and returns to the neutral points of the supply transformer. The fault current passes to the substation earth electrode, which because of its impedance to the current flow, results in a potential rise of the earth electrode and of the earth in the vicinity of the substation [2.19].

Magnitudes of the potential of the earth electrode and of the ground surface of the surrounding area depend on the location of fault and the distance from earth electrode respectively. The potential is greater at the substation electrode and it reduces with distance away from the electrode at the point of the earth fault. [2.18, 2.20].

Therefore, under earth fault conditions, potential differences that occur inside and outside of high voltage installations can be hazardous when human bridges these points

[2.21]. There are different electrocution scenarios which may occur depending on where the person is standing and the contact conditions with earth conductors.

(i) A **touch voltage** scenario occurs when a person comes in contact with metalwork connected to the earth electrode and picks up a portion of the EPR. It is assumed that the current travels through the human body from hand to feet and that the horizontal distance of the feet from the exposed part is 1m. A slightly different touch voltage scenario occurs when a person bridges two points of metalwork of different potential allowing current to flow through the human body.

(ii) **Step voltage,** on the other hand, is the part of the potential rise due to an earth fault that can be picked by a person with a step-width of 1m, assuming that the current is flowing via the human body from foot to foot [2.22]. However, the magnitude of the voltages that a person can be exposed to, will vary depending on the conductor that he/she comes in contact with or the location where he/she stands. When assessing the safety of a high voltage system, it is considered impractical to include all the possible touch and step voltage scenarios; That is why under current practice, the risk assessment is based upon the maximum touch and step voltages [2.21].

Step voltages are usually considered less hazardous compared to touch voltages. The main reason is that the human body, as shown in the latest version of IEC 479-1 [2.17], can tolerate higher currents for a path from foot to foot as we will see later on in further detail. Moreover, for any given position, the step voltage is lower than the touch voltage so when a system is safe for touch scenarios it should also be considered safe for step voltage scenarios [2.21]. However, there could be places where there is no touch voltage hazard (i.e. no exposed metalwork) but step voltages may be experienced.

(iii) A scenario of **transfer potential** occurs when a potential rise of an earthing system is transferred by a connected conductor (e.g. rail, pipeline, metallic cable sheath or fence) into areas of low or no potential rise relative to reference earth [2.22].

Various standards worldwide have been developed, providing guidelines and limits concerning the design and operation of these systems in order to control the hazardous voltages. The Electricity at Work Regulations 1989 [2.23] describes the main health and safety requirements for the UK for all electrical equipment, including high voltage apparatus. According to the regulations, *electrical equipment* is defined as "anything used or intended to be used and installed to generate, provide, transmit, transform, rectify, convert, conduct, distribute, control, store, measure or use electrical energy". Also, *system* is defined as "an electrical system in which all electrical equipment is or may be electrically connected to a common source of electrical energy and includes such source and electrical equipment" [2.4, 2.23].

The regulation, classifies all employers, employees, self-employed persons as "duty holders" and requires them to cooperate in order to control risks. Furthermore, "all electrical equipment must not be put into use where its strength and capability may be exceeded so as to give rise to danger. Finally, all systems shall, so far is reasonably practicable, be constructed and maintained so as to prevent danger".[2.23] Further guidelines are given to the HSE document 'Memorandum of guidance on the Electricity at Work Regulations 1989' [2.24] that accompanies these regulations. Other relevant regulations include the 'Electrical Equipment (Safety) Regulations, 1994' [2.25] and the 'The Electricity Safety, Quality and Continuity Regulations 2002' [2.26]. Such legal requirements of electrical companies are specifically referenced in the technical specifications of individual companies [2.27-2.29].

2.5 Deterministic Risk Assessment of High Voltage Earthing Systems

British Standard BS 7430 [2.30] concerning the earthing practice in power stations and substations, is based on the legal requirements described in Section 2.4. For safety purposes, the earth bonding should make certain that any voltage, which could possibly appear on equipment under normal or abnormal conditions, and can be accessible should be below a dangerous level. Furthermore, in order to protect certain auxiliary plants, it is recommended that the rise of earth potential and fault clearance time should be as low as practicable [2.30].

In order to ensure that these conditions are met, the earthing system should have certain essential characteristics; a low resistance of the earthing system must be obtained regardless of the weather variations, under normal operating conditions or in case of fault or surge discharge conditions, the current-carrying capability of the earth electrodes should be guaranteed. Also the earth connection conductors from any devices need to be as short and straight as possible to keep surge impedance at minimum and, importantly, these installations should be robust and constructed of appropriate materials to avoid corrosion.

It is interesting to note that BS 7430 specifies that the resistance of the earthing system for high voltage systems should be such that the rise of earth potential is "as low as can be achieved reasonable and economically" [2.30]. Maximum values of EPR are indicated in order to provide deterministic guidelines to follow. Hence, for earth faults of short duration, the potential rise should not exceed 430 V rms, or if the fault is cleared in less than 0.2 s, then the EPR cannot be more than 650 V rms. The same voltages are also accepted for the telecommunication systems [2.30].

Another relevant standard (ITU-T K.33) [2.31] specifies limits for safety of people exposed to coupling between telecommunications systems and ac electric power systems. In this standard, a distinction is made between limits applicable under (i) 'typical' and (ii) 'severe' conditions. Typical conditions are described by work carried out by trained or experienced personnel, and when the electrocution circuit consists of current paths only from hand to hand or hand to feet. In this situation, the tolerable current is assumed to be curve c_2 of IEC 479-1 [2.17] and on which the following Table 2.1 is based.

Table 2.1: Limit Voltage Values for Fault Duration Ranges [2.31].

Duration of faults t (s)	Admissible Limit (V)
$t \leq 0.1$	2000
$0.1 < t \leq 0.2$	1500
$0.2 < t \leq 0.35$	1000
$0.35 < t \leq 0.5$	650
$0.5 < t \leq 1.0$	430

A situation is considered severe when the current paths also include hand to hip or hand to chest. The source impedance is neglected, and in this case, the maximum allowable body current is deduced from curve c_1 of IEC 60479-1. Table 2.2 summarises the allowable voltages.

Table 2.2: Limiting Values for Severe Situations [2.31].

Duration of faults t (s)	Admissible Limit General (V)	Admissible limit when current paths through chest or hip need not be considered (V)
$t \leq 0.06$	430	650
$t \leq 0.1$	430	430
$0.1 < t \leq 1.0$	300	300

Hence, the deterministic approach of assessing an earthing system consists of assuming a worst case scenario, estimating the maximum touch and step voltages and comparing these calculated voltages with the allowable limits.

Chapter 3 gives a detailed description of the various assumptions made by the main earthing standards, and quantifies their discrepancies when assessing earthing systems. These variations are a result not only of the different approaches of calculating the maximum touch and step voltages but are also due to determination of the accidental circuit and adopted allowable body current. It is a concern that deterministic assessments could lead to conservative results and over-designing of the earthing system.

The probabilistic nature of many of these parameters has led to a gradual adoption of quantitative risk assessment in the electrical industry as a second stage assessment of the earthing systems following the application of the aforementioned deterministic criteria.

2.6 Probabilistic Risk Assessment of High Voltage Earthing Systems

Over the past few years, the electrical industry worldwide has started recognising the probabilistic nature of the exposure to earth potential rise and the effect of current on the human body. Significant research for the last twenty five years has taken place worldwide in order to develop procedures for calculating the risk of death associated with substations or other high voltage installations. These processes were developed either as a guide for the design of new earthing systems or as tools for the assessment of the already existing installations.

Such processes have recently started being employed by various transmission and distribution companies [2.27, 2.32-2.34], and the industry is looking for even more rigorous and comprehensive procedures for the assessment of their systems.

Figure 2.6 shows the integration of probabilistic risk assessment in earthing system design as a second stage assessment, as applied in industry. As can be seen, once the possible hazards have been identified, the maximum step and touch voltages representing the worst case scenario are being calculated.

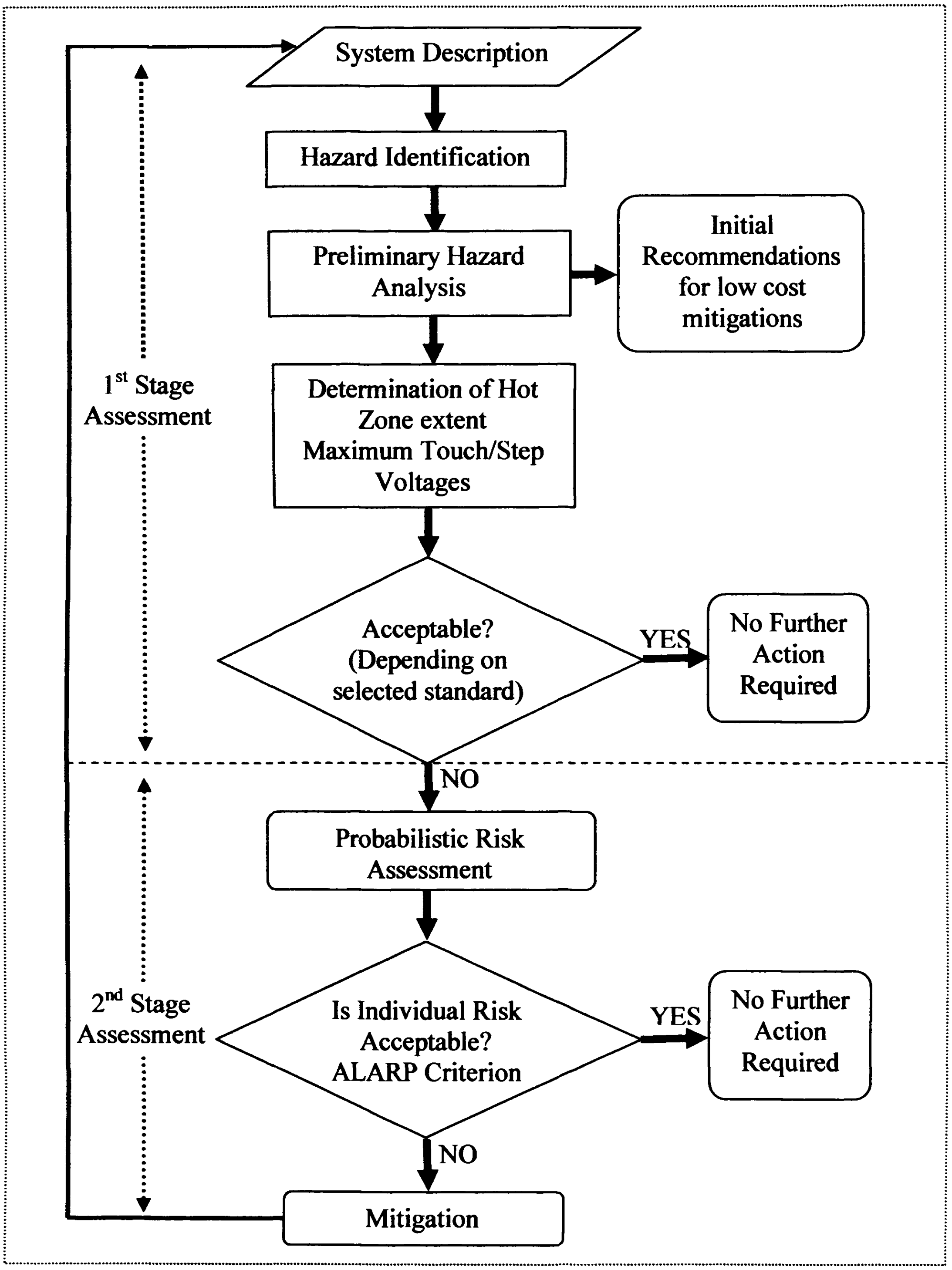


Figure 2.6: Integration of Probabilistic Risk Assessment as a second stage assessment of earthing system design.

Then, the obtained voltages are compared with the selected criteria and the first stage assessment is completed by deciding whether the levels of these voltages are acceptable or not. If the maximum touch and step voltages are below the predefined limits, the system is considered safe. If not, as seen in Section 2.3.4, the likelihood of the hazard materializing (i.e. probability of occurrence of an earth fault and rise of earth potential) and the likelihood of a person being present in a position that gets him/her exposed to a hazardous voltage (i.e. probability of presence) are taken under consideration [2.21]. If electrocution does occur, death is not certain but depending on the current magnitude that flows through the body and the shock duration, the probability of ventricular fibrillation can be deduced.

Therefore, the main principle for assessing the risk of death from electrocution or individual risk (IR) is to calculate the product of three probabilities:

$$IR = P_{EPR} \ x \ P_{Pr} \ x \ P_{VF} \tag{2.1}$$

With P_{EPR} : probability of earth potential rise, P_{Pr} : probability of presence and P_{VF} : probability of ventricular fibrillation. It should be emphasized, however, that there are several variations in calculating each of these terms, and depending on the approach followed, the focus maybe different on the modelled parameters since various assumptions can be made for their estimation based either on measurements, historical data or simulation. In this review, the working principles behind each approach are recalled and those that have gained acceptance in time are highlighted.

The approach followed in this investigation is to consider each of the three parameters separately and keep the same notation of the various probabilities so that it is easier to discuss and compare them.

2.6.1 Probability of EPR (P_{EPR})

The Probability of EPR is calculated from historical fault records kept by transmission companies. Although the historical data in most cases are not enough to estimate the fault frequency for a specific substation, national statistics give a good estimate of the expected faults throughout the year. It is worth mentioning that only 25% to 50% of the faults will result in significant current flow to or from the substation earth mat [2.27].

2.6.2 Probability of Presence (P_{Pr})

The Probability of Presence (P_{Pr}) is the likelihood of a person being in a position that exposes them to a hazardous voltage. Depending on whether touch or step voltage scenarios are investigated, the exposure will vary. In the first case, for touch voltages, the total time of a person coming in contact with a metallic structure over one year period can be estimated. In the case of step voltages, exposure can be estimated as the time that a person will be in a substation or outside where he/she can be exposed to EPR over the period of one year.

2.6.3 Probability of Ventricular Fibrillation (P_{VF})

As seen in Section 2.4.1, heart fibrillation is considered as the primary cause of death and, therefore, all earthing standards worldwide have based their limits of allowable body current on the maximum current that does not cause this heart condition. However, experimental work on livestock [2.35-2.37] has shown that the fibrillating current is not the same for all animals of the same species including humans, but there is a statistical variation.

Two standards, namely IEEE Standard 80 [2.18] and IEC 60479-1 [2.17], provide limits of allowable body current. IEEE Std-80 provides allowable body currents as a function of shock duration for:

- For body weight of 50 kg: $I_B = \dfrac{0.116}{\sqrt{t}}$ and (2.2)
- For body weight of 70 kg: $I_B = \dfrac{0.157}{\sqrt{t}}$ (2.3)

On the other hand, IEC 60479-1 proposes curves c_1, c_2 and c_3 given on Figure 2.4 which give body current against shock duration which correspond in 0%, 5% and 50%

probability of ventricular fibrillation respectively. Based on these two standards, various approaches have been developed.

2.6.4 Probabilistic Risk Assessment in Practice

A straightforward practice is to assume a fault clearance time (i.e. 200 ms) and then determine the maximum allowable step and touch voltages for that shock duration based on the selected IEEE equation or IEC curve for allowable body current. If this limit is exceeded, death from ventricular fibrillation is considered certain, hence, the probability of heart fibrillation is equal to one [2.32].

A probabilistic risk assessment of step and touch potentials near transmission line structures was published by El-Kady et al. [2.38-2.41]. The outline of the process consists of determining the applied voltage and the withstand voltage distributions.

A probabilistic fault analysis program is used to evaluate the tower potential rise in case of a fault. Once the locations of interest have been defined, the program using the Monte-Carlo simulation method calculates the probability distributions of line currents and voltages. The simulation process takes into consideration the random variations in the system generation, transmission operating conditions and the fault time, location and type. The analysis calculates the potential rise at the tower or towers of interest. Finally, the step and touch voltages are calculated either by modelling the tower and soil in the vicinity or by the use of empirical equations. For a number of simulations, the obtained voltages are used to generate the "*applied voltage*" distribution [2.38, 2.40, 2.41].

The next stage of this approach involves the generation of the "*withstand voltage*" distribution. The withstand voltages are calculated from IEEE St-80 electrocution equation $I_B = \frac{0.116}{\sqrt{t}}$, where I_B is the threshold current for ventricular fibrillation. Then, the withstand step and touch voltages can be calculated from:

$$V_{WS} = \frac{0.116(R_b + 2R_g)}{\sqrt{t}} \quad \text{and} \tag{2.4}$$

$$V_{WT} = \frac{0.116(R_b + 0.5R_g)}{\sqrt{t}} \tag{2.5}$$

A uniform distribution for a range of fault durations, t, from 0.03 s to 3 s is used to sample randomly possible shock durations. The body impedance, R_b, can be either of a single value (e.g. 1000 Ω) or can be voltage dependent, in which case the 5% curve of the IEC 60479-1 [2.17] is used. R_g corresponds to the foot to ground impedance which is proportional to soil resistivity and is given by $R_g = 3 \cdot \rho_s$. A single value can be provided for soil resistivity but it is suggested that if its statistical distribution for the area of interest is available, then it should be incorporated in the process. The withstand voltages calculated for the different values of the three contributing parameters are used to generate the "***withstand voltage***" distribution. The convolution of the withstand and the applied voltage distributions yields Probability of Ventricular Fibrillation.

The Probability of Presence is the probability that a ground fault occurs in the area under investigation and that a person is present at the time of fault. Here, it is assumed that the number of ground faults that occur during certain periods of time follows the Poisson distribution. Then, the probability of a ground fault over the period of one year, T, is found for number k of ground faults during the period T and λ the average frequency of ground faults per year. The period that a person is present in the selected area over a year is also estimated assuming that if he/she is present, he/she will be exposed. The Probability of Presence is calculated analytically [2.41] and then is multiplied to the Probability of Ventricular Fibrillation to obtain the overall risk [2.38-2.41].

Based on this work, Wang et al. [2.42-2.44] have worked on refining the equations corresponding to the fault clearance time, body impedance and foot to ground resistance. As before, the withstand voltage distribution was derived from IEEE std-80 equation of threshold current for ventricular fibrillation.

In 1992, building upon the previous concept and Wang's work, Sverak et al. [2.45] published an enhanced method for determining the total probability of a fatal accident. The main improvements concerned the introduction of the frequency and duration of ground faults and the frequency and duration of a man's presence in the hazardous area, as random variables. The frequency of a person's presence and the frequency of ground faults were assumed to follow Poisson's distribution law. The duration of presence was randomly selected from a time range, and the duration of fault was taken from system operational statistics. The joint probability that the random presence of someone in the exposure area will coincide with the occurrence of a ground fault is then solved analytically. For all the possible different visiting frequencies and corresponding durations as well as for all the probable number of faults and their durations, the overall probability of a person getting exposed over a period of a year is then calculated [2.45].

2.6.5 Different Approaches to Calculation of Ventricular Fibrillation

The previous approaches do not implement the probabilistic nature of the effect of body current suggested by IEC 60479-1 since the generated withstand voltage distribution was based on the statistical variation of parameters such as the fault duration, body impedance and soil resistivity. An approach that takes into consideration this effect, and is currently adopted by some UK electricity utilities [2.21, 2.33] is presented in the following flowchart.

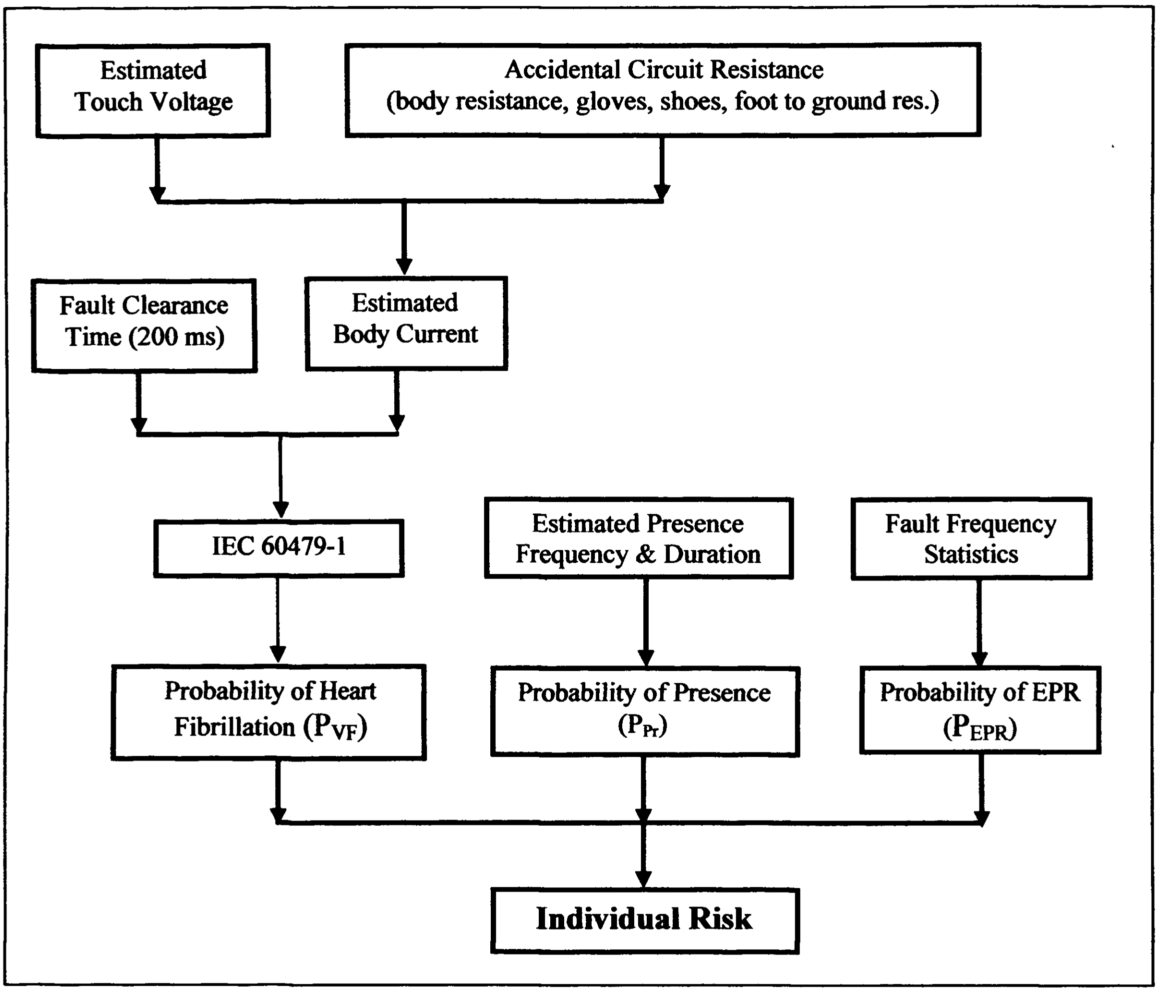


Figure 2.7: Risk Assessment Process followed in the UK.

Initially, for the estimation of Probability of Ventricular Fibrillation, the worst case scenario conditions are assumed which would result in a maximum touch/step voltage. Then, by using single values for body resistance (i.e. 1000 Ω), footwear resistance (i.e. 4000 kΩ per shoe) and soil resistivity, the maximum current that will flow through the human body is calculated. For a fault clearance time of 200 ms, the Probability of VF (P_{VF}) is determined using the three curves c_1, c_2 and c_3 of Figure 2.4, and applying a simplified **stepwise model** approach. This condition, is described by a point falling between curves c_2 and c_3 meaning that the Probability of VF is more than 5% but less than 50%. The stepwise model errs on the safe side, and a 50% value of P_{VF} is selected.

If a current-time point falls to the left of the c_1 safety curve, then P_{VF} is considered to be zero. However, if it is above the c_3 curve and the 50% value, then the probability of VF is considered to be one [2.21, 2.33]. The Probability of Exposure and the Probability of EPR are calculated as described in Paragraphs 2.6.1 and 2.6.2

A similar methodology for calculating the probability of VF is suggested by Raafat [2.27], with the difference that the IEC curves of body current against time are converted to touch/step voltage against time curves. Then, the voltage exposure is estimated by assuming a worst case scenario and the band on which the probability of VF lies is found for a given shock duration [2.27].

A different approach for calculating the fibrillation probability is suggested by Nahman [2.46-2.48]. Curve c_3 which corresponds to the 50% percentile is approximated by the following equations,

$$I_{F50} = \begin{cases} 1.6\ \text{A} & \text{for} \quad t \leq 0.1\ \text{s} & (2.6) \\ 0.16/t\ \text{A} & \text{for} \quad 0.1\ \text{s} \leq t \leq 2\ \text{s} & (2.7) \\ 0.08\ \text{A} & \text{for} \quad t \geq 2\ \text{s} & (2.8) \end{cases}$$

where t is the shock duration. A lognormal probability density function for the fibrillating current is assumed with: $I_F = I_{F50} \cdot 10^{1.176RN}$ (2.9)

The coefficient 1.176 in Equation (2.9) is the standard deviation of the probability distribution of $\log(I_F/I_{F50})$ and was obtained from the IEC curves including the 95% percentile curve [2.49]. RN is a normally distributed random number with zero mean and a unity standard deviation. For every random number RN, a different fibrillating current is produced which later is compared to an applied body current to determine whether fibrillation occurs.

If the applied body current is higher or equal to the fibrillating current, then depending on the shock duration which is also randomly selected, there are two cases.

$$P_{(VF)} = \begin{cases} 0.2 \quad \text{for} \quad t \leq HC/3 & (2.10) \\ 1 \quad \text{for} \quad t > HC/3 & (2.11) \end{cases}$$

where HC is the heart cycle, estimated at 0.6 s for a heart rate of 100 per minute. This is based on the assumption that for every short shock duration, even with high current, ventricular fibrillation will not occur unless the shock occurs within the vulnerable period of the heart cycle.

Moreover, we need to note that in the approximate equation of the fibrillating current $I_F = I_{F50} \cdot 10^{1.176RN}$, it is assumed that the standard deviation remains constant for any shock duration. This is discussed further in Section 4.3 where the development of the probability surface of ventricular fibrillation is described, and an alternative approach with the advantage of providing more accurate probability values is proposed.

A comprehensive process was suggested by Carman [2.50-2.52] who used IEC curves to build triangular distributions based upon the 5%, 50% and 95% percentiles for random shock durations. The shock durations are sampled from a uniform distribution across a range of selected times. Then, the generated triangular distributions were randomly sampled. Furthermore, considering the voltage dependency of the body impedance, the sampled fibrillating currents are used to develop a "withstand voltage" distribution.

Carman also took into consideration the different locations that a fault may occur at, for example on a transmission line, producing for each case a different fault current and hence a different earth potential rise. For any given EPR, a maximum and minimum touch voltages that may appear in a substation were deduced, and these values were used to generate uniform distributions which are then randomly sampled. All the sampled values of possible touch voltages form the "applied voltage" distribution. The probability of ventricular fibrillation was then derived from the convolution of the applied and withstand probability functions [2.50-2.53].

2.7 Acceptable Levels of Risk

Once the level of risk has been calculated through a quantitative risk assessment, it is assessed against criteria to determine whether the risk is acceptable, and if not, to decide the degree of mitigation that is required.

There is a distinction between tolerable risk and acceptable risk according to HSE publication "Tolerability of Risk from Nuclear Stations" [2.54] "Tolerability does not mean acceptability". Tolerable risk means that the risk is not regarded as negligible and is not ignored but is kept under review and is further reduced if practicable. In other words, tolerability refers to a certain degree of risk that is considered to be acceptable in order to secure some benefits, while at the same time being confident that it is properly controlled. Therefore, if a risk is characterized as tolerable, it should be reduced to a level that is "As Low As Reasonably Practicable" or ALARP. The concept of ALARP was initially introduced in 1992 for safety in nuclear stations [2.54] but now finds application more generally [2.6].

On the other hand, if a risk is acceptable it means that the risk level is low enough not to require any further reduction and it is acceptable as it is. However, reviewing on a regular basis may be required to make certain that the risk remains to the same level [2.21, 2.55]. The framework for the tolerability of risk according to the HSE is shown in Figure 2.8.

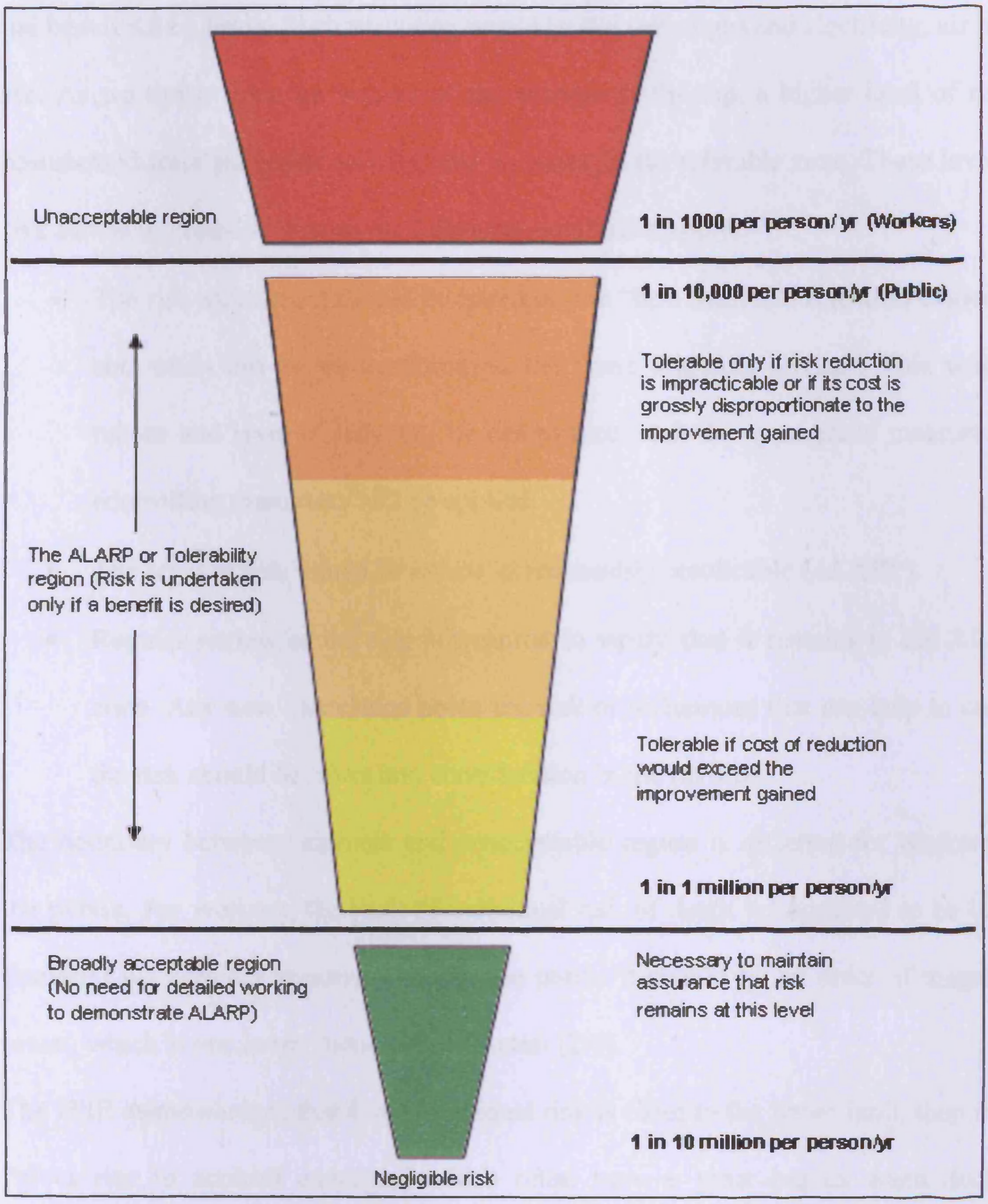


Figure 2.8: HSE framework for the tolerability of risk [2.6].

The green zone represents the broadly acceptable area of individual risk and HSE sets the boundary between the acceptable and tolerable areas to be one in a million per annum for both workers and the public. The levels of risk represented in this region are described as "insignificant and trivial" compared to the risks that people take in their daily activities. Indeed, studies have shown that people involve themselves daily in activities which bear much higher risks and they are prepared to accept them because of the benefits they bring. Such activities would be the use of gas and electricity, air travel etc. As we move from the bottom of the triangle to the top, a higher level of risk is represented for a particular activity, and we enter in the tolerable zone. These levels of risk can be tolerated as long as the following conditions apply:

- The risk assessment should be based on the "best available scientific evidence", and when this is not available on the "best scientific advice". This way the nature and level of risk will be determined, and the appropriate measures for controlling these risks will be applied.
- The level of risk should be as low as reasonably practicable (ALARP).
- Regular review of the risk is required to verify that it remains in the ALARP zone. Any new knowledge about the risk or techniques that can help to control the risk should be taken into consideration in the reviews.

The boundary between tolerable and unacceptable region is different for workers and the public. For workers, the limit of individual risk of death is suggested to be one in thousand workers per annum, while for the public it should be an order of magnitude lower, which is one in ten thousand per annum [2.6].

The HSE acknowledges that if the individual risk is close to the upper limit, then it also "gives rise to societal concerns" which often have a great impact when deciding whether a risk is tolerable or not [2.6].

It should be noted that British industry, generally, manages to control risks well below those limits and often they set the limits of upper tolerability of risk to even lower levels. For example British Rail in their safety plan in 1992, set the upper tolerability risk limit for employees as one in ten thousand per annum while for passengers the upper limit is one in hundred thousand [2.34].

The red zone is the unacceptable region regardless of the benefits gained by the practice of the hazardous activity. Therefore, any activities or practices that are of such high risk should be excluded from any working process unless changes can be applied in order to reduce the level of risk to tolerable or acceptable levels [2.6].

The HSE criteria find great application in the UK electricity industry as evidenced in several risk assessment reports obtained from the utilities. The calculated risk of death from electrocution is assessed against these criteria in order to base their decision making for further mitigation or not [2.27, 2.33, 2.34]. Also, the Energy Networks Association follows the same practice, as set out in documents assessing risk for BT operators working in EPR zone and for third parties using equipment connected to BT lines [2.56, 2.57].

2.8 Mitigation in Power Systems

If the risk assessment process has shown that the risk is unacceptable, steps need to be taken to control those risks. The measures taken to reduce the risk are called mitigation. In power systems, there are several ways that the standards suggest in order to deal with hazardous touch and step voltages.

If the impedance of the earth grid is too high, the grid can be interconnected with other grids. Another way to reduce the overall earth impedance is the use of extended earthing systems formed by tower lines and cables and connected to the main grid. It is also suggested that for a substation placed in an area of high soil resistivity, a satellite grid in a nearby low resistivity area can be connected. However, this may result in exporting the earth potential rise to a greater distance away making it harder to control presence and exposure of the public. Enhancement of an existing grid may also be achieved by installing deep-driven earth rods or piles or drilled earth wells. This practice is beneficial for penetrating deeper earth layers of low and stable resistivity [2.21].

The chemical treatment of the soil is another way to reduce the soil resistivity and mainly the treatment is applied to the soil surrounding the earth electrodes. Usually, the use of salts is preferred which, however, requires regular maintenance because the applied salts can be washed away by the rain. Other chemicals that may be used are Magnesium Sulphate and Calcium Sulphate. Because of the corrosion effects that some substances may have on the earth electrodes, it is suggested that the treatment is applied only when no alternative option exists and there is the need for immediate mitigation [2.21, 2.32].

Apart from trying to reduce the overall impedance of the earthing system, various practices are utilized in order to increase the resistance of the accidental path so that a smaller current passes through the human body. The most common method of achieving this is through the application of a layer of gravel on the surface of the substation. This provides a high resistance barrier even under wet conditions although the thickness of the layer can be compromised by vehicles traveling or poor practice, so yet again maintenance is a major issue [2.21, 2.32]. Additional series resistances such as gloves or special boots can have significant effects on the tolerability of touch and step voltages, and various standards take them into consideration when calculating allowable voltages [2.20, 2.22, 2.31, 2.58].

In Section 2.4.3, it was noted that ventricular fibrillation depends not only on current magnitude but also on the shock duration. The fault clearance time that is assumed to be equal to the shock duration varies depending on the kind of fault, the magnitude of return current and the circuit breaker. Technological advances in breakers have resulted in shorter clearance times, therefore, fast-operating circuit breaker may be installed in a substation especially if there is a great need to control the risk.

In cases where there is a proven hazardous voltage at a specific location in the substation or at a tower base, access can be prevented by the use of fences, and signs are erected to warn the public or worker of the potential hazards. Finally, at locations which are frequently visited, it is possible to provide insulation to earthing downleads or any other exposed metalwork and reduce the possibility of electrocution [2.21].

2.9 Conclusions

In this chapter, an extensive literature review on risk and the various approaches of probabilistic risk assessment was carried out. First, the regulatory framework upon which the risk assessment is based on was investigated, and it was shown that probabilistic risk assessment in power systems is currently integrated as a second stage assessment of the earthing system design and is calculated by the product of three probabilities; probability of earth potential rise (P_{EPR}), probability of the presence of a person in a position that exposes them to a hazardous voltage (P_{Pr}) and probability of ventricular fibrillation (P_{VF}).

Ventricular fibrillation is the primary cause of death following electrocution, and zones of allowable body current against shock duration were produced, based on statistical results from animal experiments. In various approaches of risk assessment studied in this review, it was found that these zones are usually used to deduce threshold currents for given shock durations or estimate the probability of death from an electric shock. However, it is evident that a more rigorous approach is required for the more accurate calculation of the probability of ventricular fibrillation. Moreover, it was shown that the various parameters concerning the accidental circuit (e.g. body resistance) or the protection system (e.g. fault clearance time, fault current etc) were treated deterministically usually assuming a worst case scenario.

In this work, further investigations supported by studies of historical fault data have allowed to develop the proposed probabilistic risk assessment method.

CHAPTER 3. AN APPRAISAL OF STANDARD RECOMMENDATIONS FOR SAFETY CRITERIA ON ELECTRICAL EARTHING SYSTEMS

3.1 Introduction

Various standard recommendations are currently implemented around the world, providing guidelines for the design and testing of electrical earthing systems. IEEE 80 (2000) [3.1] is widely used in USA and other countries. BS 7354 (1990) [3.2] and EA-TS 41-24 (1992) [3.3], a British Electricity Association Standard, are in use in the UK. ITU-T K.33 (1996) [3.4] is published by the International Telecommunication Union and the CENELEC HD 637 S1 (1999) [3.5] standard comes from the European Committee of Electrotechnical Standardization.

Previous studies have shown that, due to different assumptions used for calculating the various parameters of a given earthing grid, there are substantial differences between the recommended values of tolerable voltages and, consequently, of the safety-limits that are applicable for an earth grid. The initial studies carried out by the author and other investigators [3.6-3.10] have established, through calculation of the generated potentials following an earth fault, that the above standards recommendations do not compare very well.

Safety is evaluated using the tolerable current values for human bodies [3.11, 3.12] and an equivalent circuit for various electrocution scenarios having a source voltage due to potentials generated from fault current flow through the earthing system.

The calculation of generated voltages on the earthing system and its vicinity relies either on simplified analytical approaches or computer simulation [3.13]. However, significant differences may also arise between these calculations depending on the approach used.

The main differences lie within the assumptions made for the accidental circuit and the definition of "touch" voltage.

In this section, the accidental circuit will be analysed according to each of the main standards, as well as the equations providing the maximum and withstand voltages. The main assumptions made by each standard will be examined in order to gain a full understanding of the results taken from the parametric analysis that will follow and the development of safety-limit surfaces.

3.2 American Standard: IEEE std- 80

3.2.1 Safety Voltage Definitions

According to the American standard IEEE std-80 [3.1], the following definitions are applicable:

- Mesh voltage: The maximum touch voltage within a mesh of a ground grid
- Touch voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.
- Step voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object.
- Transferred voltage: A special case of the touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site.

3.2.2 Calculation of maximum mesh and step voltages

The IEEE 80 Standard [3.1] provides equations for determining the design parameters and calculating the values of both touch and step voltages. In deriving these equations, it was assumed that the earth grid is of rectangular shape, equally spaced and buried at depth h in a homogenous soil of constant resistivity. The grid can consist of n parallel conductors all of them assumed to be of diameter d each, spaced D meters apart, and of an undetermined number of connections.

The following equation determines the value of a mesh voltage on the ground surface above the centre of a corner mesh,

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \tag{3.1}$$

where

E_m is the mesh voltage in V,

ρ is the average soil resistivity in Ωm

I_G is the maximum rms current flowing from ground grid to earth

L_M is the total length of buried conductors, including cross connections and the combined length of ground rods in m,

K_m is the spacing factor for mesh voltage,

and K_i is the corrective factor for current irregularity.

The relationship between E_m and K_m depends largely on the current density in the perimeter conductors versus the current density in the inner conductors with K_m provided from the following equation.

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d} \right] + \frac{K_{ii}}{K_h} \cdot \ln\left[\frac{8}{\pi(2 \cdot n - 1)} \right] \right] \tag{3.2}$$

With K_{ii} and K_h being further correcting terms. In order to determine the worst case for step voltage, the following equation is provided.

$$E_s = \frac{\rho \cdot I_G \cdot K_s \cdot K_i}{L_s} \tag{3.3}$$

where

E_s is the step voltage in V,

L_S is the total length of buried conductors, including cross connections, and the total effective length of ground rods in m, and

K_s is the mesh factor defined for n parallel conductors and is determined from the following equation.

$$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \tag{3.4}$$

The standard states that "the maximum step voltage is assumed to occur over a distance of 1 m, beginning at and extending outside of the perimeter conductor at the angle bisecting the most extreme corner of the grid" [3.1]. For the calculation of K_s, the grid is assumed to be buried at depths of $0.25\text{m}<h<2.5\text{m}$.

3.2.3 Accidental circuit

The accidental circuit for a touch voltage scenario according to the IEEE 80 American practice is shown in Figure 3.1. A 1000 Ω body resistance (R_B) is assumed, which represents the resistance of a human body from hand-to-feet and also from hand-to hand, or from one foot to the other foot [3.1]. The human foot is represented as a conducting metallic disc of radius b (m). Its ground resistance in ohms on the surface of a homogeneous earth of resistivity ρ $(\Omega \cdot m)$ is given by Laurent [3.14].

$$R_f = \frac{\rho}{4b} \tag{3.5}$$

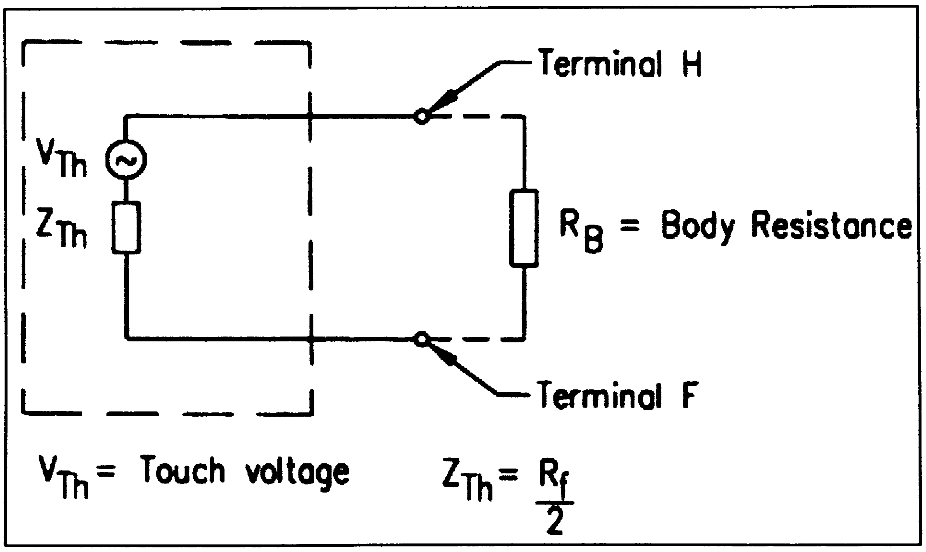


Figure 3.1: Touch voltage circuit [3.1].

According to IEEE 80, this metallic disc is considered to be of 0.08 m radius. The equations the equivalent Thevenin impedance (Z_{Th}) are then given by:

For touch voltage accidental circuit: $Z_{Th} = 1.5\rho$ (3.6)

For step voltage accidental circuit: $Z_{Th} = 6\rho$ (3.7)

In order to account for the effect of a surface layer ρ_s in a substation (usually high resistivity crashed rock layer), a corrective factor C_s is introduced in the computation of the foot resistance. If no protective surface layer is used then, $C_s = 1$ and $\rho_s = \rho$. The consideration of higher C_s values in the latest version of IEEE std-80 has lead to higher values of foot resistances and, consequently, higher tolerable step and touch voltages [3.15].

Any other additional resistances in series with the body resistance such as hand and foot contact resistances and glove and shoe resistances are ignored. The American standard acknowledges that the above equations are "conservative in the sense that they underestimate the Thevenin equivalent impedance and, therefore, will result in higher body currents" [3.16-3.18]. In this investigation, a parametric analysis was carried out to determine to what extent the permissible voltages are affected by additional resistances and hence, develop better understanding of the safety criteria.

Therefore, the permissible total equivalent voltages are:

For touch voltage equivalent circuit: $E_{touch} = I_B(R_B + 1.5\rho)$ (3.8)

For step voltage equivalent circuit: $E_{step} = I_B(R_B + 6\rho)$ (3.9)

3.3 The UK Practice: BS 7354

3.3.1 Safety Voltage Definitions

In the BS 7354 [3.2], touch voltage is defined as "the sum of the voltage across 1 m of surface along a diagonal outside the corner of a grid with the voltage difference of the grid with the ground surface above. The corners are where the maximum voltage gradients occur". It is acknowledged that IEEE std-80 uses the mesh voltage as the touch voltage and, thus, the two practices correspond to step voltage but not for touch voltage. The step voltage is defined as "the voltage over 1 m of surface diagonally outwards from a corner of a grid".

3.3.2 Calculation of touch and step voltages

The maximum predicted touch and step voltages are given as:

- $$V_T = \frac{\rho V}{\pi RL}\left\{\ln\left(\frac{h}{d}\right)^{0.5} + \left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1-0.5^{n-2}}{D}\right)\right\}K_i \qquad (3.10)$$

And

- $$V_S = \frac{\rho V}{\pi RL}\left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1-0.5^{n-2}}{D}\right)K_i \qquad (3.11)$$

where h is the grid depth, d is the diameter of the conductors, L is the total length of the conductors and the rods, D is the spacing of the conductors and n the number of the parallel conductors.

The corrective factor K_i is slightly different from the one used in IEEE std-80 and is given by: $K_i = (0.15n + 0.7)$ (3.12)

3.3.3 Accidental circuit

According to BS 7354 [3.2], the accidental circuit can be described using the following figure.

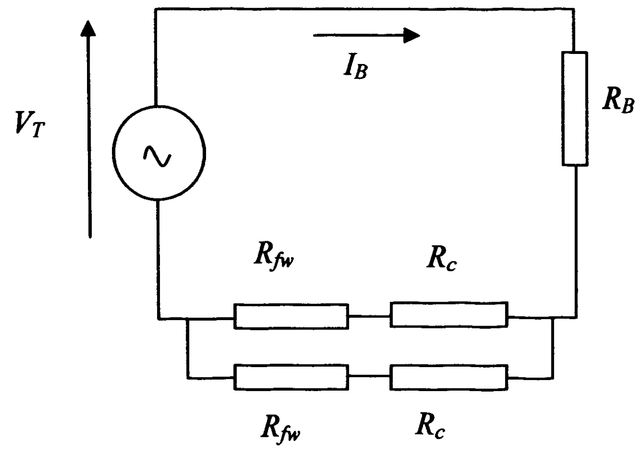


Figure 3.2: Touch voltage circuit.

Similar to IEEE std-80, BS 7354 assumes a 1000 Ω body resistance (R_B). However, it also takes into account the footwear resistance (R_{fw}) using a value of 4000 Ω per foot, and as can be seen in Figure 3.2, the so-called 'contact resistance' (R_c) at the surface of the ground is also included with a value of 3ρ per foot.

Therefore, the permissible voltages are:

For touch voltage equivalent circuit: $V_t = I_t\left\{R_B + \frac{(R_{fw} + R_c)}{2}\right\}$ (3.13)

For step voltage equivalent circuit: $V_s = I_t\{R_B + 2(R_{fw} + R_c)\}$ (3.14)

The allowable body current I_t here is taken from curve c_2 of Figure 20 of IEC 479-1 [3.12] corresponding to 5% probability of ventricular fibrillation.

3.4 CENELEC Standard HD 637 S1

3.4.1 Safety Voltage Definitions

The European Committee for Electrotechnical Standardization (CENELEC) [3.5], in an attempt to create a harmonized standard in support of European legislation and provide a more complete approach of the earthing problem, has introduced the concept of the "prospective touch voltage" and a more analytic accidental circuit.

- Touch voltage (V_T): The part of the earth potential rise due to an earth fault which can be picked up by a person, assuming that the current is flowing via the human body from hand to feet.
- Source voltage for touching (V_{ST}) ("prospective touch voltage"): The voltage which appears during an earth fault between conductive parts and earth when these parts are not being touched (source voltage).
- Step voltage (V_S): The part of the earth potential rise due to an earth fault which can be picked up by a person with a step-width of 1 m, assuming that the current is flowing via the human body from foot to foot.

3.4.2 Accidental circuit

CENELEC standard recognizes that the body impedance depends on the touch voltages and the current path. The body impedance values for current paths of hand to hand or hand to foot are taken from the IEC 60479-1 standard [3.12] where the values of 50% confidence level are used. Moreover, a correction factor is introduced in order to care for the different current paths i.e. 0.75 for hand to feet current. As can be seen in

Figure 3.3, the standard utilises additional resistances $R_a = R_{a1} + R_{a2}$, where R_{a1} is the resistance of the footwear (equal to 1 $k\Omega$) and R_{a2} the resistance to earth of the standing point.

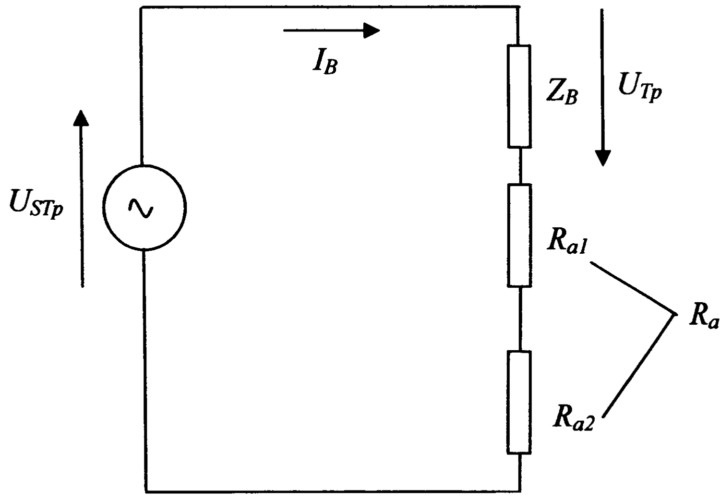


Figure 3.3: Accidental circuit for touch voltage [3.5].

U_{STp} is the "voltage difference acting as a source voltage in the touching circuit with a limited value that guarantees the safety of a person when using additional known resistances" [3.5]. When no additional resistances are taken into account, U_{STp} is equal to U_{Tp}.

The maximum permissible voltage is calculated through an iterative process described by:

$$U_{STp}(t_F) = U_{Tp}(t_F) + (R_{a1} + R_{a2})I_B \qquad (3.15)$$

where t_F is the fault duration and I_B the current flowing through the human body obtained from curve c_2 of Figure 20 in IEC 60479-1 [3.12].

3.5 EA-TS 41-24:1992

The Electrical Association in 1992 produced a Technical Specification (EA-TS 41-24) [3.3] which is used by the electricity industry in the UK.

3.5.1 Calculation of maximum predicted voltages

For the calculation of maximum voltages, EA-TS 41-24 provides equations which are based on "the recognised concept of integrating the voltage gradient, given by the product of soil resistivity and current density through the soil, over a distance of one metre" [3.3]. It is very important to be able to calculate the touch voltages on the fence surrounding a substation since fences can easily be accessed by the public. The equations are very similar to those provided by IEEE std-80, and they also consider the case where the fence is separately earthed and bonded [3.3]. So, for substations with a separately earthed fence and normal buried grid depths, the external touch potential at the edge of the grid is given by:

$$E_{t(grid)} = \frac{k_e \cdot k_d \cdot \rho \cdot I}{L} \tag{3.16}$$

where k_e is a factor which accounts for the effect of a uniformly distributed electrode current over the grid, and k_d is a factor which modifies k_e to consider the non-uniform distribution of electrode current. The external touch potential at the fence is given by:

$$E_{t(fence)} = \frac{k_f \cdot k_d \cdot \rho \cdot I}{L} \tag{3.17}$$

where $k_f = 0.26k_e$

When the fence is bonded to the earth grid system, the external touch potential at the fence $E_{t(fence)}$ without an external peripheral electrode is the same as the $E_{t(grid)}$ in (3.16). In the case where the external buried peripheral conductor is 1 metre away from the fence, then $E_{t(fence)}$ is given by:

$$E_{t(fence)} = \frac{k_{fe} \cdot k_d \cdot \rho \cdot I}{L} \tag{3.18}$$

where k_{fe}, k_d, k_e and k_f are factors that depends on grid geometry, and L is the total length of the conductors and rods.

3.5.2 Accidental circuit

The accidental circuit in EA-TS 41-24 is similar to that in BS 7354 since it utilises a constant body resistance of 1 $k\Omega$ and footwear resistance of 4 $k\Omega$ per shoe. In the case of a surface of chippings (typically 150 mm of thickness), another 2 $k\Omega$ per shoe is added. Moreover, the standard provides curves of statistically safe step and touch voltages based on curve c_1 of IEC 60479-1. It is interesting to mention that, of the standards making use the IEC 60479 curves to determine allowable touch and step voltages, EA-TS 41-24 is the only one that uses curve c_1.

3.6 Derivation of safety-limit curves

As was seen in previous sections, IEEE 80, EA-TS 41-24 and BS 7354 provide equations to calculate maximum predicted voltages as well as equations or guidelines for the calculation of tolerable step and touch voltages. For each case, these equations were used for the calculation of the maximum tolerable magnitude of fault current, and hence deducing the recently suggested [3.1] safety limit-curves for the standards considered in this study.

3.6.1 Derivation of safety-limit curves for IEEE std 80

The maximum allowable grid current that generates touch voltage magnitudes that are within the tolerable limits for a person weighing 50 kg is obtained by combining Equations (3.1) and (3.8):

$$\frac{\rho \cdot I_G touch_{50} \cdot K_m \cdot K_i}{L_M} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t_s}} \tag{3.19}$$

which gives

$$I_G touch_{50} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t_s}} \left(\frac{L_M}{\rho \cdot K_m \cdot K_i} \right) \quad (3.20)$$

Similarly, the maximum allowable grid current that generates safe touch voltages for a 70 kg person is given by the following:

$$I_G touch_{70} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.157}{\sqrt{t_s}} \left(\frac{L_M}{\rho \cdot K_m \cdot K_i} \right) \quad (3.21)$$

Using the same approach for the evaluation of step voltages, it can be shown that the maximum allowable grid currents for persons having 50 kg and 70 kg body weights are respectively:

$$I_G step_{50} = (1000 + 6 \cdot C_S \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t_s}} \left(\frac{L_S}{\rho \cdot K_s \cdot K_i} \right) \quad (3.22)$$

$$I_G step_{70} = (1000 + 6 \cdot C_S \cdot \rho_s) \cdot \frac{0.157}{\sqrt{t_s}} \left(\frac{L_S}{\rho \cdot K_s \cdot K_i} \right) \quad (3.23)$$

3.6.2 Derivation of safety-limit curves for BS 73-54

Following the procedure described in the previous section, it can be shown that the maximum allowable grid current that generates safe levels of touch voltages is given by:

$$I_G touch = \left(1.027 \cdot e^{\frac{-t}{0.282}} + 0.051 \cdot e^{\frac{1}{t + 1.766 \cdot 10^{90}}} \right) \left(R_b + \frac{R_F}{2} + \frac{R_C}{2} \right) \cdot \left(\frac{\pi \cdot L_C}{\left(\left(\ln \left(\frac{h}{d} \right)^{0.5} + \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1 - 0.5^{n-2}}{D} \right] \right) \cdot K_i \cdot \rho \right)} \right)$$

(3.24)

and the corresponding step voltage equation is given by:

$$I_G step = \left(1.027 \cdot e^{\frac{-t}{0.282}} + 0.051 \cdot e^{\frac{1}{t + 1.766 \cdot 10^{90}}} \right) (R_b + 2R_F + 2R_C) \cdot \left(\frac{\pi \cdot L_C}{\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1 - 0.5^{n-2}}{D} \right] \cdot K_i \cdot p} \right) \quad (3.25)$$

3.6.3 Derivation of safety-limit curves for EA-TS 41-24

As shown previously, combining the generated voltages arising under earth fault current with the tolerable levels, as determined from the tolerable current curve, allows the safety-limit-curves to be derived. In this investigation, the following equations were derived:

(a) Grid current for allowable external touch potential at the edge of the electrode:

$$I_G touch1 = (0.501 \cdot e^{\frac{-t}{0.286}} + 0.039 \cdot e^{\frac{1}{t+2.657 \cdot 10^{115}}})(3000 + 1.5\rho_{eff})\frac{L}{k_e k_d \rho} \tag{3.26}$$

(b) Grid current for allowable external touch potential at the fence:

$$I_G touch2 = (0.501 \cdot e^{\frac{-t}{0.286}} + 0.039 \cdot e^{\frac{1}{t+2.657 \cdot 10^{115}}})(3000 + 1.5\rho_{eff})\frac{L}{k_f k_d \rho} \tag{3.27}$$

(c) Grid current for allowable external touch potential at fence with no external buried peripheral electrode:

$$I_G touch3 = (0.501 \cdot e^{\frac{-t}{0.286}} + 0.039 \cdot e^{\frac{1}{t+2.657 \cdot 10^{115}}})(3000 + 1.5\rho_{eff})\frac{L}{k_e k_d \rho} \tag{3.28}$$

(d) Grid current for allowable external touch potential at fence with external buried peripheral conductor 1 metre away from the fence:

$$I_G touch4 = (0.501 \cdot e^{\frac{-t}{0.286}} + 0.039 \cdot e^{\frac{1}{t+2.657 \cdot 10^{115}}})(3000 + 1.5\rho_{eff})\frac{L}{k_{fe} k_d \rho} \tag{3.29}$$

3.7 Parametric analysis of safety-limit surfaces

3.7.1 Previous work

Previous work [3.6] resulted in the establishment of worst-case safety-limit curves, to allow better comparison between the standards. Significant differences in the safety limit-curves based on the different standards were obtained. The differences were attributed to a combination of factors: (i) difference in assumed tolerable body current; (ii) differences in the parameters of the electrocution circuit; (iii) differences in the predicted touch voltage; and (iv) differences in the assumed worst-case shock location. However, the initial studies were limited to considering a generic 100x100m earth grid and only two values of earth resistivity 100Ωm and 1000Ωm.

The above work has been extended in this chapter by developing a fully computerised process for the determination of the safety-limits for grids of different size and design in terms of the maximum allowable fault current for a given fault duration. A full parametric variation of earth resistivity body resistance, grid size and mesh density was undertaken. The computations allow the construction of safety-limit surfaces, which are the threshold surfaces of maximum permissible fault current magnitude and duration, for the earthing parameter under consideration.

3.7.2 Effect of earth resistivity

Figure 3.4 shows the safety limit-surface for earth resistivity ranging from 100Ωm to 1000Ωm. A 100-mesh grid was used in this case with dimensions of 100mx100m. The green surface corresponds to '50 kg' touch voltage limit in IEEE 80, which is the most conservative case for nearly any earth resistivity. The red and yellow surfaces (top and middle surfaces) correspond to touch voltages limits in BS 7354 and EA-TS 41-24 respectively.

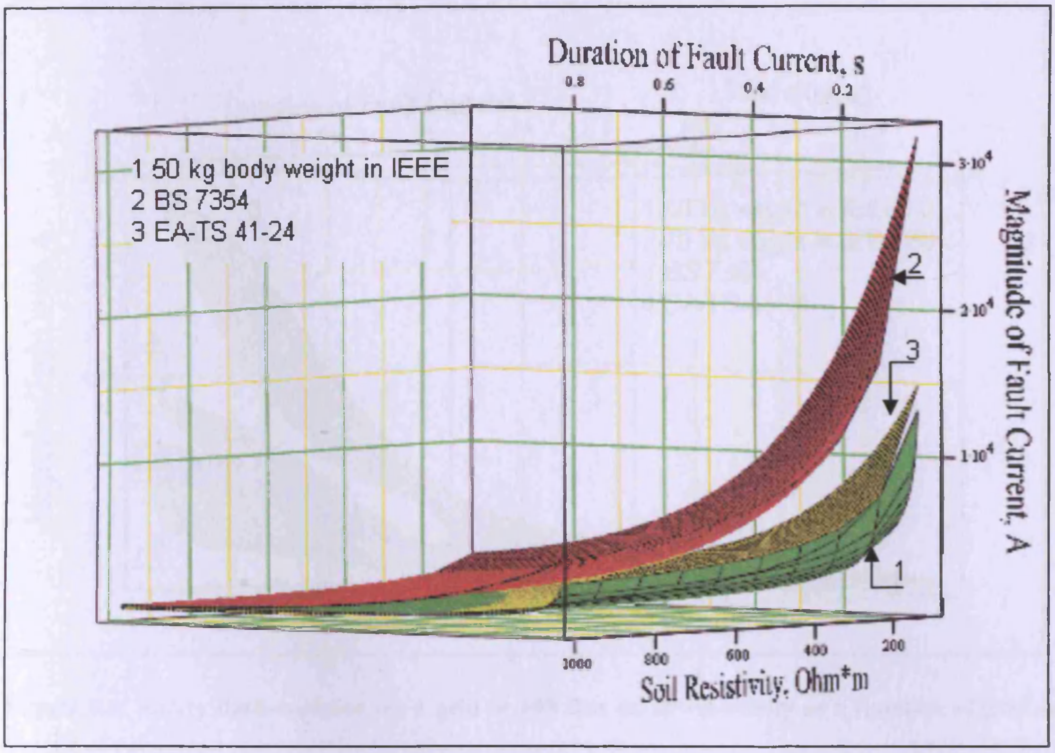


Figure 3.4: Safety limit-surfaces for 100x100m, 100-mesh grid as a function of earth resistivity.

3.7.3 Effect of grid size

The effect of changing grid area while keeping the number of meshes constant is shown in Figure 3.5. As can be seen, the allowable fault current magnitude increases with the grid area. The safety-limit surface for BS 7354 (red/top surface) is by far the least conservative case, followed by EA 41-24 (yellow/2nd from top surface) and, finally, blue and green (bottom) surfaces corresponding to IEEE 80 for 70kg and 50kg body weights respectively.

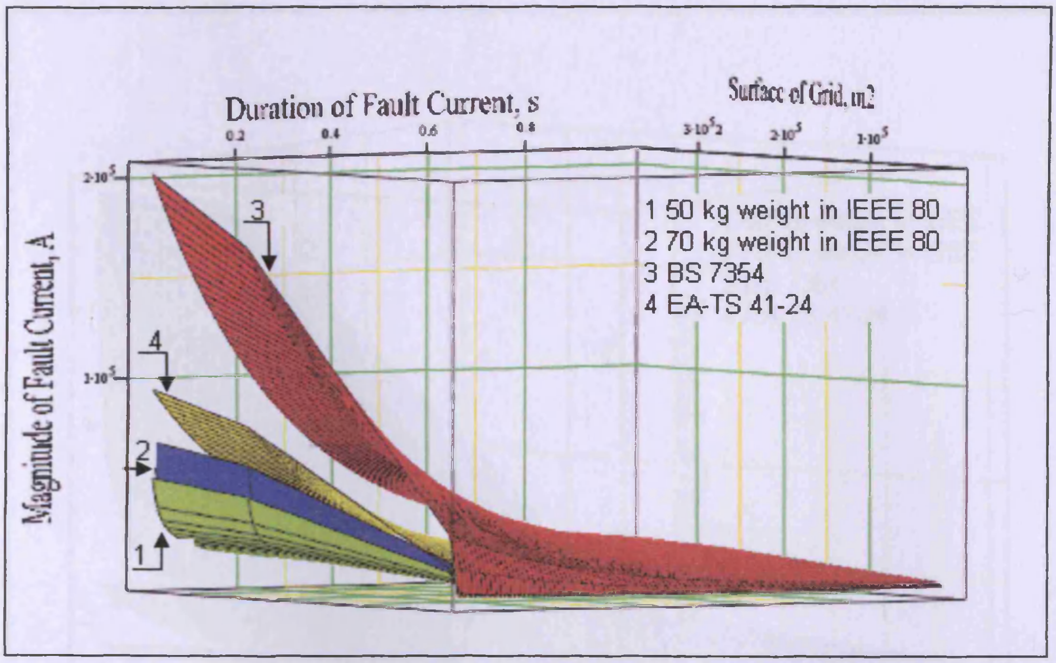


Figure 3.5: Safety limit-surfaces for a grid in 100 Ωm earth resistivity as a function of grid surface area.

3.7.4 Effect of mesh density

The influence of the number of earth grid meshes on the safety-limit surfaces is shown in Figure 3.6. The number of meshes was varied from 9 to 10,000 for the 100mx100m earth grid under investigation. From Figure 3.6, it can be seen that the safety limit-surfaces corresponding to IEEE 80 70kg and 50kg body weights (blue/top and green/near top surfaces respectively) intersect with the surface of BS 7354 (red/2nd from bottom surface) for particular parameter ranges. These ranges correspond to conditions of low mesh density which give high generated mesh voltages. This means that there is a range of possible scenarios for which BS 7354 is more conservative than IEEE 80 and vice versa.

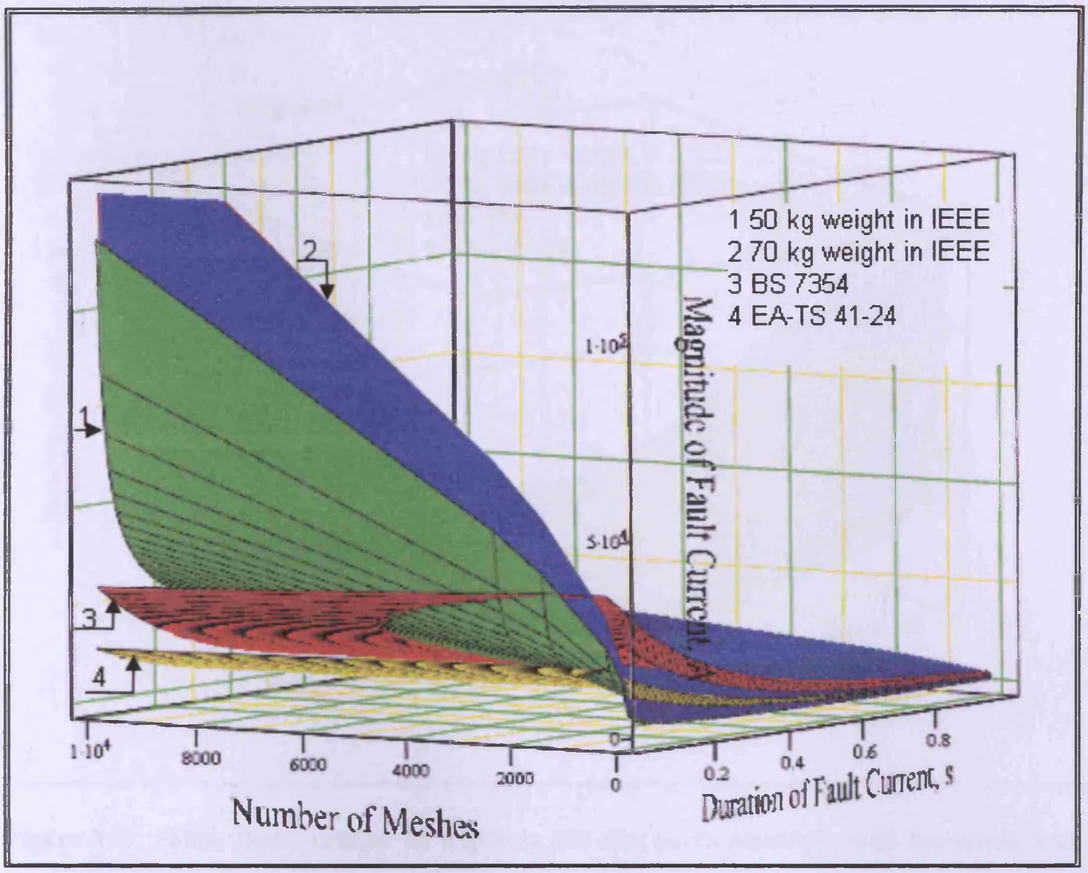


Figure 3.6: Safety limit-surfaces for a 100mx100m grid in 100 Ωm earth resistivity as a function of number of meshes.

3.7.5 Effect of increasing area with constant mesh density

In Figure 3.7, the effect of increasing grid area while keeping the mesh density constant is examined. For this case, the mesh density is maintained at 1mesh (square) per 25m^2, corresponding to a grid conductor spacing of 5m. This particular study reveals that as the size of the grid increases, the safety limit-surfaces of the different standards will overlap.

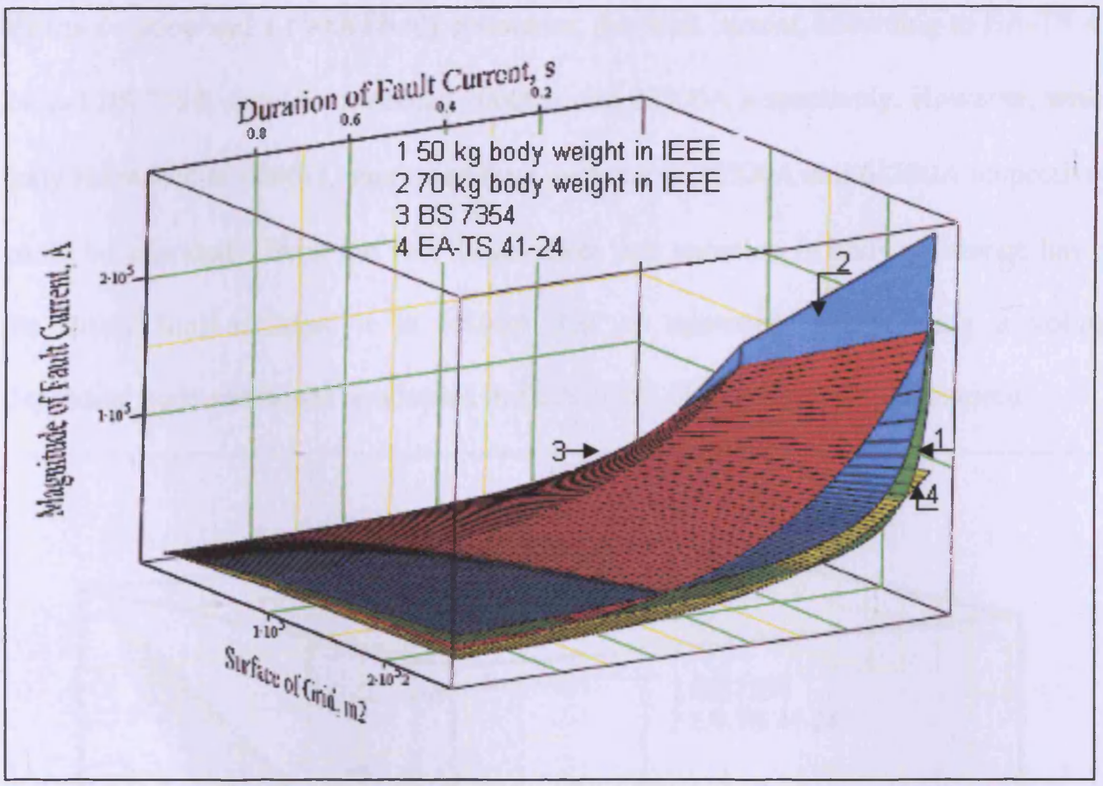


Figure 3.7: Safety limit-surfaces for a grid in 100 Ωm earth resistivity with increasing area and constant mesh density.

3.7.6 Effect of body resistance

The estimation of body resistance is an important factor for the calculation of the tolerable current, and is considered by some investigators [3.9] to be mainly dependent on body weight, current path, surface area of contact and the applied voltage. IEC standard IEC 479-1 [3.12] specifies body resistance as a function of applied voltage but with a statistical spread of values about a mean curve. Each of the standards considered in this study assumes a constant 1000Ω of body resistance without voltage dependence. However, it is useful to consider a variation in body resistance from 500Ω to 6kΩ which would represent well the practical extent of statistical variation.

Figure 3.8 shows the values of maximum magnitude of fault current for both BS 7354 and EA-TS 41-24 as calculated for variable body resistance which show considerable variation in the allowable fault current-time thresholds. For example, with a fault of

100ms duration and a 1000Ω body resistance, the fault current, according to EA-TS 41-24 and BS 7354, should not exceed 10600A and 23300A respectively. However, with a body resistance of 6000Ω, maximum fault currents of 28500A and 63300A respectively could be tolerated. Given the very large effect that variation in body resistance has on the safety limit-surfaces, it is evident that an approach incorporating a voltage dependent body resistance as adopted in CENELEC HD 637 S1 [3.5] is required.

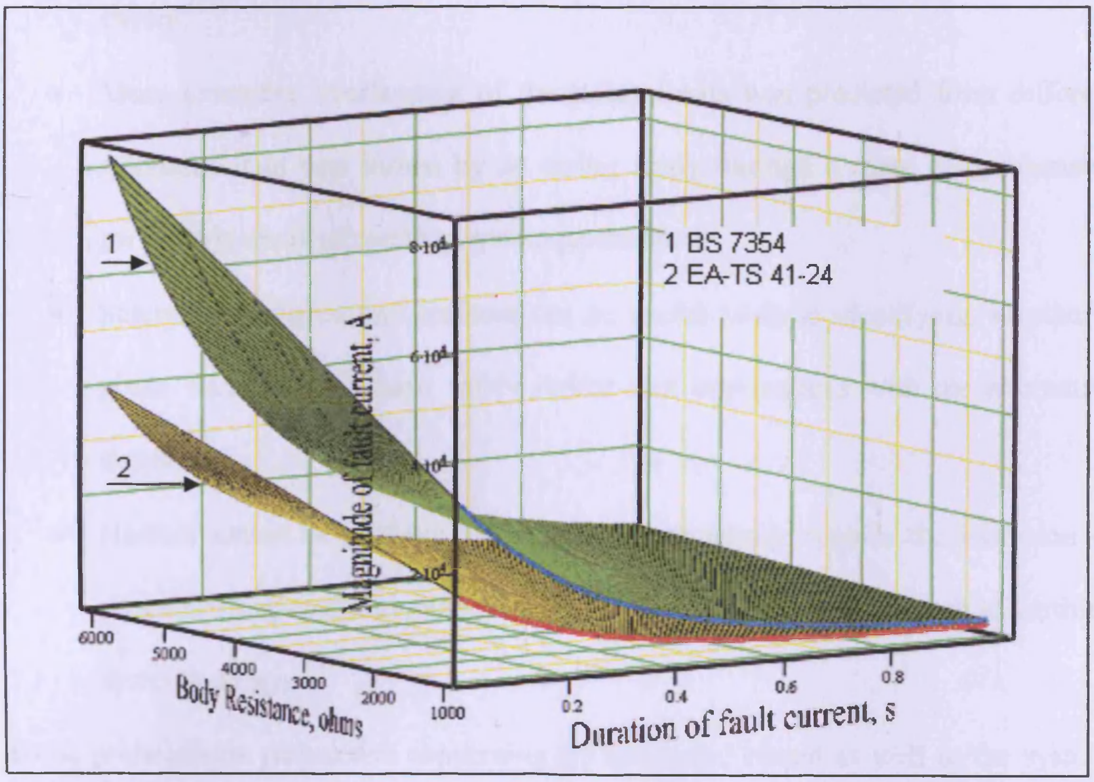


Figure 3.8: Safety limit-surfaces for a 100mx100m grid in 100 Ωm earth resistivity as a function of assumed body resistance.

3.8 Conclusions

Three standards; IEEE 80, BS 7354 and EA-TS 41-24, were considered in this parametric study of the effects of earth resistivity, grid area and mesh density on the maximum allowable fault current for a given fault duration. Firstly, the safety limit equations were derived. Then, using a newly developed computer procedure, the results were visualised in the form of safety limit-surfaces as a function of the earthing parameters. A wide range of generic grid designs and earth resistivities have been considered and it is found that:

- Large variations exist between the safety limit-surfaces determined by the different standards.
- Differences found in these comparative studies are attributed mainly to the assumed probability of ventricular fibrillation, shock location and electrocution circuit.
- More extensive overlapping of the safety limits was predicted from different standards than was shown by an earlier study through a more comprehensive parametric study of earthing system parameters.
- Safety limit-curves and surfaces can be useful tools in identifying, whether a given standard may have safety and/or cost implications with the alternative standards.
- Harmonisation of earthing systems design standards require the inclusion of probabilistic parameters, and may lead to a less subjective approach to earthing systems design.

These probabilistic parameters concerning the accidental circuit as well as the system, are investigated in full detail in Chapters 4 and 5 respectively, with the scope of integrating them in the proposed risk assessment process presented in Chapters 6 and 7.

CHAPTER 4. DEVELOPMENT OF COMPUTERISED PROCEDURES FOR ELECTRICAL SAFETY CRITERIA

4.1 Introduction

In the previous chapter, it was shown that the safety criteria adopted in different earthing standards vary significantly. This results in quite significant differences between what is regarded as safe. The parametric analysis has identified that apart from the differences in the accidental circuit and the calculation of prospective voltages, the standards do not compare well also because of the different criteria used for determining the allowable body current.

In order to compare the current practices of assessing safety, and understand the different criteria of allowable body current, it is necessary to examine the origin of these criteria and analyse their course of development over the past seventy years.

Although there are a great number of recorded electrical accidents and because of the various accident conditions, it is almost impossible to have accurate estimates of the current magnitude and shock duration and other parameters, necessary to deduce safety limits.

4.2 Review of previous work on allowable body current criteria

4.2.1 Early Work

In 1936, Ferris et al. [4.1] at Columbia University appear to be the first to conduct experiments on animals in an attempt to determine threshold current of electrocution. In 1959, Kouwenhoven et al. [4.2] conducted further animal experiments, whose results were in agreement with work carried out by Ferris et al. [4.1]. They observed that the sheep's heart was most vulnerable to electric shock, when the shock occurred during the

'T-phase' of the electrocardiogram of the heart. The T-phase was discussed in Section 2.4.3 and indicated the severe effect of current when the shock falls within this vulnerable phase of heart. So, for a current path from the right foreleg or chest to the left hind leg and with the use of a square wave generator with a variable delay circuit, they managed to position the shock at any desired point in the heart-cycle. The resistance of the current pathway through the animal was measured with an average of 650 Ω. The result was a first quantitative determination of the minimum current causing ventricular fibrillation and that for "short shock durations, the susceptibility of the heart to fibrillate depends upon the relative timing of the shock to the heart cycle" as Dalziel C.F. pointed out in his discussion of Kouwenhoven's work [4.2]. An interesting point made by Ferris [4.1] and later verified by Kouwenhoven is that, if the heart is not damaged and, given time to return to normal, successive shocks have no cumulative effect on the susceptibility of the heart to fibrillate.

Moreover, Kouwenhoven's work also verified Dalziel's analytical derivation of the relationship between shock duration and fibrillation threshold current [4.3]. Finally, it is important to mention that although Kouwenhoven recorded the body weights of the animals, he did not find any correlation between the body weights and the minimum fibrillation current. More experimental data was obtained in 1963 from Kiselev A.P. [4.4] of the U.S.S.R. Academy of Medical Sciences. The latest results were used by Lee W.R [4.5] in an extensive study where important conclusions were drawn but which also questioned Dalziel's analysis presented in [4.6].

4.2.2 Dalziel's work and IEEE approach

In 1968, Dalziel and Lee [4.7], re-evaluated the lethal electric currents and their published results were used as the basis for the development of the current IEEE St-80

[4.8] safety criteria. Figure 4.1 shows the minimum current vs. duration that causes fibrillation to dogs.

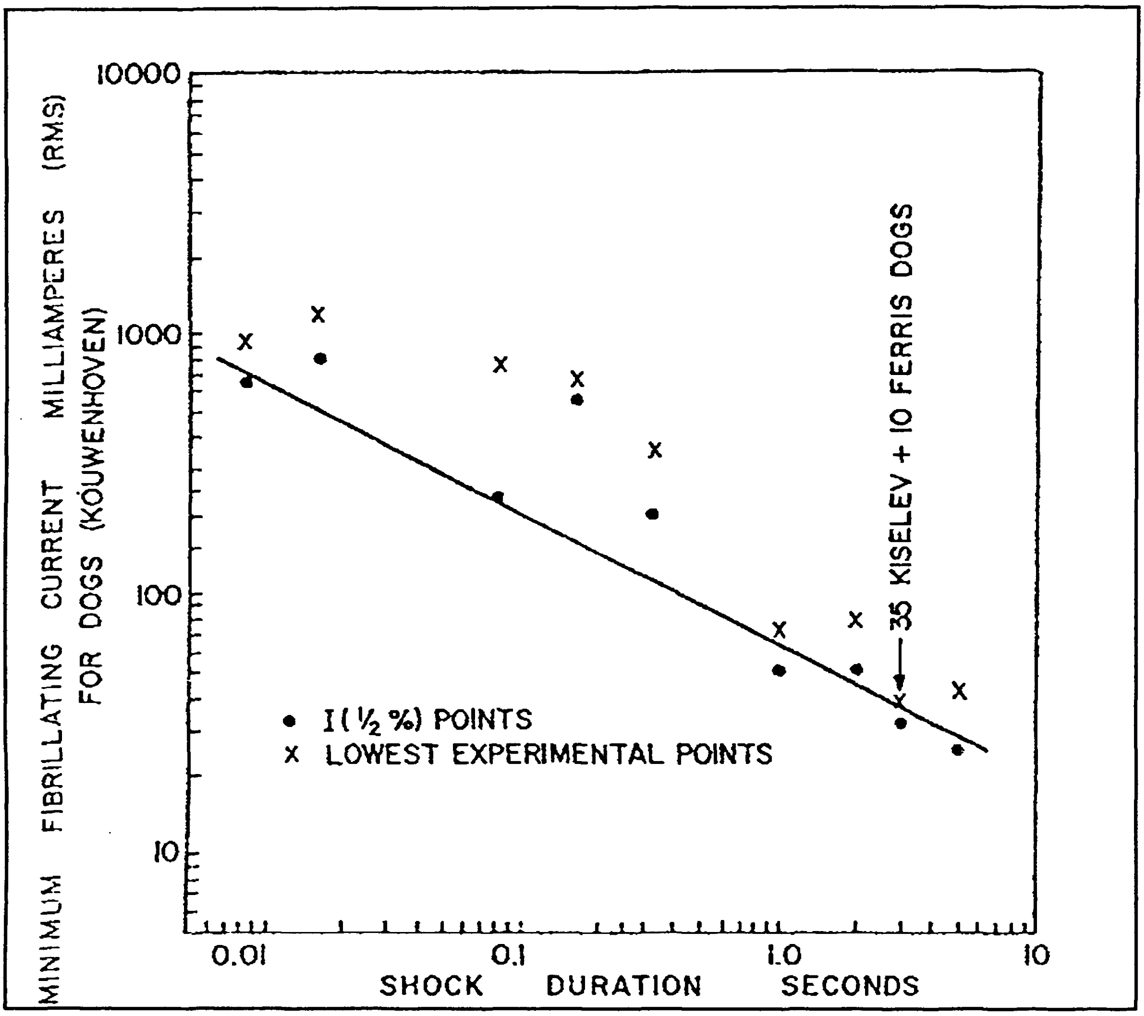


Figure 4.1: Relation to minimum fibrillating current to shock duration for dogs [4.7].

A straight line below all experimental points was derived and given by:

$$I = \frac{K}{\sqrt{T}} \tag{4.1}$$

where K is a constant value depending on body weight and T the shock duration . A closer examination of the results [4.7] revealed that the minimum current required to produce fibrillation is "approximately proportional to the individual's body weight, not only within the single species, dog, but among the larger animals, probably including man". Further studies [4.9] on accidental electrocutions of almost two hundred cases showed that 30% of the victims were female and another 26% were persons under the age of twenty. Based on these numbers, Dalziel justified his assumption that the body weight for the typical victim of electrocution to be at less than 70 kg. However, as Dalziel mentioned "there is certainly a case for selecting a most conservative value for the body weight for use in evaluating K (see Equation 4.1) for the electrocution of a man" and, therefore, he proposed a value of 50 kg body weight to be accepted as a conventional value for the typical victim of electric shock [4.7].

Figure 4.2 shows the 50th percentile points corresponding to both the maximum nonfibrillating current and the minimum fibrillating current for various animals in relation to body weight.

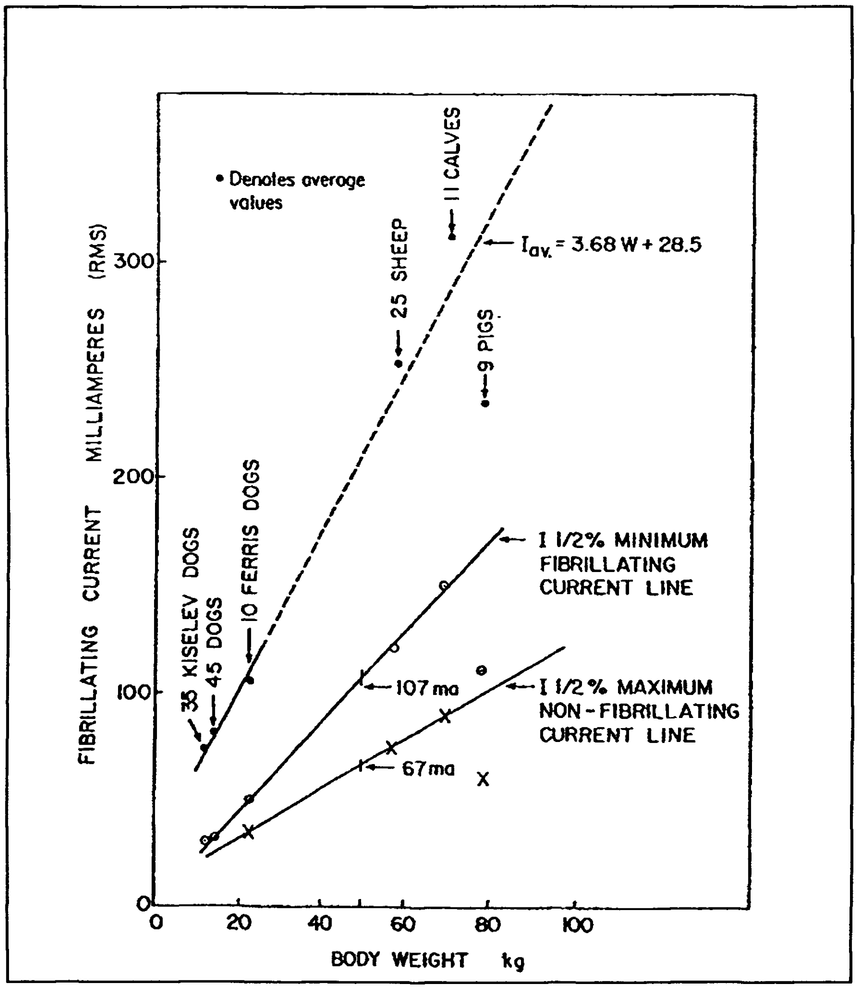


Figure 4.2: Relation of fibrillating current to body weight for various animals, 3.00-second shocks [4.7].

From the figure, it can be inferred that the current magnitude necessary to cause fibrillation for a given mammal is somewhere between these two 50th percentile lines, depending upon body weight.

Hence, the constant K for the electrocution for a man of body weight of 50 kg can be deduced from Figure 4.2 to be 116 and 185 for the maximum nonfibrillating current and the minimum fibrillating current respectively yielding the following equation:

$$I = \frac{116\_to\_185}{\sqrt{T}} \quad \text{for 8.3 ms to 5 s} \qquad (4.2)$$

Dalziel concluded that the threshold results of ventricular fibrillation for at least up to the 50th percentile follow a normal distribution. However, if the results for any shock duration are plotted on a log-probability paper, the skewing that was observed when plotting the results on arithmetic probability paper will disappear [4.10].

When Biegelmeier and Lee [4.10] investigated the relationship between the fibrillating current and shock duration, they commented on Kouwenhoven's experiments on dogs, that for shock durations from 8.3 ms to 5 s ranging from 8 to 16 kg, the distribution curves drawn on log-probability paper resulted in straight lines indicating that the current values follow the logarithmic normal distribution. Moreover, according to the same authors, the measurements in Ferris experiments [4.1], which were made on several large animals including sheep, dogs, calves and pigs, and spanned shock durations from 30 ms to 3s, followed a log-normal distribution. Finally, the same conclusions were drawn when Kiselev's [4.4] experiments with dogs were examined.

That meant that for a given shock duration, the distribution of the threshold of current to produce ventricular fibrillation is log-normal with the exception of shock durations of 0.167 s from Kouwenhoven's experiments that raised questions and required further explanation.

In 1980, Biegelmeier et al. [4.10], described the reasoning behind the phenomenon of the Z-shaped current threshold from which the IEC 479 threshold S-curves originated. As can be seen in Figure 4.3, the probability of fibrillation curve can be represented by two straight lines. This observation provided evidence that there are two different physiological mechanisms that should be considered; (a) First, if the shock occurs during the vulnerable period of the heart cycle, fibrillation will be produced immediately and the threshold was also found to be the same as that found for any shorter duration shocks that fell during the vulnerable period , (b) Otherwise, if the shock starts during diastole, which is the period of relaxation and filling of the ventricles, a premature heartbeat may be initiated [4.10].

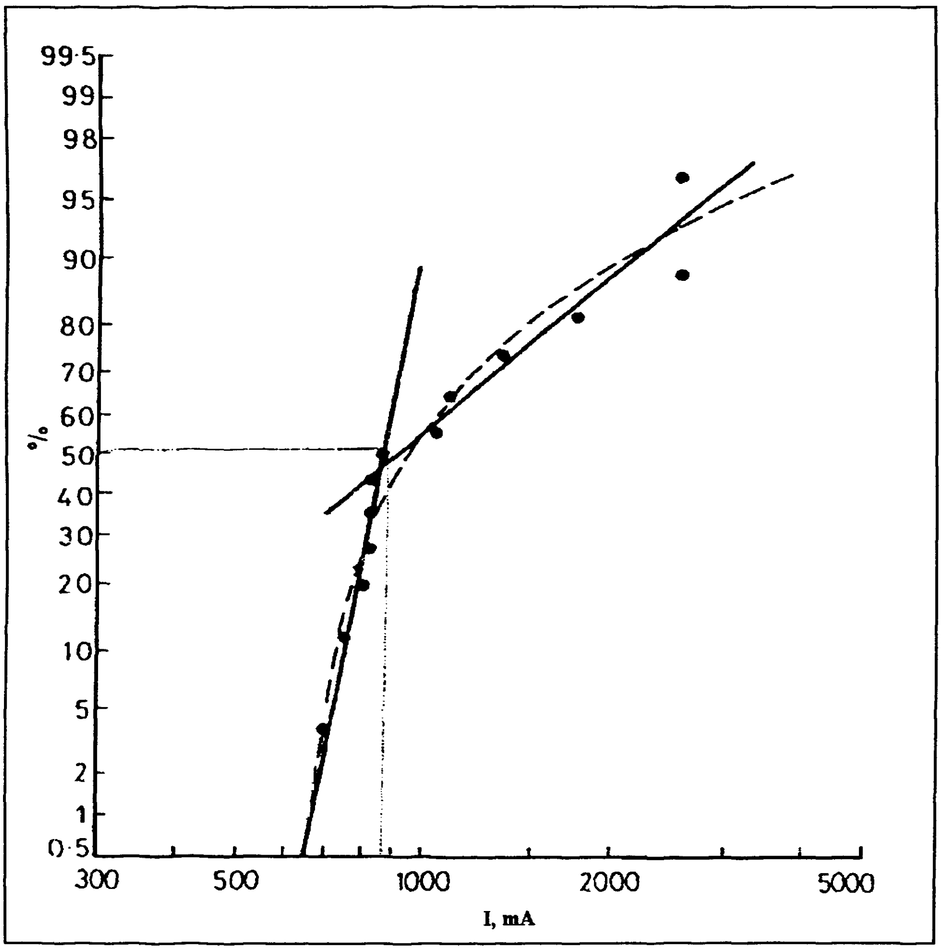


Figure 4.3: Minimum fibrillating current distribution curve for dogs [4.10].

If the shock is long enough to fall in the vulnerable period of the second premature beat, then the threshold of ventricular fibrillation becomes significantly lower, bearing in mind of course that fibrillation can only be caused during the vulnerable period. Biegelmeier, staying on the safe side, made the assumption that the shocks would fall within the vulnerable period and by combining the results Kouwenhoven [4.2], Lee [4.5] and Kiselev [4.4] as well, produced the graph of Figure 4.4, showing the minimum fibrillating current for 50% fibrillation probability as a function of shock duration.

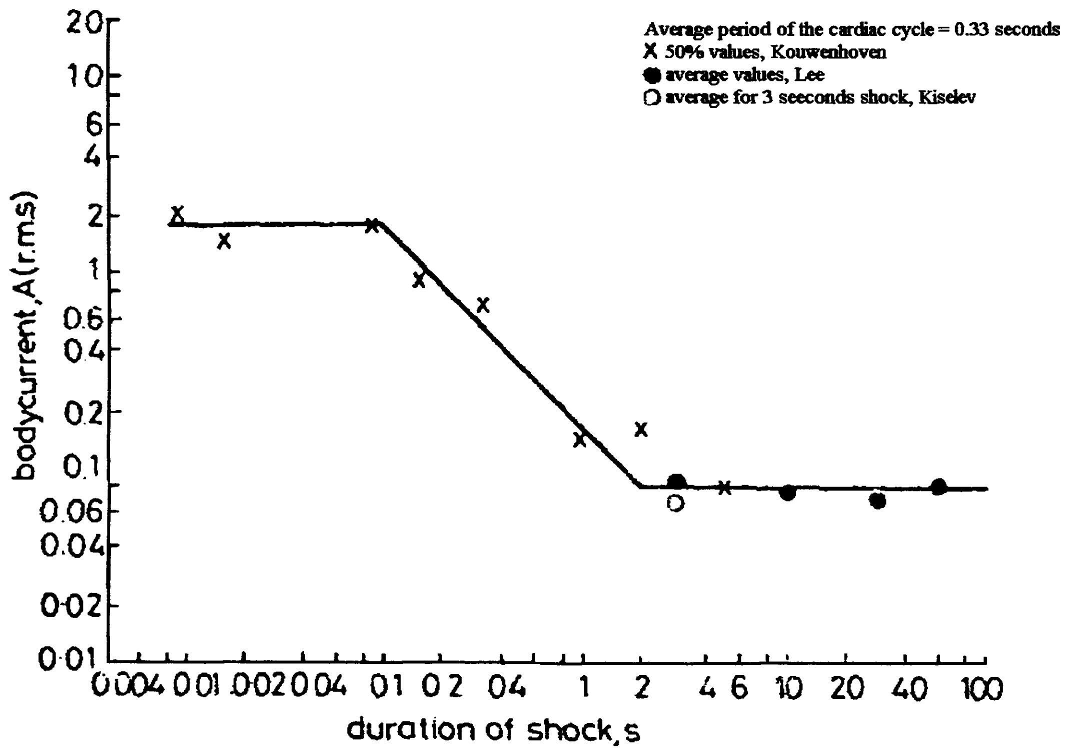


Figure 4.4: Threshold of ventricular fibrillation current for dogs (50% probability) for shock durations from 8.33 ms to 60 s [4.10].

As can be seen, for shock durations below 1/3 of the cardiac cycle, the level is constant at about 2 A, while for shock durations longer than 6 heart cycles a constant level of 80 mA is observed.

A heart rate of 100 per minute was assumed for the calculation of the standard duration of the cardiac cycle and the upper level was calculated to be about 1.96A [4.10]. Moreover, further safety limits were proposed beyond which there would be no danger of ventricular fibrillation by setting the lower and upper limit to 50 mA and 500 mA respectively, as shown in Figure 4.5.

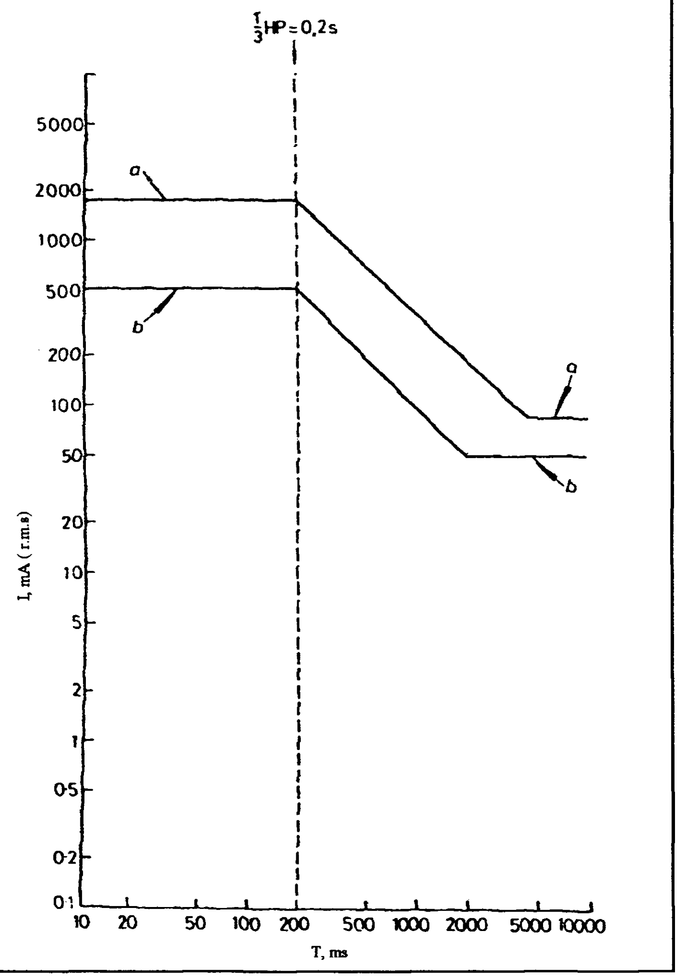


Figure 4.5: Threshold of ventricular fibrillation for men for 50% fibrillating probability and safety limit against ventricular fibrillation for men [4.10].

4.2.3 IEC approach

Based on Biegelmeier and Lee's work [4.10], the IEC Working Group produced a report in 1987 [4.11, 4.12] with the thresholds of 5%, 50% and 95% probability of fibrillation. Moreover, another curve was added below which no risk of fibrillation existed named the *S* or *Safety curve*. It is interesting to note the smoothing of the initial *Z*-shaped lines in order to get the *S*-shaped curves.

The final limits published in IEC 60479 document [4.13] seem to be further lowered, especially the *Safety curve*. These latest fibrillation threshold limits are presented below in Figure 4.6, and are currently widely introduced in various standards around the world.

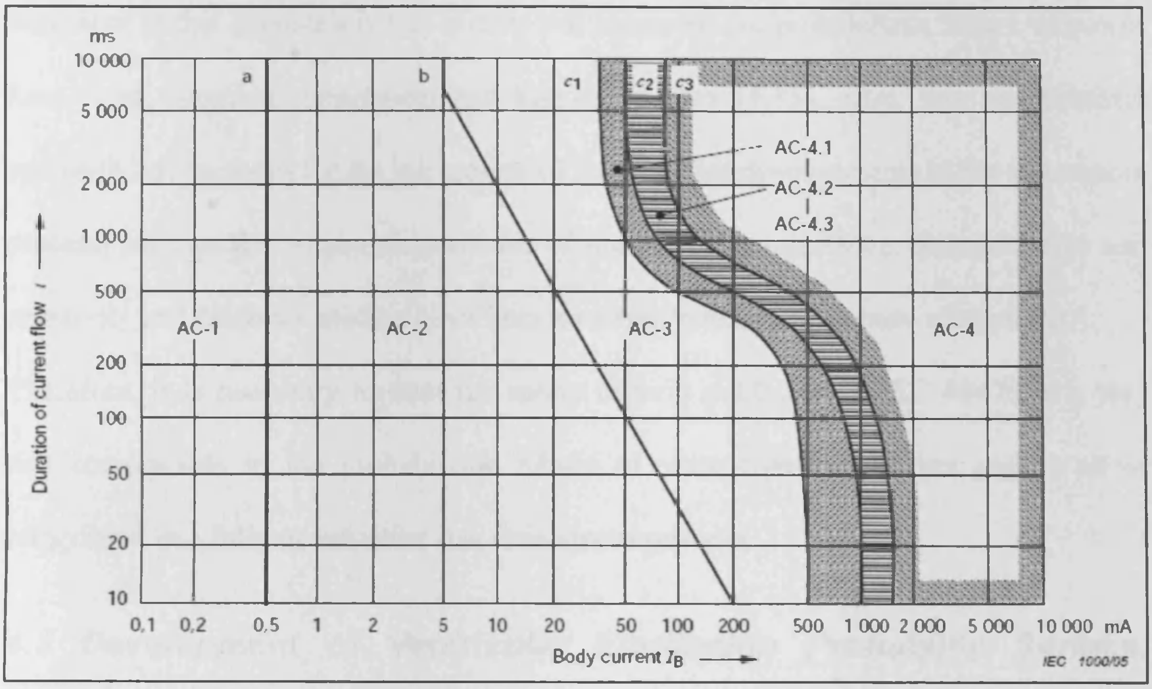


Figure 4.6: Conventional time/current zones of effects of a.c. current (15 Hz to 100 Hz) on persons for current path corresponding to left hand to feet [4.13].

Although the *Safety curve (c1)* produces rather conservative fibrillation current thresholds, it is currently used by EA-TS 41-24 [4.14]. BS 7354 [4.15] and CENELEC HD-63751 [4.16] have adopted the c_2 curve corresponding to 5% fibrillation probability in order to produce allowable touch and step voltage limits. In the case of ITU-T K.33 standard [4.17], a distinction is made between typical and severe cases, using curves c_2 and c_1 respectively.

It is interesting to note that the probabilistic criteria proposed in IEC 60479 have been used to produce deterministic values of acceptable step and touch voltages. These values are usually produced by accepting either the *Safety Curve* or the 5% *Curve* as thresholds for allowable body currents and at the same time setting the shock duration to a value that would be accepted to account for the worst case scenario (usually 200 ms). The deterministic criteria have served the power industry for years. The basic weakness in this approach is that it does not represent the probabilistic nature of power flow, load variation, component and human failures [4.18]. Also, this deterministic approach left no room for the integration of more recent developments in the assessment process, such as the voltage dependence of human body resistance, the multilayer soil resistivity and presence studies in various locations within and outside substations.

Therefore, it is necessary to treat the safety criteria published in IEC 60479 in a way that corresponds to the probabilistic nature of ventricular fibrillation and to allow integration in a fully quantitative risk assessment process.

4.3 Development of Ventricular Fibrillation Probability Surface: Cardiff Probabilistic Model

In this work, IEC 60479 curves of allowable body current (*Safety Curve, 5% and 50% confidence level)*, and also the *95%* curve provided in the initial report of the working group (WG 4) [4.11], were digitised using 'FindGraph' software in order to produce analytical expressions useful for the development of more flexible safety limits (Figure 4.7).

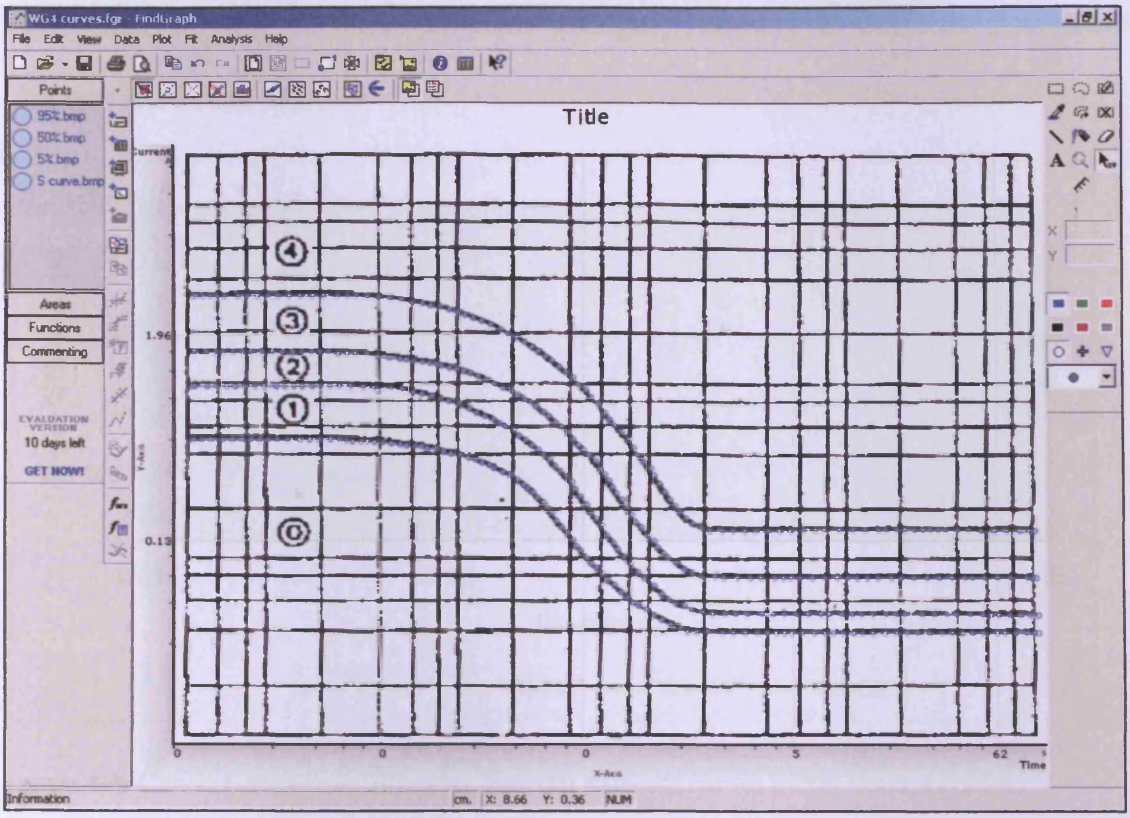


Figure 4.7: Sampling process of the IEC 479-1 curves for the generation of corresponding equations.

Using non-linear regression as a curve fitting technique, the following equations were obtained to fit data contained in IEC 479-1 curves (see Figure 4.6).

Safety curve c_1: $$I_{b1} = 0.501 \cdot e^{-\frac{t}{0.286}} + 0.039 \cdot e^{\frac{1}{t+2.657 \cdot 10^{115}}} \tag{4.3}$$

Curve c_2: $$I_{b2} = 1.027 \cdot e^{-\frac{t}{0.282}} + 0.051 \cdot e^{\frac{1}{t+1.766 \cdot 10^{90}}} \tag{4.4}$$

Curve c_3: $$I_{b3} = 1.578 \cdot e^{-\frac{t}{0.316}} + 0.08 \cdot e^{\frac{1}{t+7.962 \cdot 10^{150}}} \tag{4.5}$$

Curve c_4: $$I_{b4} = 3.309 \cdot e^{-\frac{t}{0.333}} + 0.151 \cdot e^{\frac{1}{t+5.46 \cdot 10^{96}}} \tag{4.6}$$

When examining the difference of body current between c_2 (5%) & c_3 (50%) and between c_3 & C_4 (95%) for all shock durations, it can be seen that the difference does not remain constant. This is illustrated in Figure 4.8 which suggests that the shape of the distribution for any of these durations changes, resulting in different distribution characteristics each time.

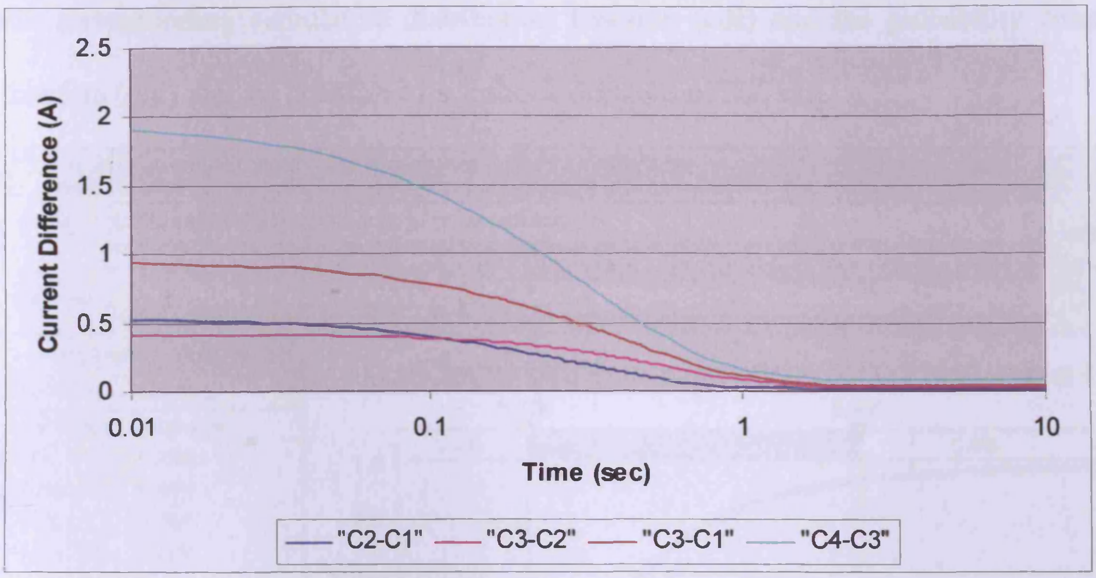


Figure 4.8: Current magnitude difference between adjacent curves across shock duration.

In order to build a probability surface that would give the allowable body current corresponding to a given shock duration and probability of VF, a computer program was developed that allows to build a unique distribution for each duration by using the values of allowable body current corresponding to 0%, 5%, 50% and 95% probabilities as given in Equations (4.3. to 4.6).

For the process of this analysis, a special statistical software was used, namely @Risk [4.19]. The software allows modelling a variable not only from standard parameters (i.e. mean & standard deviation), but also by specifying values for specific percentile locations of an input distribution, given that the type of distribution is known. As discussed above, the fibrillating current follows a lognormal distribution, and the 5^{th}, 50^{th}, and 95^{th} percentile values for any shock duration can be calculated from the corresponding equations.

For a shock duration of 200 ms, the values of 5^{th}, 50^{th}, and 95^{th} percentile are used to form the corresponding lognormal distribution. Moreover, the value taken from the

Safety Curve is used as maximum body current limit where the probability of ventricular fibrillation is considered 0%. Figure 4.9 and Figure 4.10 show respectively the corresponding cumulative distribution function (cdf) and the probability density function (pdf) that are generated for a shock duration of 200 ms.

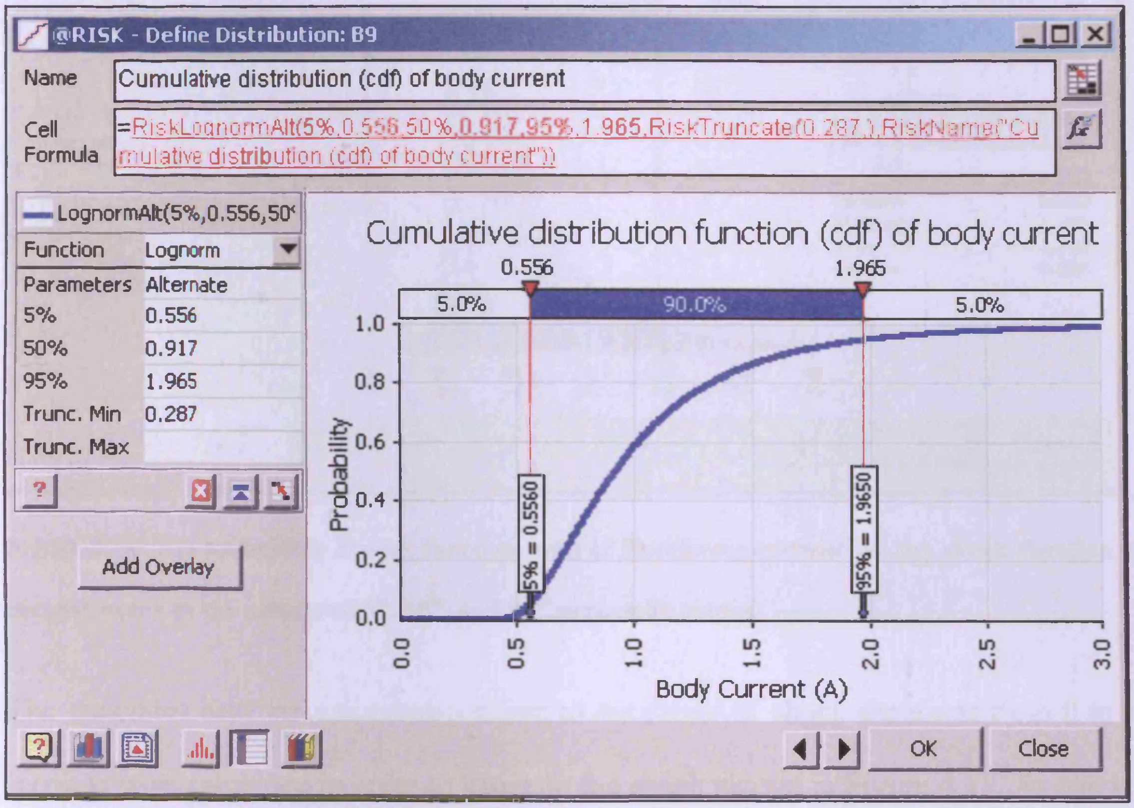


Figure 4.9: Screenshot of modelling the fibrillating current by a three-point distribution for a given shock duration (200 ms).

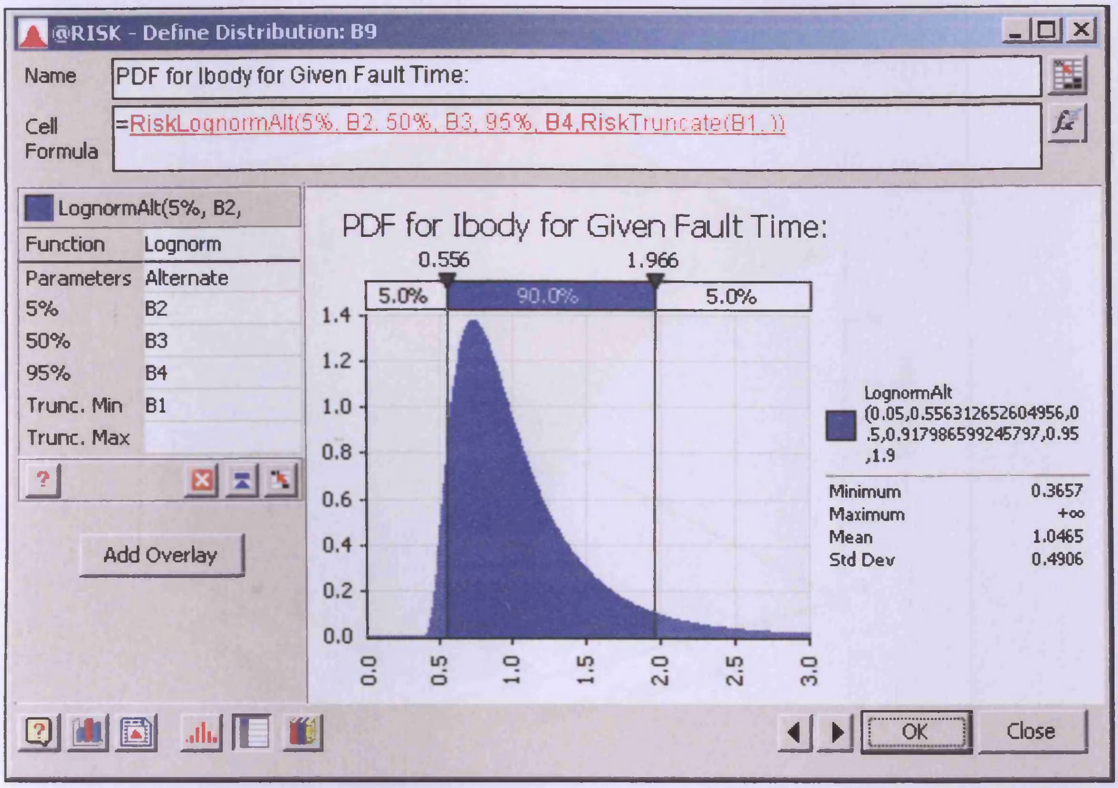


Figure 4.10: The probability density function (pdf) of fibrillating current for any shock duration is created based on the calculated 5th, 50th, and 95th percentile values.

The generated distributions corresponding to the range of shock durations from 0 to 1 seconds were combined in order to generate the graph shown in Figure 4.11. As can be seen in the figure, for any shock duration and body current magnitude, a probability of ventricular fibrillation can be deduced. This allows greater choice from the pre-selected *Safety, 5% and 50%* limits provided in IEC 60479 and therefore, there is greater flexibility in integrating the safety criteria in a probabilistic risk assessment. Another perspective of the surface can be given from the combination of the pdfs generated for the range of shock duration from 0 to 1 s, as shown in Figure 4.12.

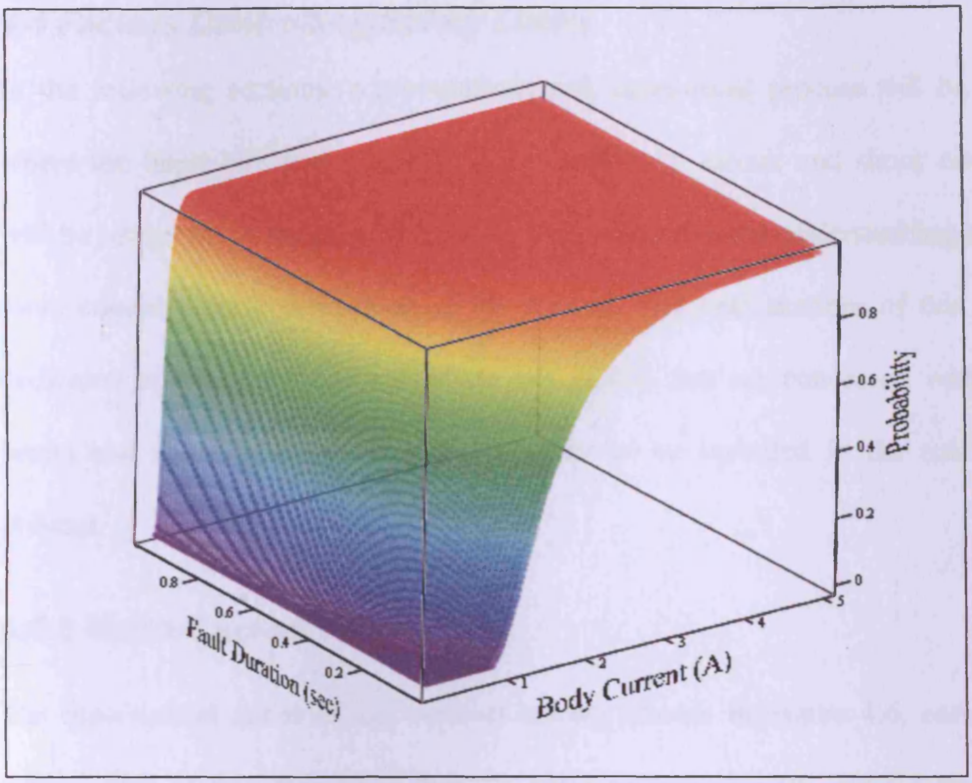


Figure 4.11: Probability Surface of Ventricular Fibrillation against Body Current and Shock Duration.

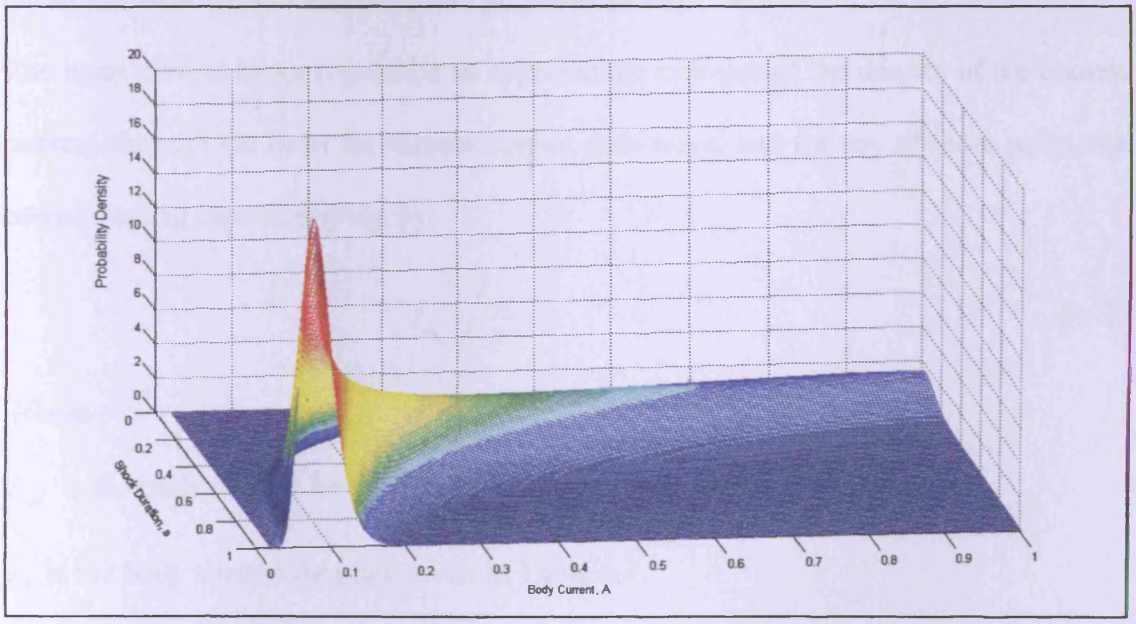


Figure 4.12: Surface generated from the combined lognormal distributions.

4.4 Factors Controlling Safety Limits

In the following sections, a probabilistic risk assessment process will be developed, where the latest advances concerning the accidental circuit and shock circumstances will be integrated in the process in order to develop a better understanding and create a more comprehensive description of the system. The next sections of this chapter are dedicated to examining some of these key points that are concerned with the safety limits and showing the steps taken in order to be included in the risk assessment process.

4.4.1 Heart-Current Factor

The time/current zones of a.c. currents effects, shown in Figure 4.6, correspond to a current path from left hand to feet. In order to calculate the current for a different current path that would have the same danger of ventricular fibrillation as the reference current, a heart current factor (F) was proposed [4.13].

The heart current factor represents an approximate estimate of the density of the current passing through the heart for various current path-ways, and for any of these paths, the corresponding current is given by:

$$I_h = \frac{I_{ref}}{F} \tag{4.7}$$

Where

I_{ref} is the body current for the path left hand to feet given in Figure 4.6.

I_h is the body current for paths given in Table 4.1.

F is the heart-current factor given in Table 4.1.

Table 4.1: Heart-current factor F for different current paths [4.13].

Current Path	Heart-current factor F
Left hand to left foot, right foot, or both feet	1.0
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 to both hands	0.7
Left foot to right foot	0.04

It should be noted that the "left foot to right foot" current path was added to the latest version of IEC 60479 [4.13]. Based on the fact that for this current path, the main body current misses the heart, the heart factor was calculated to be 0.04, which results in allowable step voltages twenty five times higher than before.

4.4.2 Modelling of Human Body Impedance

The total impedance of human body (Z_T) consists of resistive and capacitive components. This impedance depends on the touch voltage, the current frequency, the degree of moisture of the skin, the current path and the surface area of contact. IEC 60479-1 [4.13] provides values as a function of these parameters. However, for high touch voltages, the total impedance becomes less dependent on the skin impedance. IEC 60479-1, by adopting a conservative approach for the human body impedance dependence on touch voltage, provides values of body impedance for a current path hand to hand, for large surface areas of contact (5000 mm^2 to 10000 mm^2) and dry conditions [4.13].

These values, shown in Figure 4.13, were used to derive empirical equations to express this dependence.

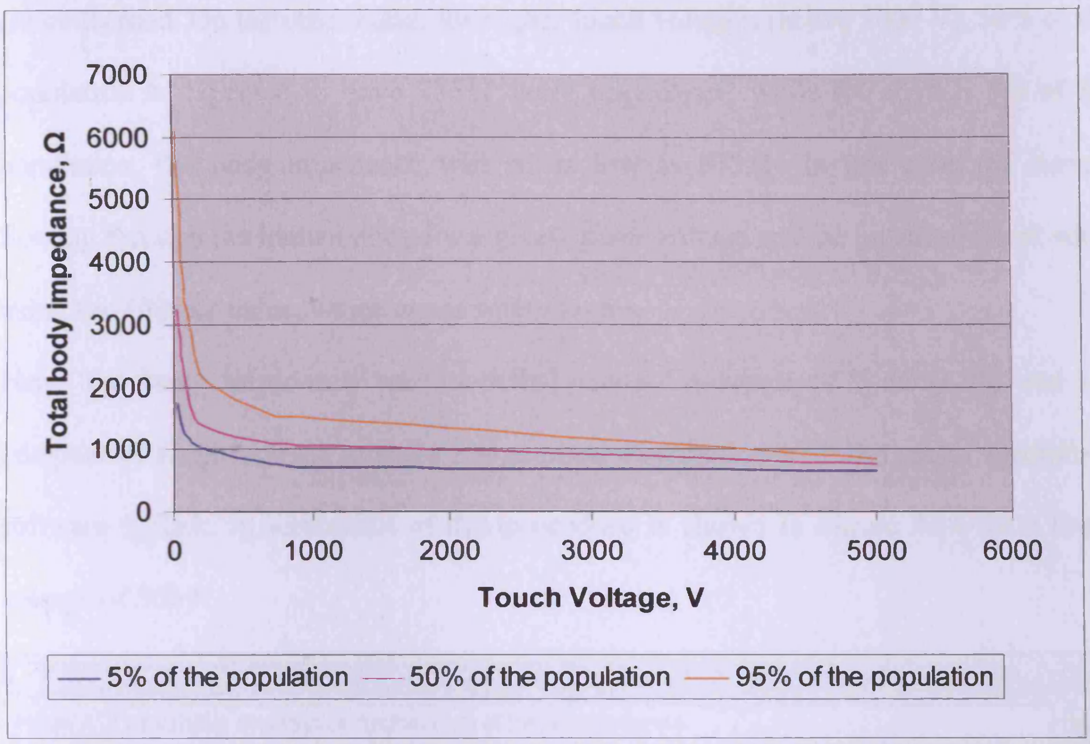


Figure 4.13: Total body impedances for a current path hand to hand for large surface areas of contact in dry conditions (a.c. 50/60 Hz) [4.13].

In this work, the following empirical equations for body impedances $Z_{B(5\%)}$, $Z_{B(50\%)}$ and $Z_{B(95\%)}$ corresponding to 5%, 50% and 95% of the population respectively were derived:

$$Z_{B(5\%)} = 1.499 \cdot 10^3 \cdot e^{-0.014 V_T} + 641.47 \tag{4.8}$$

$$Z_{B(50\%)} = 3.053 \cdot 10^3 \cdot e^{-0.012 V_T} + 870.96 \tag{4.9}$$

$$Z_{B(95\%)} = 6.228 \cdot 10^3 \cdot e^{-0.011 V_T} + 1176 \tag{4.10}$$

Although these probabilistic values have been published in IEC standards, in practice a single value of body impedance was often used by earthing standards e.g. BS 7354, TS 41-24, ITU-T K.33 and IEEE st-80 use $1000\,\Omega$ for body impedance. As can be seen in

Figure 4.13, the impedance can be as high as $6000\,\Omega$ for lower touch voltages, which suggests that a rather conservative limit is created as far as the allowable touch voltages are concerned. On the other hand, for higher touch voltages (above 1000 V), 50% of the population is expected to have $775\,\Omega$ body impedance, while for another 5% of the population, the body impedance will be as low as $575\,\Omega$. In this case, the current flowing through the human body for a given touch voltage will be underestimated when using the $1000\,\Omega$ value, which arises safety issues.

Here, the body impedance was modelled using Equations (4.8) to (4.10) and the prospective touch voltage to build a lognormal distribution with the use of specialised software @Risk. A screenshot of this procedure is shown in Figure 4.14 for a touch voltage of $500\,V$.

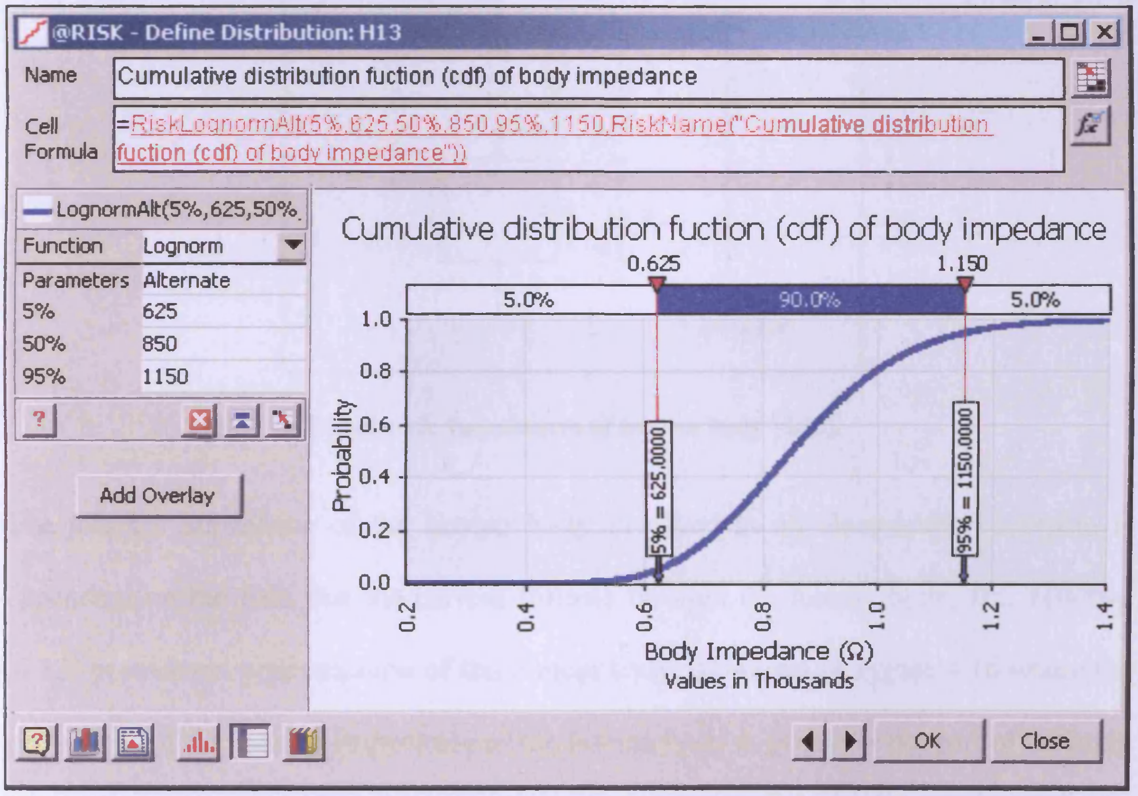


Figure 4.14: Development of cumulative distribution function (cdf) of body impedance for a 500 V corresponding touch voltage.

This process is repeated for the whole range of values between 0V and 5000V. In this way, the generated distribution takes into consideration the voltage dependence and statistical deviation for any touch voltage.

4.4.3 Effect of current path on body impedance

In Figure 4.15, it can be seen that the total body impedance (Z_T), consists of the internal impedance as well as the impedance of the skin, where Z_i is the internal body impedance and Z_{S1}, Z_{S2} are the skin impedances.

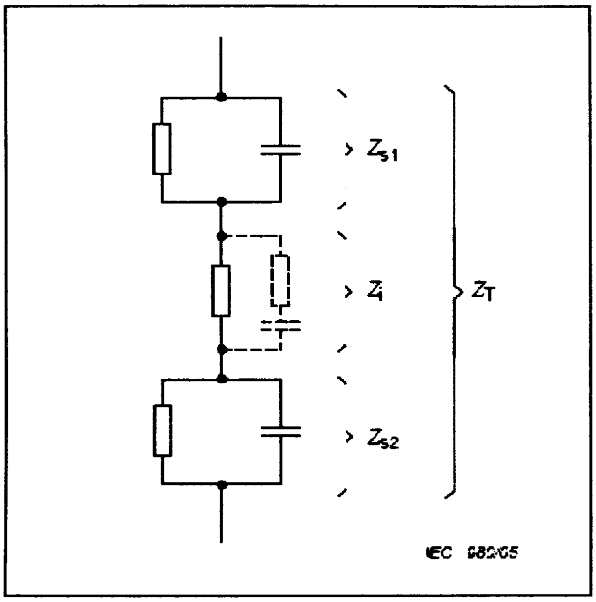


Figure 4.15: Impedances of human body [4.13].

The internal impedance of the human body involved in an electrocution scenario is dependent on the path that the current follows through the human body. IEC 60479-1 [4.13] provides a representation of the human body, as shown in Figure 4.16 where the percentage of the internal impedance of the human body is given for the part of the body concerned, in relation to the path hand to foot [4.13].

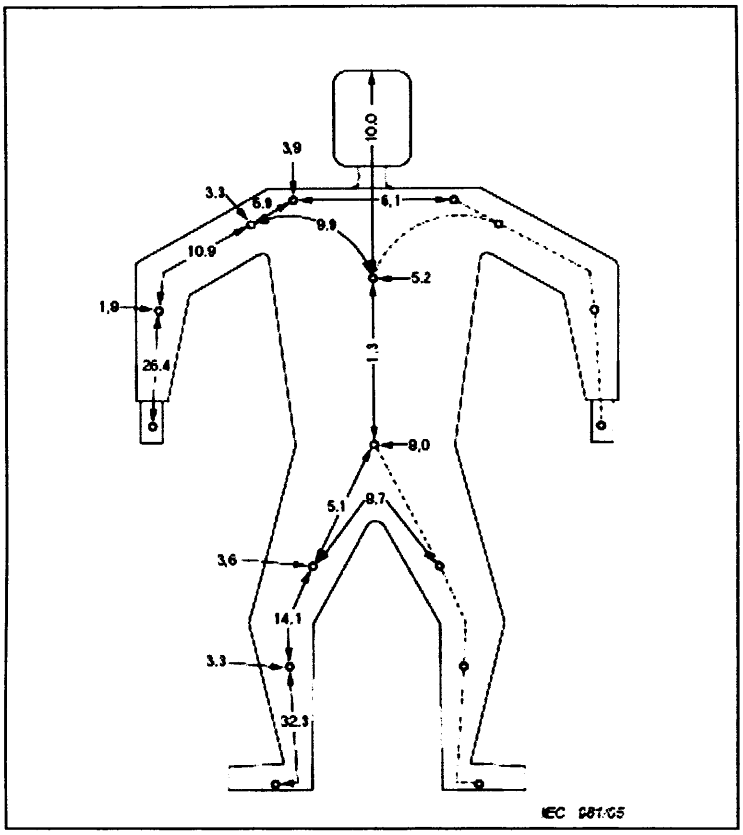


Figure 4.16: Percentage of the internal impedance of the human body [4.13].

Since, the values of body impedance against touch voltage in Figure 4.13 correspond to a current path from hand to hand, the standard suggests that a factor of 0.8 can be applied to these values in order to calculate the hand to foot body impedance. The standard notes that, for living humans, the statistical values provided for body impedance apply to shock duration of about 0.1 s. However, as it will be seen later in Chapter 5, from the statistical analysis of fault clearance data, a significant amount of faults are expected to be cleared well above this duration. In such cases, a reduction of 10% to 20% of body impedance is recommended [4.13]. The following diagram of Figure 4.17 summarizes the developed modelling process of the body impedance.

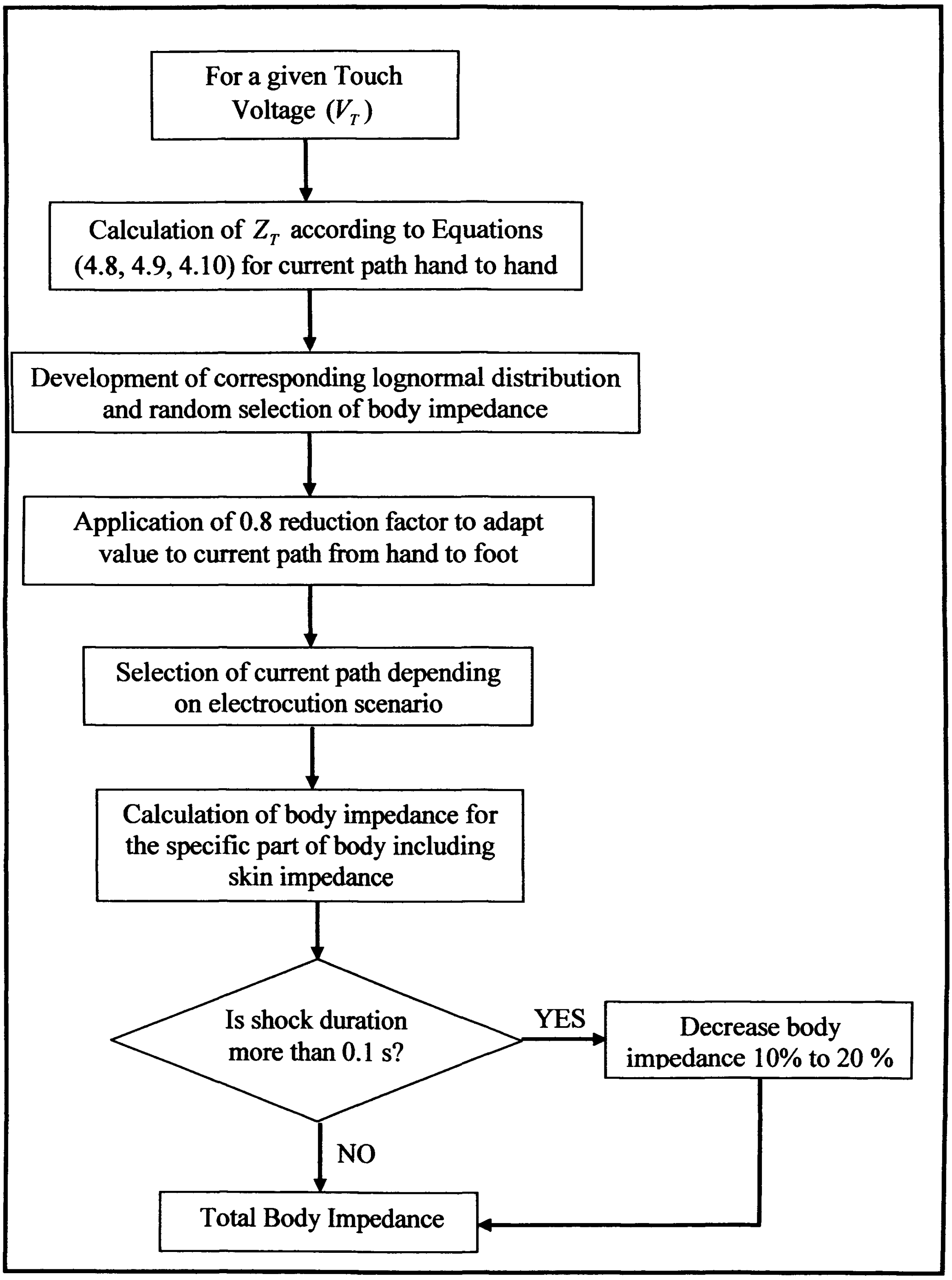


Figure 4.17: Developed Modelling Process of Total Body Impedance.

The total body impedances for different paths have been calculated as percentages of the body impedance for current path hand to foot, and are shown in Table 4.2. Moreover, the heart-current factor (F) for the same path was considered.

Table 4.2: Possible current paths and corresponding heart-current factors and body impedances.

Current Paths	Heart-current factor (F)	Body impedance as proportion of hand to foot body impedance
Left hand to left foot	1	1
Left hand to right foot	1	1
Right hand to left foot	0.8	1
Right hand to right foot	0.8	1
Left hand to right hand	0.4	0.8
Right hand to both feet	0.8	0.75
Left hand to both feet	1	0.75
Both hands to both feet	1	0.5
Seat to left hand	0.7	0.56
Seat to right hand	0.7	0.56
Seat to both hands	0.7	0.33
Back to right hand	0.3	0.52
Back to left hand	0.7	0.52
Chest to right hand	1.3	0.52
Chest to left hand	1.5	0.52
Left foot to right foot	0.04	0.275

4.5 Conclusion

In this chapter, IEC 60479 tolerable body current curves have been analysed and further developed to obtain surface probability curves. This surface probability will allow more accurate assessment of risk compared with the approach using the conventional c_1, c_2 and c_3 curves of the original IEC recommendations. Moreover, a procedure to obtain a surface probability for ventricular fibrillation was developed. This procedure takes into account current magnitude and path, and shock duration. The body impedance was also modelled based on its voltage and time dependency as well as accounting for the current path through the body. The various additional resistances as seen in the previous chapter such as footwear and contact resistance complete the accidental circuit giving a model as close as possible to real life conditions.

The next chapter deals with the probabilistic parameters of the system and the conditions under which a fault may occur based on system fault historical data. The study aims to show the statistical deviation of faults from the worst case scenario and to represent the fault parameters in a way closer to real system conditions.

CHAPTER 5. ANALYSIS OF LONG TERM SYSTEM FAULT DATA FOR RISK ASSESSMENT

5.1 Introduction

In Chapter 3, the various deterministic approaches to risk assessment and the generation of safety limits were studied and compared with the aim of showing that the safety limits created do not fully correspond to the probabilistic nature of the load, protection system and grid characteristics.

In this chapter, such contributing parameters (e.g. clearance time) will be addressed in detail, based on data provided from the UK transmission company (National Grid). These parameters were modelled so that they can be used in the suggested probabilistic risk assessment methodology that follows in Chapter 7. Moreover, through the data analysis, the correlation of the various parameters with the imposed risk levels and the implications when using a worst case scenario value will be shown.

The purpose of this study is to support a risk assessment methodology that will allow practising engineers to make the most cost effective decisions based not only on historical data but also on their personal experience and local knowledge of the site.

5.2 Fault Clearance Time

5.2.1 System Requirements

The Grid Code [5.1] describes the operating procedures and principles governing National Grid's relationship with all users of the GB Transmission System. According to this document, "the fault clearance time for faults on the Generator's or DC Converter Station owner's equipment directly connected to the GB Transmission System and for faults on the GB Transmission System directly connected to the

Generator or DC Converter Station owner's equipment, from fault inception to the circuit breaker arc extinction, shall be set out in accordance with the Bilateral Agreement". The times specified in the agreement cannot be faster than:

- 80 ms at 400 kV
- 100 ms at 275 kV
- 120 ms at 132 kV and below

However, it is clarified that the above times are maximum values, and users or NG if possible should always aim for faster fault clearance times. Also, slower fault clearance times can be agreed for faults on the GB Transmission System. Finally, the circuit breaker fail protection is required to initiate tripping of all the necessary electrically adjacent circuit breakers targeting to interrupt the fault current within the next 200 ms. However, slower fault clearance times that do not exceed 300 ms can only be accepted in cases where the faults occur on the Network Operator's or Non-Embedded Customer's apparatus [5.1].

According to a technical specification [5.2] by National Grid addressed to external companies/users of the Transmission System, plant and equipment should be suitable for operation under the conditions provided in Table 5.1.

Table 5.1: Target Fault Clearance Requirements [5.2].

Nominal Voltage (kV)	Target fault interruption time of main in-feeding circuit (ms)	Target total fault clearance time (all infeeds) (ms)	Target back-up clearance time (ms)
400	80	140	500
275	100	160	500
132	120	N/A	<1500
13	75	N/A	N/A

The document also states that in the event of a circuit-breaker failure, circuit-breaker fail protection shall trip all necessary contiguous circuit-breakers, capable of supplying a fault infeed, within a target fault clearance time not exceeding 300 ms.

As can be seen in Figure 5.1, the first peak of the decaying ac component after contact separation will be the largest during the arcing period. The Peak Break is the highest instantaneous short circuit current that the circuit breaker has to extinguish.

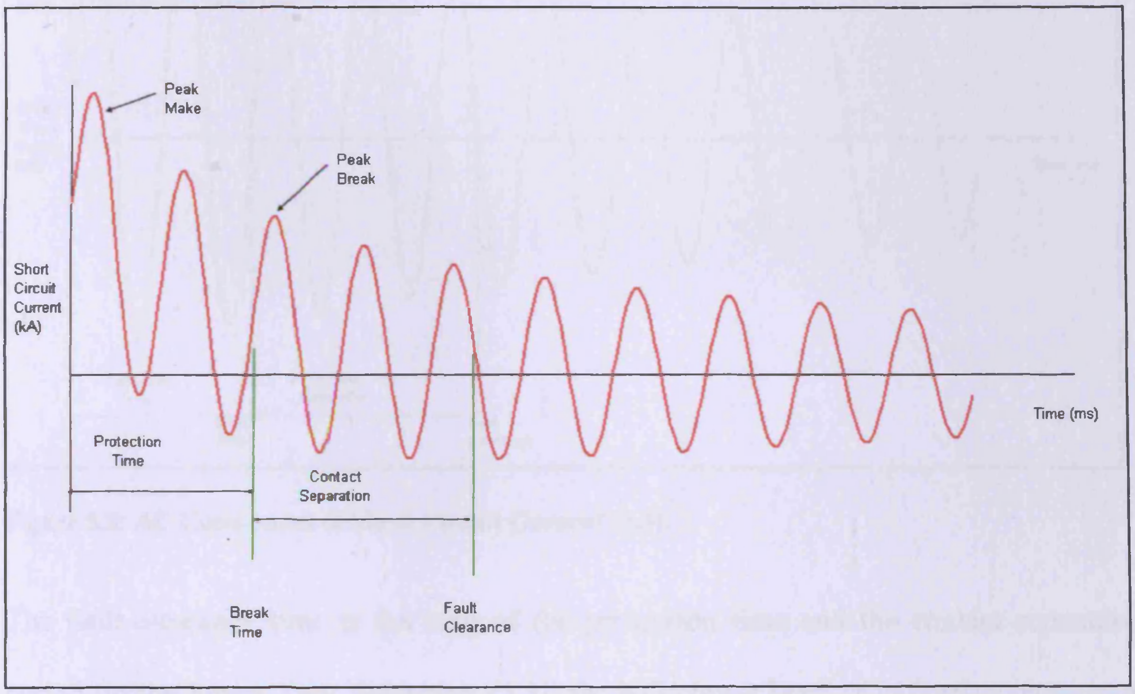


Figure 5.1: Resultant Short Circuit Current [5.3].

The Peak Break current will be significantly higher than the RMS Break shown in Figure 5.2, because like the Peak Make current, it is an instantaneous value and it also includes the DC component [5.3].

Moreover, the RMS Break current and the Peak Break current will depend on the break time because for slower protection, the break time is longer. The Seven Year Statement demands a uniform break time of 50 ms to be applied at all sites. It also states that "...for the majority of our circuit breakers, this is a fair or pessimistic assumption. In this context, it should be noted that the break time of 50 ms is the time to the first major peak in the arcing period, rather than the time to arc extinction" [5.3].

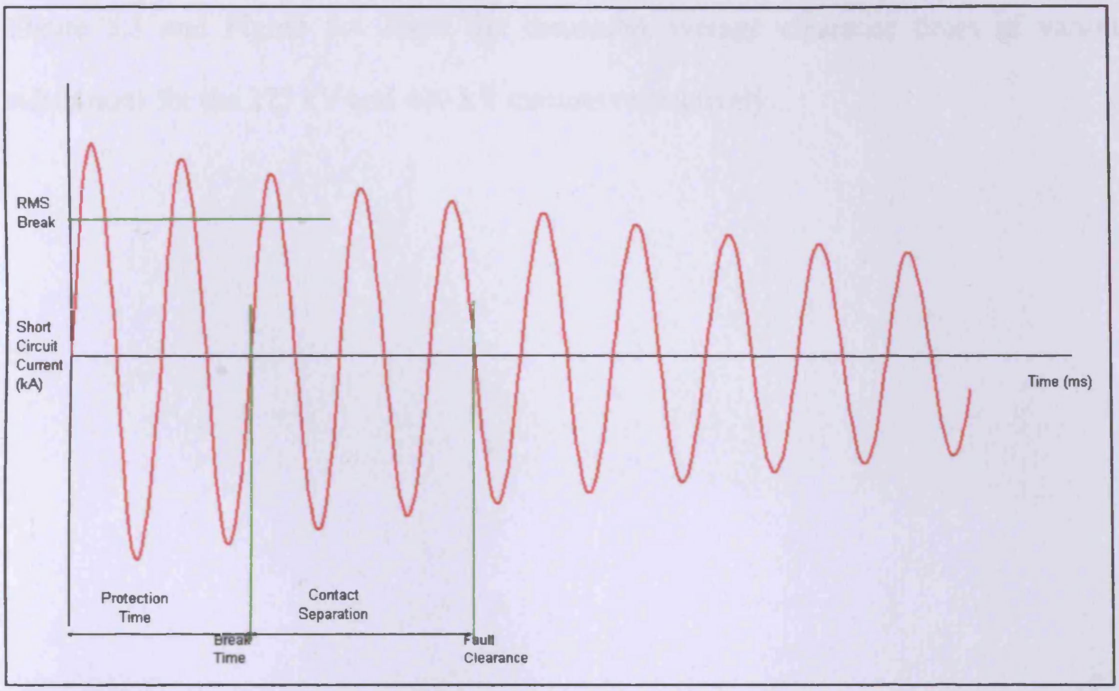


Figure 5.2: AC Component of Short Circuit Current [5.3].

The fault clearance time is the sum of the protection time and the contact separation period. In the Seven Year Statement [5.3], the NG circuit breaker indicative ratings are provided including the Break Time. From the data, it is evident that, at many sites, a combination of different types of circuit breakers is installed within a single substation, resulting in a range of ratings for these substations. In general, the substation infrastructure will have a rating very close to the associated circuit breaker.

5.2.2 System Fault Data for the Period 1993-2003

Fault data was made available by National Grid for the investigations undertaken in this project. In this investigation, the above circuit breaker ratings were compared with the averages of fault clearance times recorded over a ten year period from 1993 to 2003.

This is achieved by comparing the system fault data supplied by NG with specifications for substation equipment contained in the 7 Year Statement. As mentioned above, the majority of circuit breakers are rated at 50 ms with fewer examples of 30 or 70 ms. Figure 5.3 and Figure 5.4 show the measured average clearance times of various substations for the 275 kV and 400 kV circuits respectively.

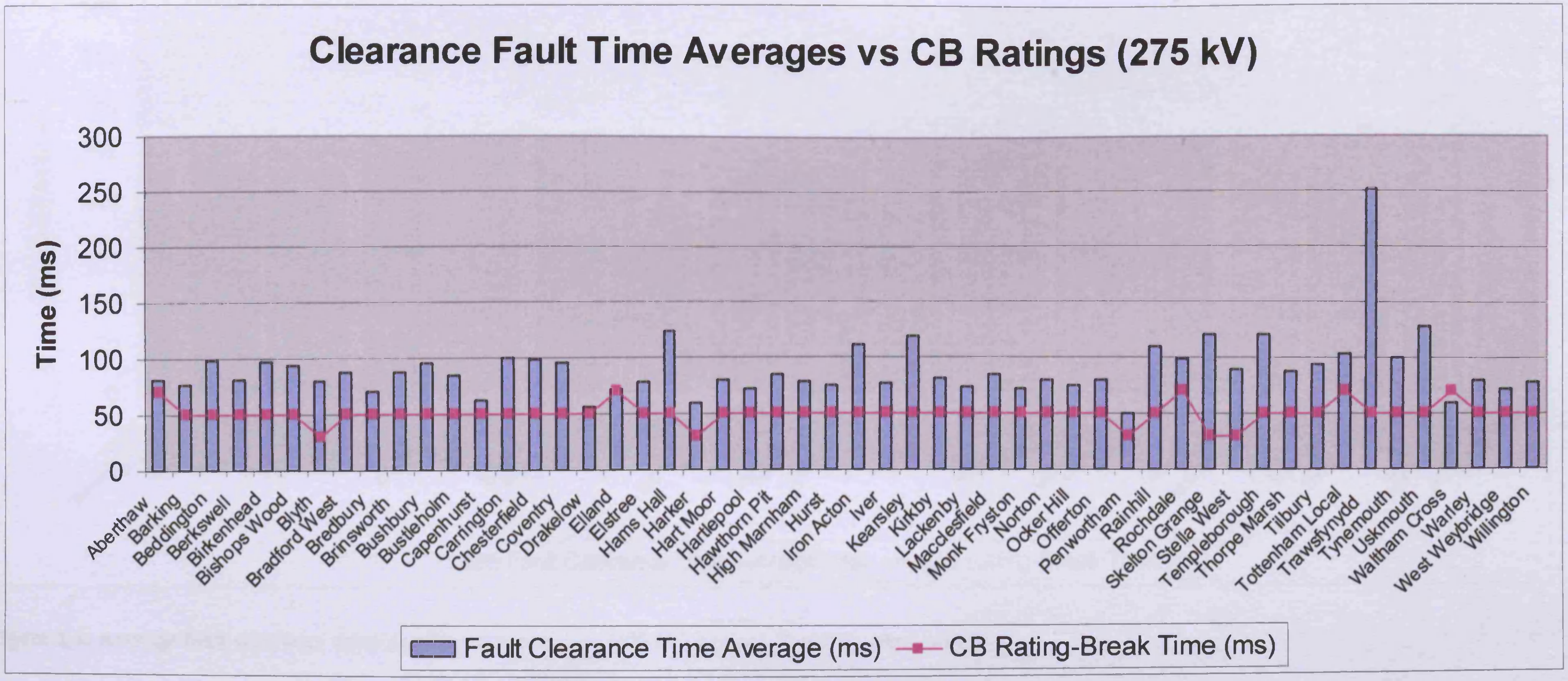


Figure 5.3 : Average fault clearance times at affected substations (275 kV) against circuit breaker ratings.

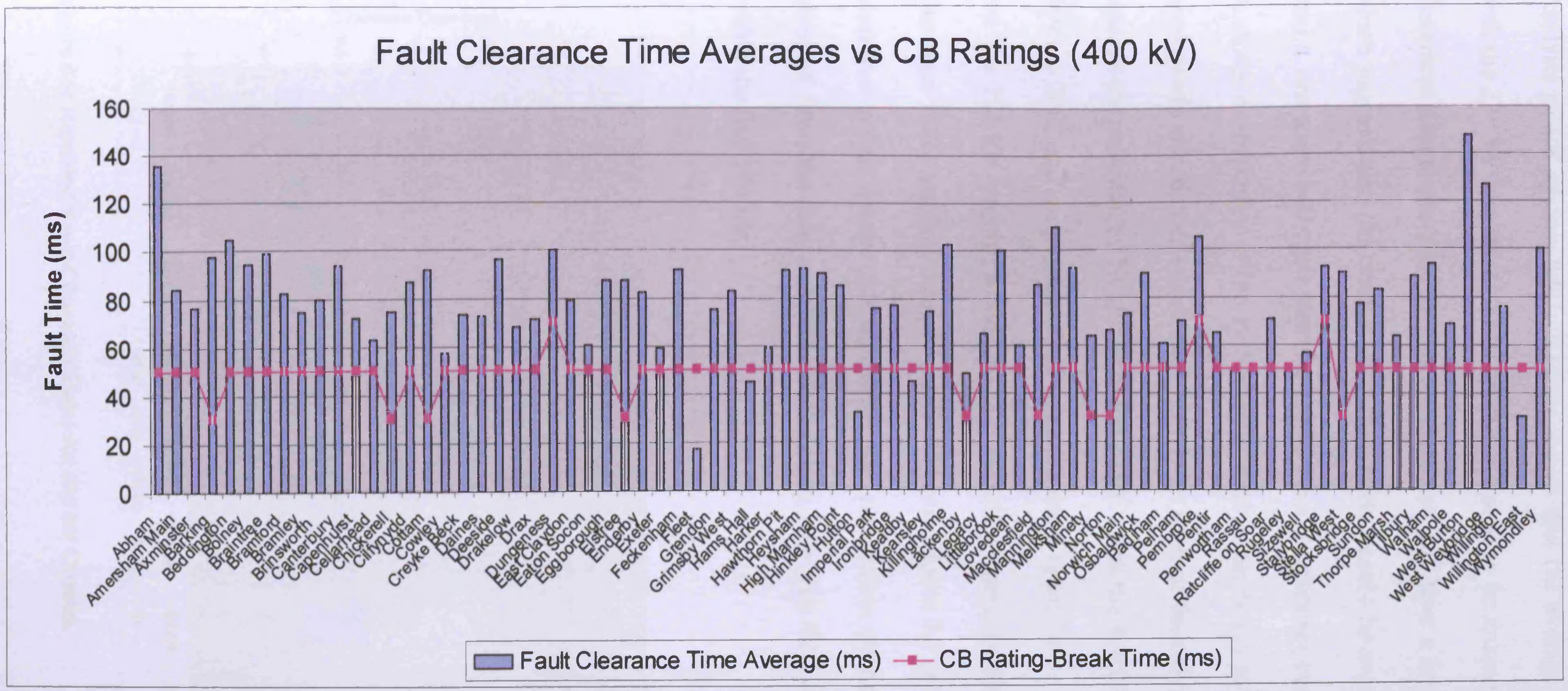


Figure 5.4: Average fault clearance times at affected substations (400 kV) against circuit breaker ratings.

Analysis of the system fault data has shown that the average fault clearance time for both the 275 kV and the 400 kV circuits is found to be around 80 ms. The Seven Year Statement data shows that the large majority of CB have a break time rating of 50 ms, which suggests that the contact separation period could be averaged to an additional 30 ms i.e. one and a half cycle later for the 50 Hz AC operating current.

A closer examination of the system fault data is necessary to draw conclusions on an appropriate selection of a clearance time to be used in the risk assessment studies. Fault records are provided by NG for both the 275 kV and the 400 kV circuits over the period 1993 to 2003 and are presented in Figure 5.5 and Figure 5.6.

For the 275 kV circuits, a total of 317 recordings give an average of 86 ms with the clearance times ranging from 40 ms to 250 ms. Figure 5.7 provides the distribution of clearance times. Figure 5.8 represents the cumulative probability of clearance time obtained from the data, and it is worth noting here that 99% of the faults were cleared within the first 146 ms.

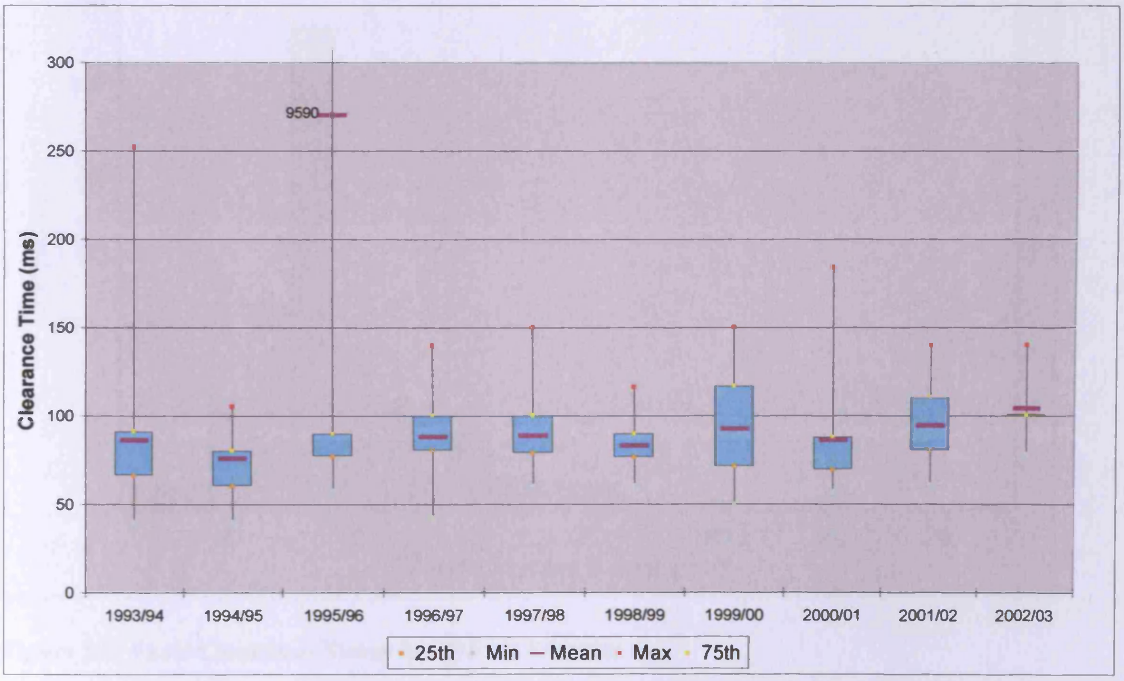


Figure 5.5: Recorded Fault Clearance Times for 275 kV Circuits.

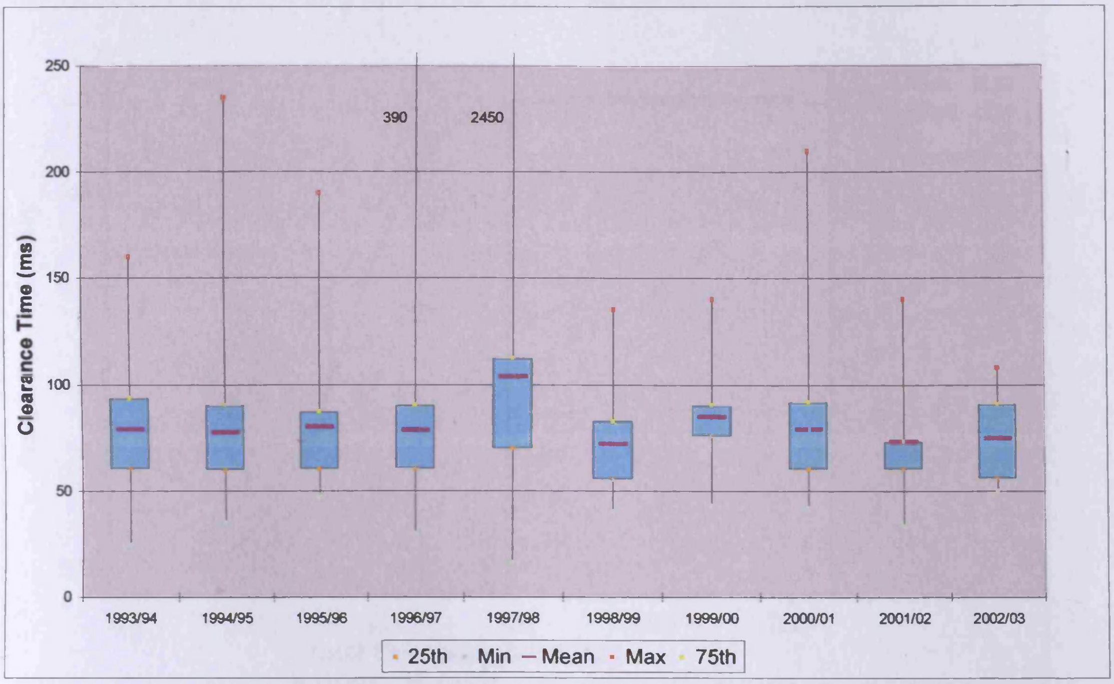


Figure 5.6: Recorded Fault Clearance Times for 400 kV Circuits.

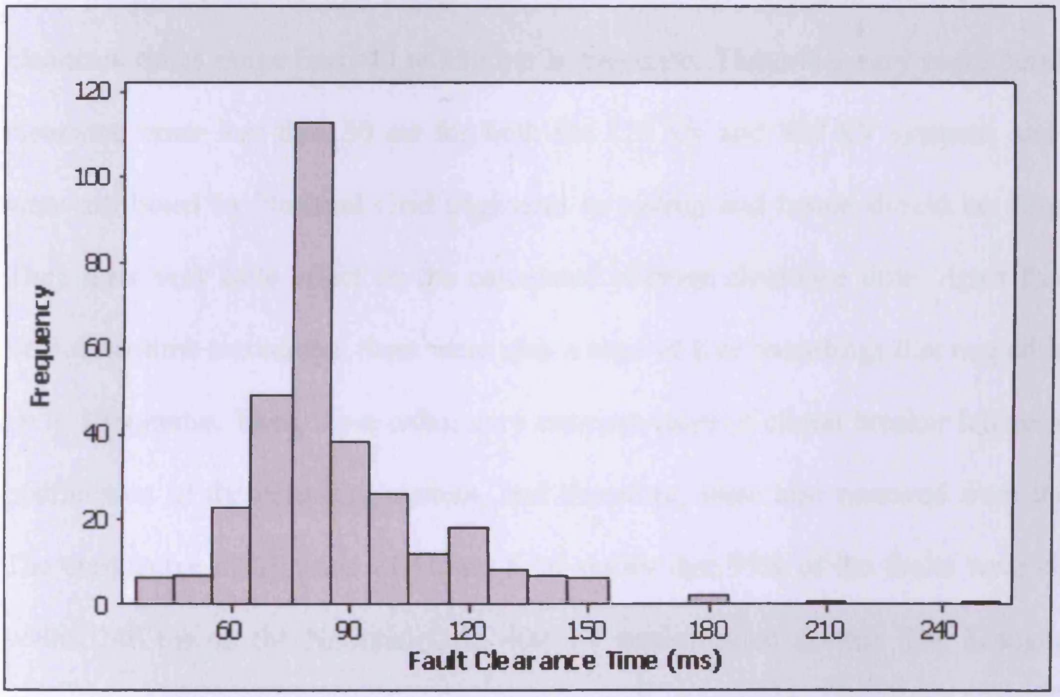


Figure 5.7: Fault Clearance Times for 275 kV Circuits.

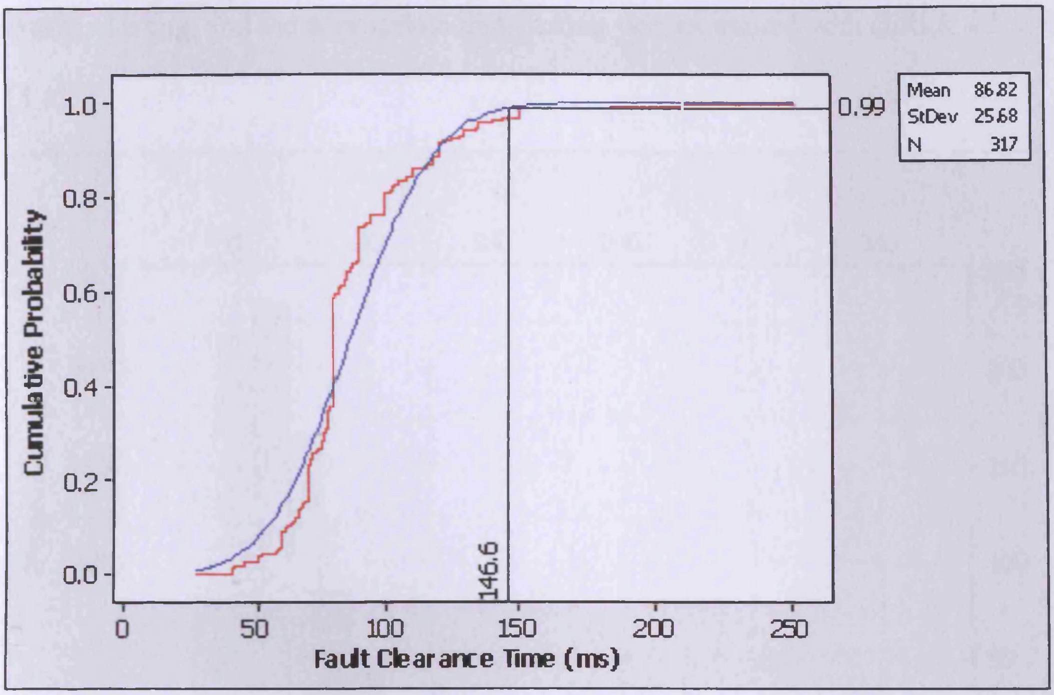


Figure 5.8: Cumulative Distribution Function (cdf) of 275 kV Fault Clearance Times.

For the 400 kV system, there were 886 recordings over the ten year period, and these give an average of 80 ms. As can be seen from the histogram of Figure 5.9, the clearance times range from 40 to 390 ms in this case. There is a very small number of clearance times less than 30 ms for both the 275 kV and 400 kV systems, and these were attributed by National Grid engineers to testing and hence should be discarded. They have very little effect on the calculated average clearance time. Apart from the very short-time recordings, there were also a total of five recordings that ranged from 1 up to 10 minutes. These were either very extreme cases of circuit breaker failure or else malfunction of the recording system, and therefore, were also removed from the list. The cumulative distribution of Figure 5.10 shows that 99% of the faults were cleared within 146 ms on the National Grid 400 kV transmission system. The histogram of Figure 5.11 shows the clearance times recorded for the 400 kV and 275 kV circuits. The data have been filtered from values that were attributed to false recording or circuit breaker testing, and the appropriate distribution was examined with @Risk 4.5 software [5.4].

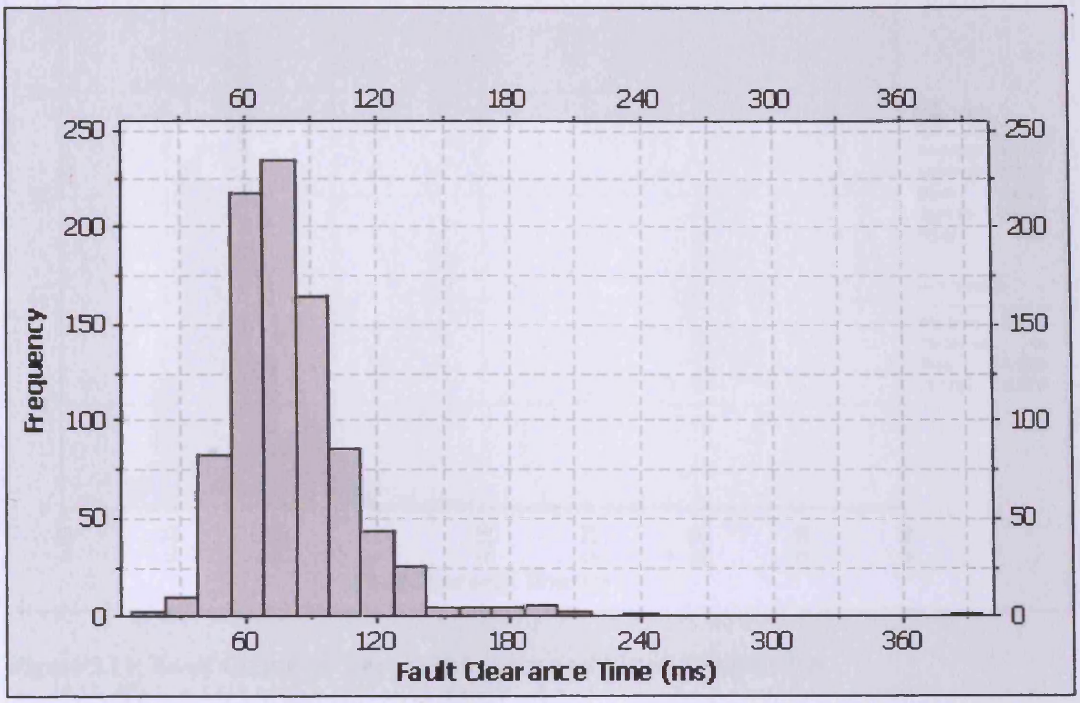


Figure 5.9: Fault Clearance Times for 400 kV Circuits

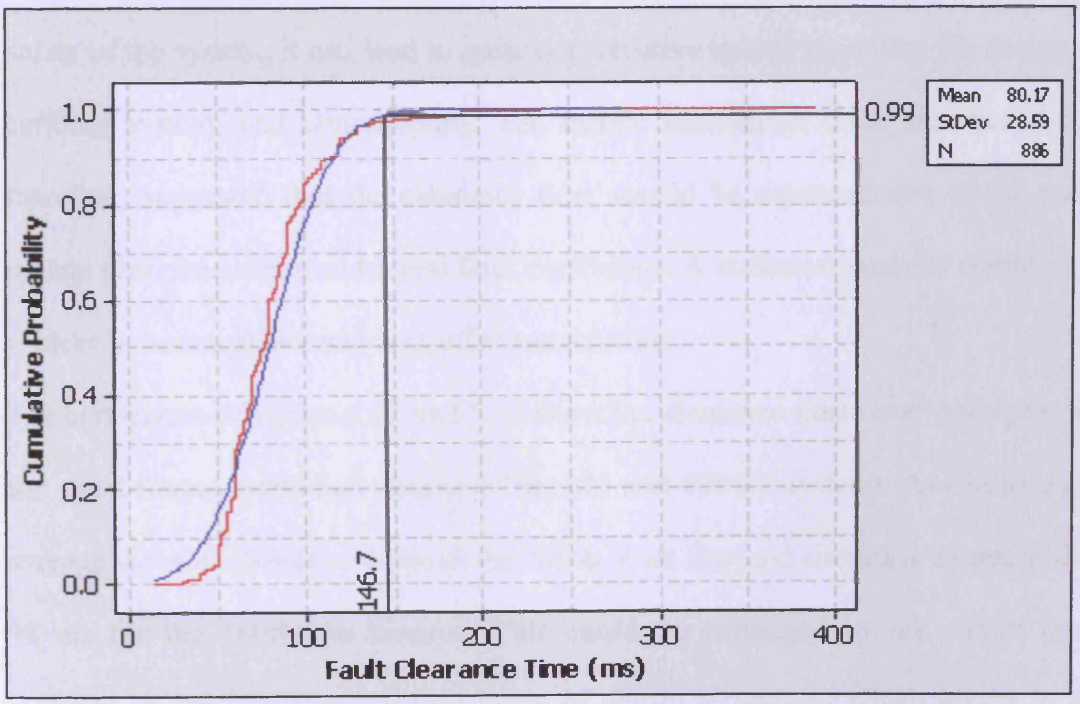


Figure 5.10: Cumulative Distribution Function (cdf) of 400 kV Fault Clearance Times.

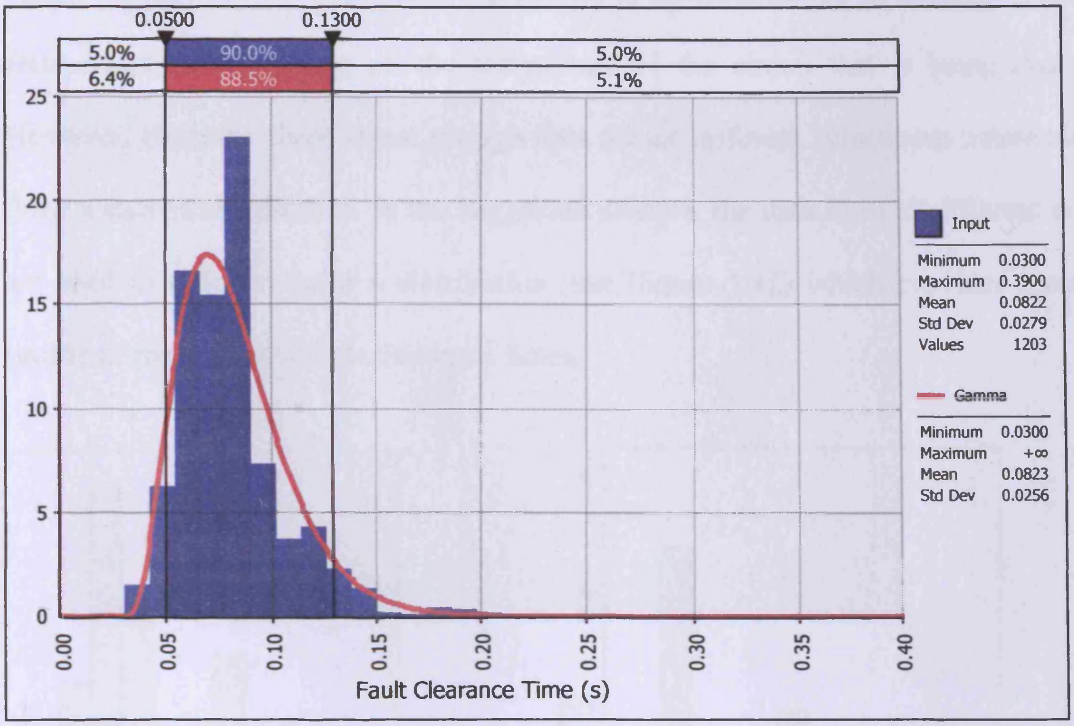


Figure 5.11: Fault Clearance Times Histogram and Fitted Distribution.

Currently, National Grid uses a clearance time of 200 ms for the purpose of risk assessment studies. However, the system indicates that a very small number of recordings reach or exceed this value. Although 200 ms clearance time guarantees safety of the system, it can lead to quite conservative results regarding the design of the earthing system, and consequently, can inflate installation costs significantly. It is, therefore, suggested that the clearance time should be representative of the recorded system clearance times under real fault conditions. A statistical analysis would allow to achieve a more realistic and cost-effective solution.

The histograms of Figure 5.12 and 5.13 show the clearance times over a ten year period for the different individual circuits of the 275 and 400 kV systems. As can be seen, the average value of clearance times in the North-West England circuits is 83 ms, while it is 98 ms for the Pembroke circuits. This could be explained by the circuit breakers installed on the Pembroke circuits being of earlier technology which results in higher clearance times. For this reason, it is proposed to consider the use of different profiles of clearance time depending on the technology of the circuit that is being examined. However, currently there is not enough data for all different substations nationwide, to draw a statistical inference. In the suggested process, the data from all different circuits are used in order to build a distribution (see Figure 5.11) which provides a national profile of the expected fault clearance times.

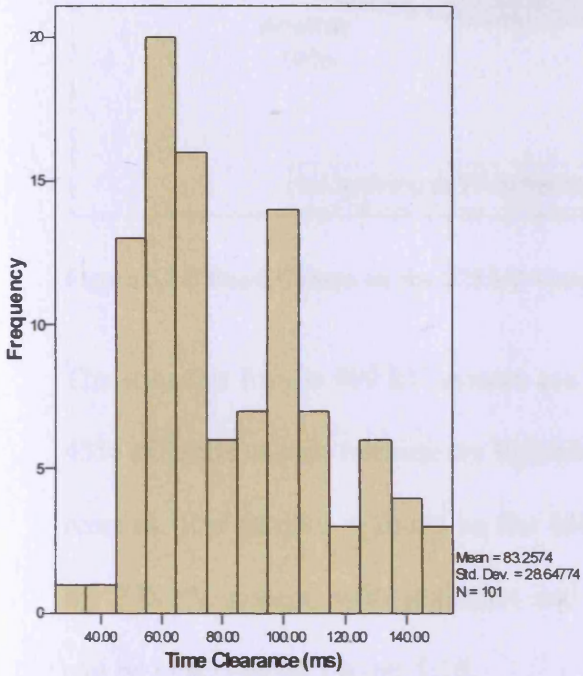


Figure 5.12: North-West England Circuits

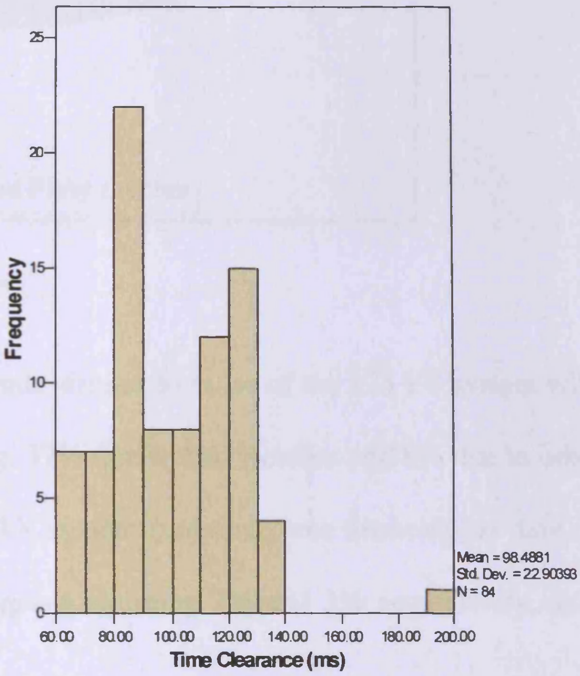


Figure 5.13: Pembroke Circuits

5.3 Fault Causes and Geographical Location

The National Grid fault data also includes the cause of each fault for the ten year period from 1993 to 2003 which are briefly summarised below. As can be seen on Figure 5.14, for the 275 kV system, 43% of the faults are due to lightning, another 39% are weather related, 3% because of third party damages to cables and overhead lines, 15% of the faults are attributed to ‘other’causes which include pollution (especially in urban and coastal areas), ageing, electronic faults, fires close to the lines, faulty manufacture of equipment, bird nests on overhead lines (OHL), failure of cables, demolition of nearby buildings or even cranes touching OHL.

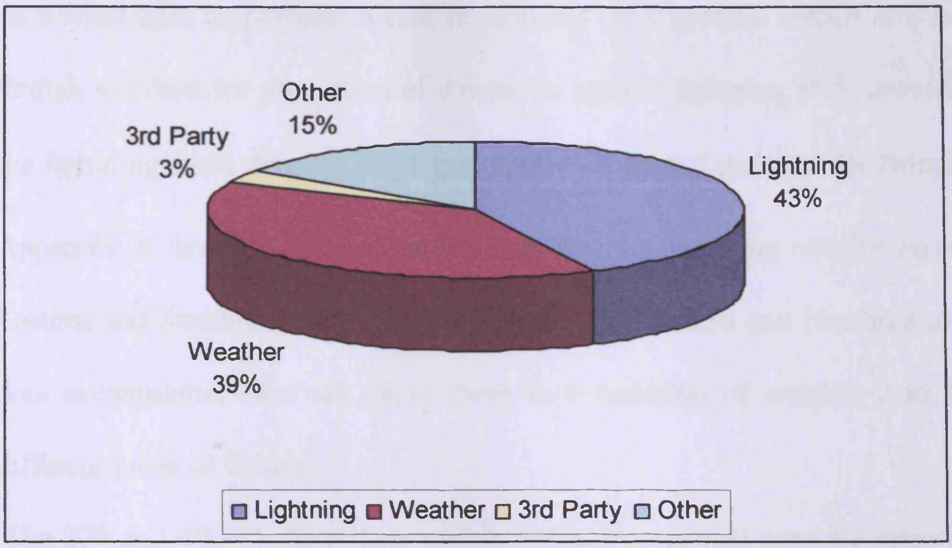


Figure 5.14: Fault Causes on the 275 kV System.

The statistics for the 400 kV system are quite similar to those of the 275 kV system with 45% of faults caused because by lightning, 37% due to bad weather and 8% due to other reasons. The number of faults on the 400 kV system is almost three times higher than on the 275 kV system, with pollution and ageing claiming 7% and 3% respectively, as it can be observed on Figure 5.15.

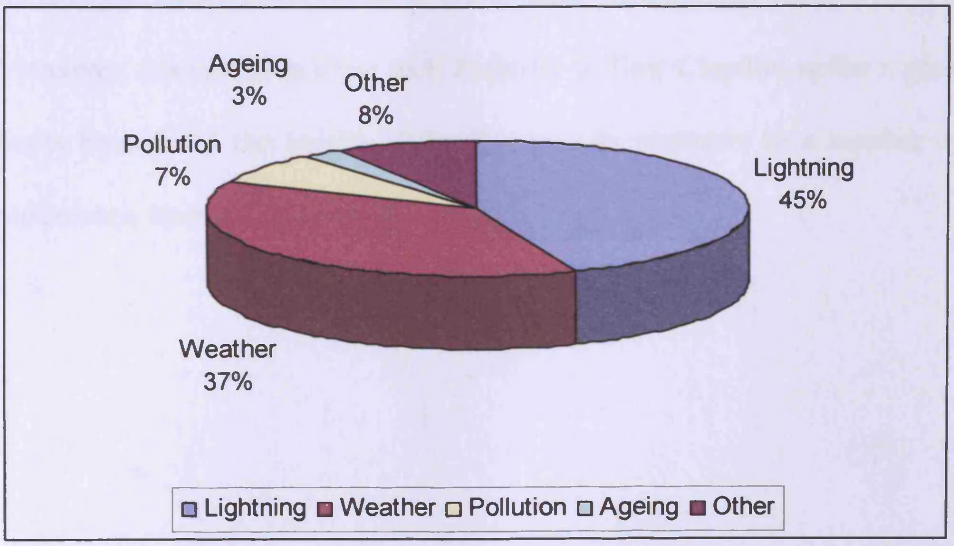


Figure 5.15: Fault Causes on the 400 kV System.

The data, as shown in Figure 5.14 and Figure 5.15 indicates clearly that the effect of lightning is a major parameter when determining the probability of EPR and focusing on a local area to perform a risk assessment on a specific circuit at a substation. The British standard for protection of structures against lightning [5.5] provides a map with the lightning flash density (N_g) per square kilometre per year for Britain as shown in Appendix A. It can be seen from the map that the lightning activity varies and that the Eastern and Southern areas more affected than Western and Northern areas. From the data accumulated over ten years there is a variation of roughly 2 to 1 between the different areas of Britain.

The 275 and 400 kV fault data were graphically mapped onto the maps of Figure 5.16 and Figure 5.17 to show the fault locations on the 275 kV and 400 kV transmission network respectively. This graphical representation of faults has shown that the faults are not evenly distributed but there are areas where the circuits are more prone to faults. Such areas are usually coastal areas or areas where severe weather conditions occur more often. For example, on the Pembroke-Swansea North and the Heysham-Penwortham-Huton circuits, a large number of faults has occurred while circuits like Indian Queens-Alverdiscott seem not to have suffered any faults over a 10 year period. Moreover, transmission lines such Enderby to East Claydon suffer a greater number of faults because of the length of the line and its exposure to a number of extreme and unforeseen weather conditions.

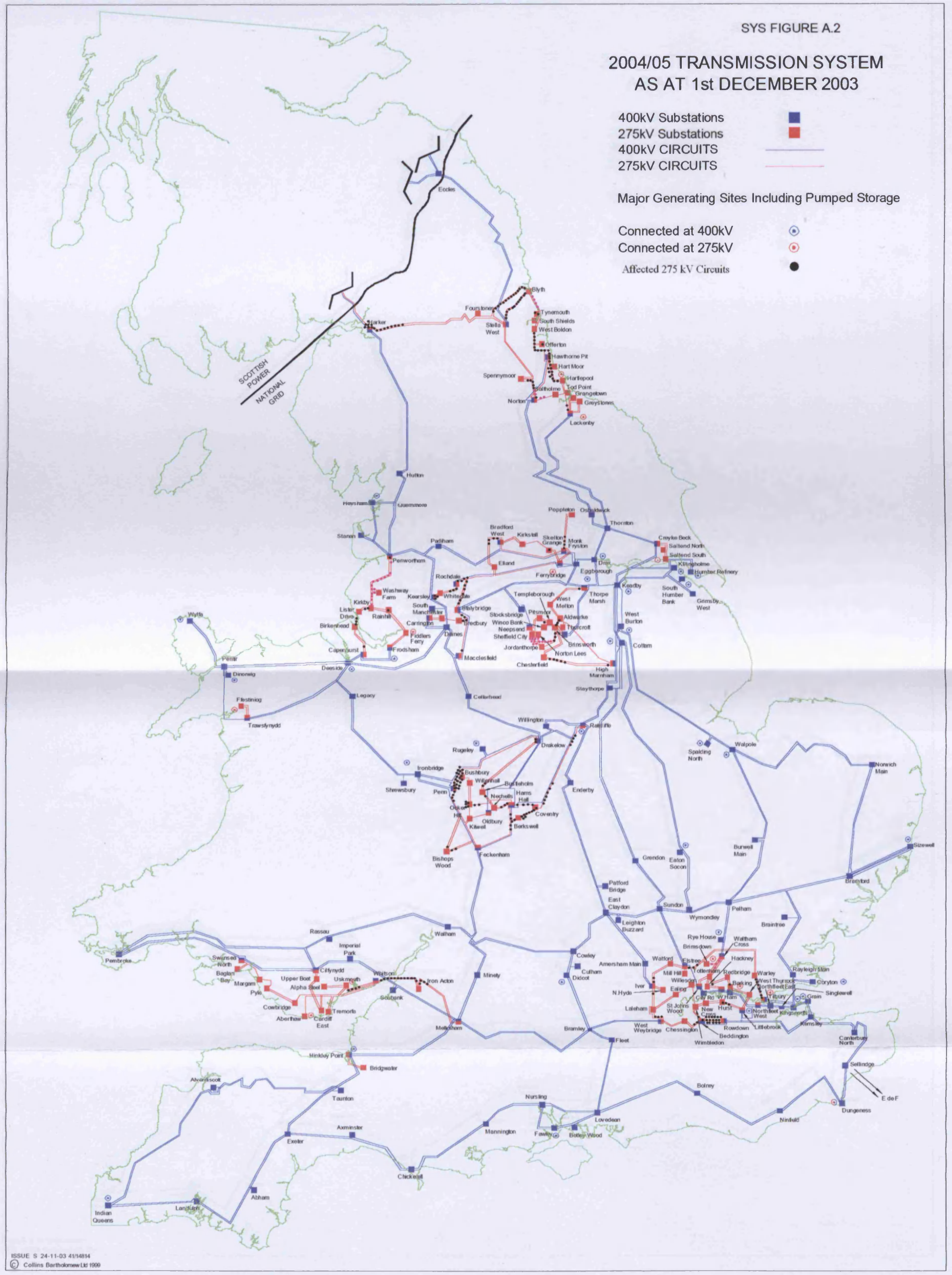


Figure 5.16: Graphical Representation of Faults Recorded from 1993 to 2003 for 275 kV Circuits.

5.4 Fault Frequency

Substations with more incoming/outgoing lines and cables, and larger numbers of equipment are expected to be more prone to faults [5.6, 5.7]. The information in the available fault data for the period 1993-2003 includes the affected circuit and the cause of each fault. However, the exact location of the fault is not specified. Hence, although the cause can be, for example, lightning or ageing, the exact location of the fault, whether it took place on an overhead line or inside the substation, was not recorded. However, since almost 80% of the faults are caused by lightning and extreme weather conditions, it can be assumed that the majority of the faults take place on the overhead lines that are exposed to such conditions.

A National Grid technical report, describing the transmission system fault performance [5.8], provided supplementary data shown in Appendix B for the three year period 1997 to 2000. This data, graphically presented on Figure 5.18, indicates that from a total of 564 faults over the three year period, 453 faults took place on overhead lines and cables.

As can be seen on the pie chart of Figure 5.18, these faults cover 81% of the total faults, followed by an 11% of faults on transformers and reactor circuits, and the remaining faults being either on busbars, other plants or unknown to NG.

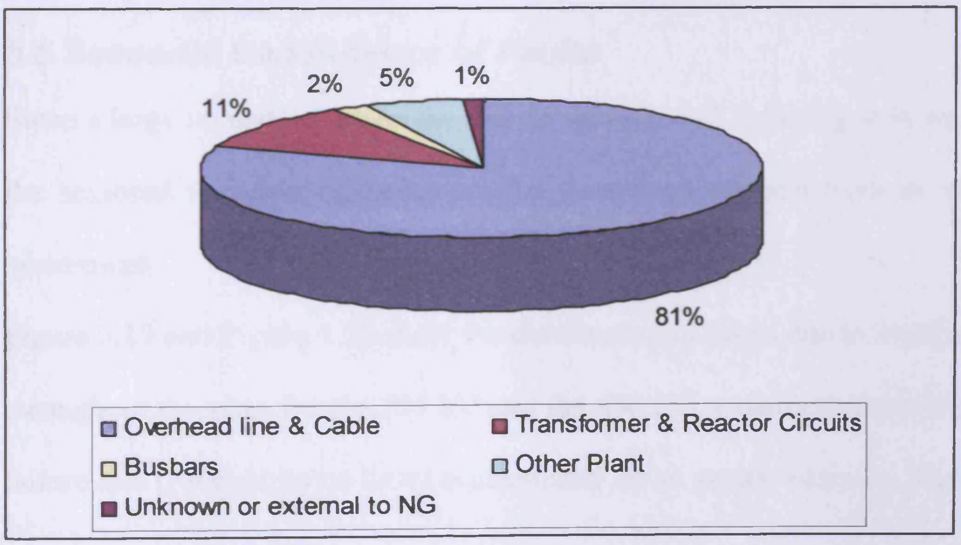


Figure 5.18: Location of Faults on the Transmission System (data from [5.8]).

Assuming that there are about 250 substations interconnected by 15000 km of overhead lines and 500 km of underground cables and that each substation contains on average 6 equipment bays [5.7, 5.9], the fault rate per substation bay is:

$111 \times \frac{12}{36} \times \frac{1}{250} \times \frac{1}{6} \approx 0.025$ faults per substation bay per year. (1 every 40 years)

The fault rate per overhead line is calculated for the first 5 km of the circuit that can cause rise of earth potential at the substation, and is estimated to:

$433 \times \frac{12}{36} \times \frac{5}{15000} \approx 0.05$ faults per line end per year. (1 every 20 years)

Similarly, the fault rate for cables is estimated for the first 5 km of the circuit and is:

$20 \times \frac{12}{36} \times \frac{5}{500} = 0.06$ faults per cable end per year (1 every 15 years)

The total fault rate of a substation is calculated using Equation (5.1):

$$f = 0.05L + 0.06C + 0.025B \tag{5.1}$$

where L is the number of line ends, C is the number of cable ends and B is the number of switchgear bays. Although some 90% of the total faults occurring in a year can be classified as earth faults [5.10], it is estimated that only 25% to 50% will result in significant current flow [5.9].

5.5 Seasonal Dependence of Faults

Since a large number of faults are due to weather and lightning, it is worth considering the seasonal variation of faults on the system which will have an effect on safety assessment.

Figure 5.19 and Figure 5.20 show the distribution of faults due to weather and lightning throughout the year, for the 275 kV and the 400 kV systems respectively. Although the failure rate (Probability of EPR) is calculated on an annual basis i.e. faults per year, it is worth noting that, during the autumn months, the percentage of faults due to lightning/weather is low.

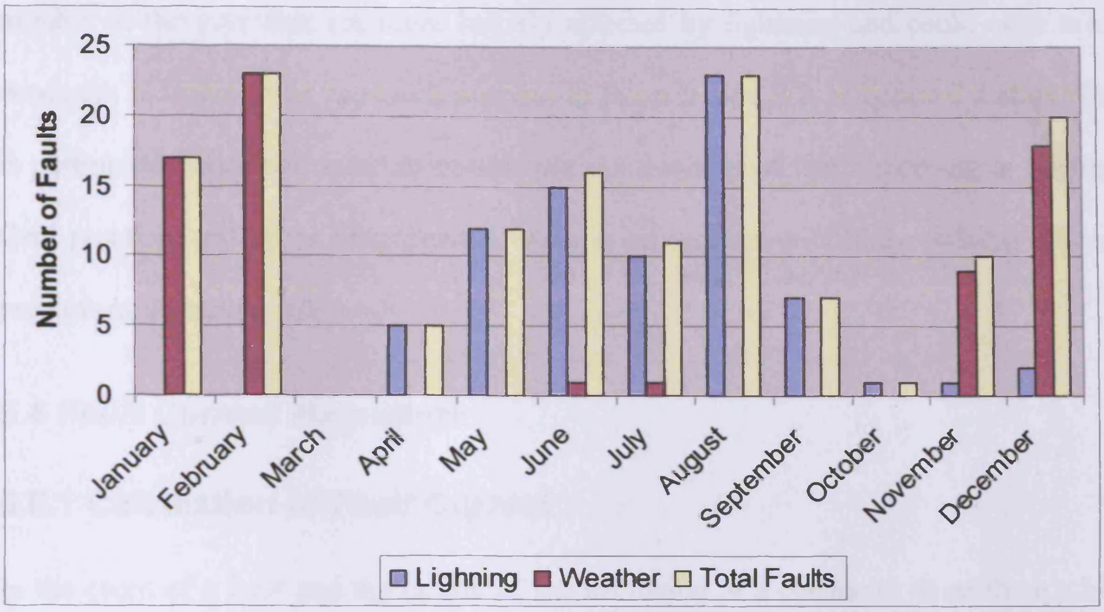


Figure 5.19: Seasonal Dependence of Weather & Lightning Faults on 275 kV Systems.

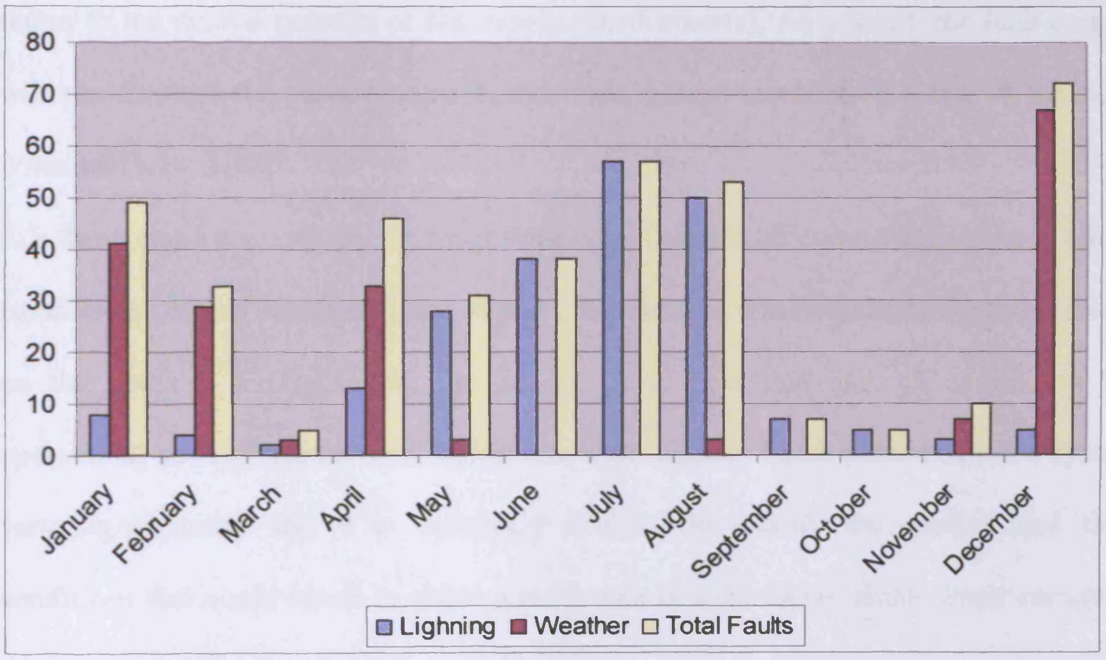


Figure 5.20: Seasonal Dependence of Weather & Lightning Faults on 400 kV Systems.

However, during the summer months, the highest lightning activity takes place, hence most lightning faults occur. Therefore, the application of a constant failure rate throughout the year, and hence, of a constant probability of rise of earth potential as described in Section 5.4, may be considered as an over optimistic estimate for those months of the year that are more heavily affected by lightning and could raise safety concerns. However, this approach remains in the safe side if it is assumed that no work is performed under bad weather conditions. As a matter of fact, according to National Grid practice, testing or maintenance work is carried out only if the weather forecast predicts no lightning risk.

5.6 Fault Current Magnitude

5.6.1 Calculation of Fault Current

In the event of a fault and the failure of the insulation of a conductor to earth on a high voltage system, the fault current or a proportion of it, will flow through the earth and return to the neutral point(s) of the supply transformer(s). As a result, the fault current will run through the substation earth electrode system resulting in a rise of the earth potential [5.11, 5.12].

In a three-phase a.c. system, the magnitude of a short-circuit current depends on various parameters. At any location in the system, the fault current magnitude depends mainly on the network configuration, the generators in operation and, of course, on the operational state of the network before the short circuit. These parameters in a system vary significantly, and it is extremely difficult to specify the special load flow conditions that could result in either a maximum or a minimum short-circuit current at the various locations of the system [5.13, 5.14].

In order to calculate the fault levels, a simplified calculation methodology was developed and was published in the International Standard IEC909 "Short-Circuit Calculation in three-phase a.c. systems". British Standard BS 7639 follows this methodology [5.3, 5.14, 5.15]. This analytical methodology is very conservative, and could lead to increased investment for earthing.

Engineering Recommendation G74 [5.16] allows three-phase to earth and single phase to earth short circuit analyses to be computed more accurately, and these are published in the Seven Year Statement [5.3].

5.6.2 Effect of Fault Locations on Fault Current Magnitude

As seen in Sections 5.3 and 5.4, almost 80% of all faults on the NG transmission system are caused by lightning and bad weather conditions, and most of these affect overhead lines. Hence, it is of importance to calculate the fault current of these faults either using analytical methods [5.17, 5.18] or simulation software.

High-voltage systems have an effectively grounded neutral. In this case, when a ground fault occurs on an overhead transmission line, the fault current returns to the grounded neutral through the tower structure, ground return paths and ground wires [5.19].

It is usually assumed that the impedance of the fault-arc itself is very small and negligible in comparison with other impedances in the circuit. Consequently, it is usually not taken into account in practice. However, the fault-impedance includes the resistance of tower-footing and (if applicable) the contact resistance between fallen conductors and earth [5.13].

Overhead line impedances can be readily calculated from the line dimensions or they are provided from look up tables for already operational networks [5.3]. Also, tables provide approximate values of the ratio of zero sequence impedance. If only approximate results are required, or if the impedance of the overhead line is small compared with other impedances in the circuit, the values given in such tables can be used. Alternatively, the actual zero-sequence impedance of the line or lines should be determined by testing or by calculation.

In parallel conductors, such as overhead line earth wires and cable sheaths/armours, substantial induced currents can flow when the associated circuit phase conductors carry earth fault currents. This current returns to the source without entering the ground, so it does not cause any rise of earth potential.

For an overhead line with a single earth wire and with the circuit long enough so that the combined value of the terminal earthing resistances at each end of the line is small compared to the earth wire impedance (Z_S), a good approximation of the current returning to the ground (I_{gr}) is given by:

$$I_{gr} = k \cdot I_r \tag{5.1}$$

and $$k = \left(1 - \frac{z_{mp.s}}{z_s}\right) \tag{5.2}$$

where $z_{mp,s}$ is the mutual impedance between line conductor and earth wire (Ω / km), and z_s is the earth wire impedance (Ω / km).

Table 5.2 provides magnitudes of current returning to ground (I_{gr}) as a percentage of the fault current (I_r) and phase angle with respect to (I_r), for most overhead line circuits which operate at 132 kV, 275 kV and 400 kV [5.11].

Table 5.2: Values of ground current (I_{gr}) as a percentage of (I_r) and corresponding phase angle Φ_{gr} [5.11].

Type of Line and Conductor Size (mm^2)	I_{gr} as a percentage of I_r	Phase Angle of I_{gr} with respect to I_r (Φ_{gr} degrees lead)
132 kV (L4) (1x175)	70.8	171
132 kV (L7) (2x175)	63.6	177
275 kV (L3) (2x175)	66.9	178
275 kV (L2) (2x400)	68.6	178
400 kV (L8) (2x400)	70.0	179

400 kV (L6) (4x400)	69.2	179
400 kV (L9) (4x400)	64.0	179

In this section, the results of an investigation of the effect of fault location on fault current magnitude for a long transmission line are presented. The study includes fault current simulations on a small network using NEPLAN software. An eight node generic network with double circuit lines was used to investigate the effect of fault location on fault current distribution. Figure 5.21 shows a line diagram of the simulated network.

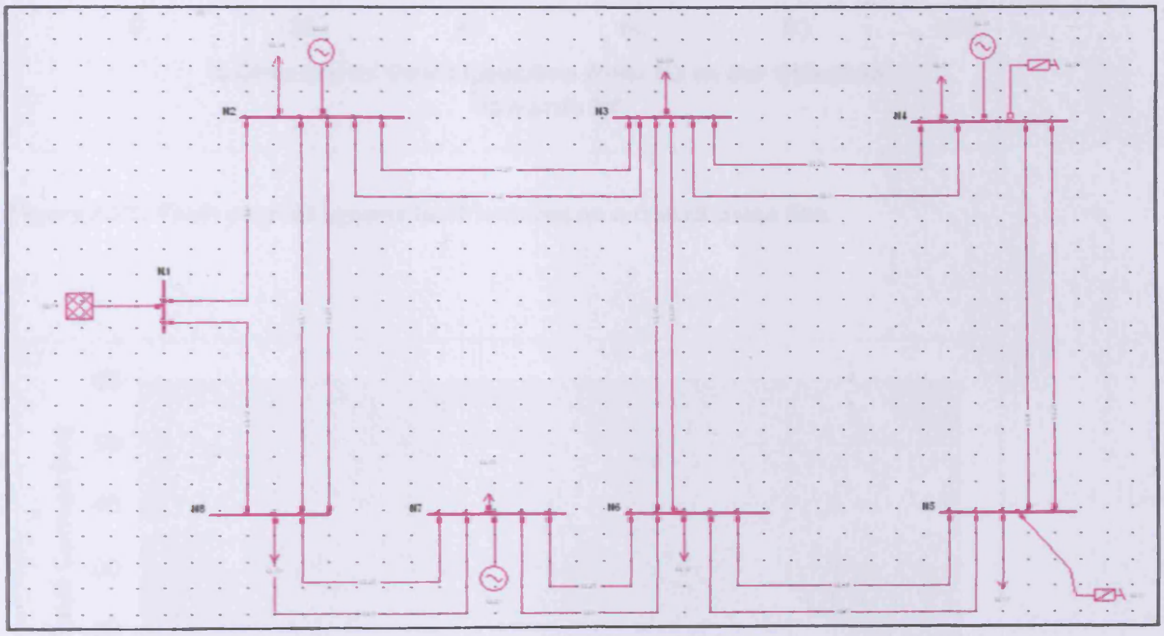


Figure 5.21: Model of the Simulated Circuit.

The transmission line and power station characteristics were taken from the Seven Year Statement of National Grid. The line under investigation is named EL3 and has a length of 168 km located between Node 3 and Node 4. Figure 5.22 shows the computed current magnitude along the line.

As can be seen, the minimum fault current is obtained when the fault occurs at mid-line. The difference between minimum and maximum possible fault currents can be as high as 41%. However, for shorter transmission lines, the difference is less significant. For a 40 km transmission line, only 25% is computed (Figure 5.23).

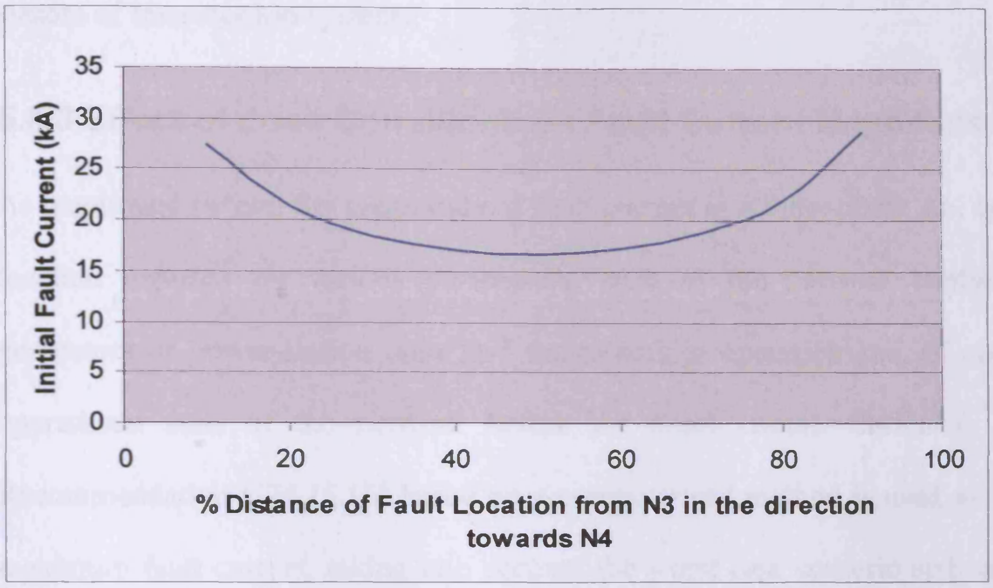


Figure 5.22: Fault current against fault location on a transmission line.

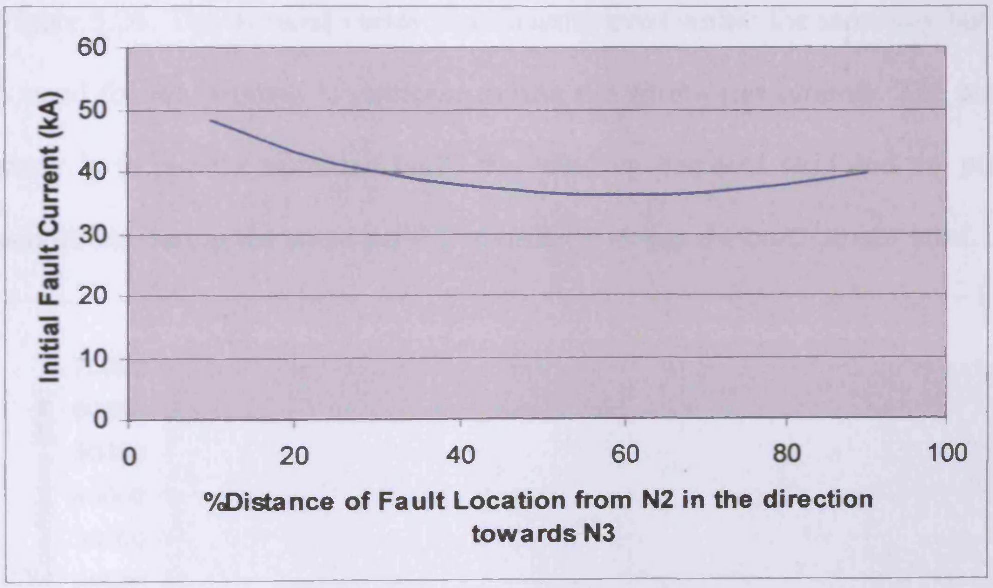


Figure 5.23: Fault current against fault location on a transmission line.

Such observation suggests that for a full risk assessment of two neighbouring substations, the dependence of fault current magnitude on line length and fault location can play a significant role. Therefore, taking into account the statistical variability of fault location [5.20] coupled with modelling Extreme-Weather-Related Transmission Line Outages [5.21] would allow more representative risk assessment on the earthing system of transmission systems.

5.6.3 Effect of Load Conditions on Fault Current Magnitude

As mentioned before, the magnitude of fault current in a three-phase a.c. system at any location depends on various parameters, such as the network configuration, the generators or power-station units and the motors in operation and, of course, on the operational state of the network before the short circuit. Currently, Engineering Recommendation G74 [5.16] based on a computerised method is used to calculate the maximum fault current, taking into account the worst case scenario and, consequently, by using maximum load conditions for the system.

Recorded data of the demand of Great Britain [5.22] for the year 2003-2004 is shown in Figure 5.24. The demand varies significantly even within the same day but also there is a trend for the demand to decrease during the spring and summer. The purpose of this study is to use the recorded faults provided by National Grid and the published load conditions during the same period, in order to assess the fault current level.

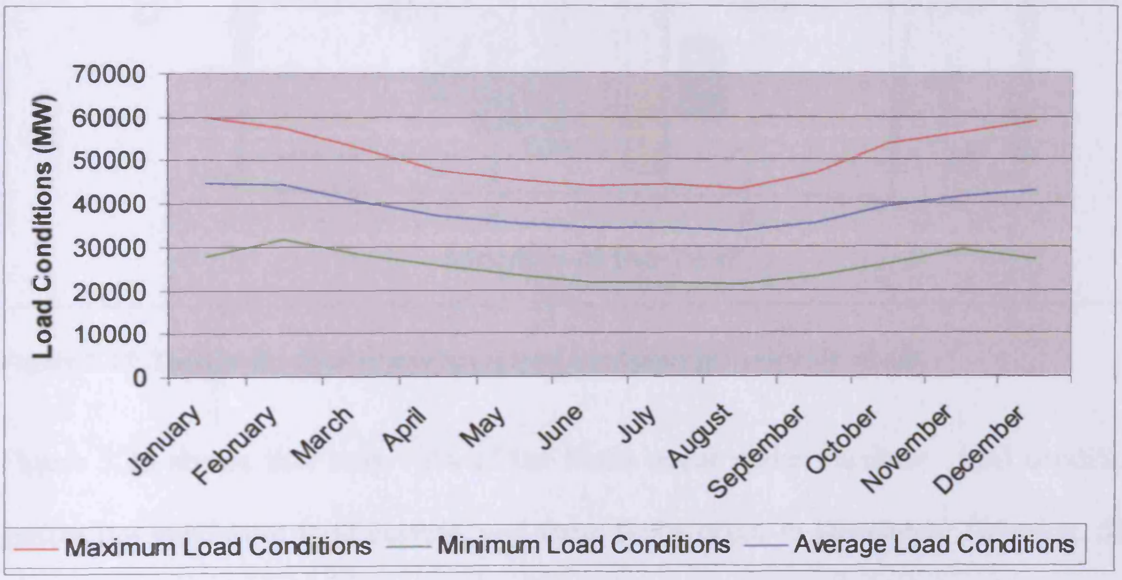


Figure 5.24: Great Britain Demand for 2003-2004 (MW) (data source [5.22]).

Unfortunately, the exact time of the fault was not recorded. Therefore, the fault current was calculated for the maximum value of load within a particular month. It is, therefore, expected that the fault current magnitude will increase with network configuration, which may be affected with load conditions. Here, the annual changes of demand were neglected. Combining the data shown in Figure 5.19 and Figure 5.20 with the demand data of Figure 5.24, the number of faults per month with the corresponding load conditions when the faults occurred, are shown on Figure 5.25.

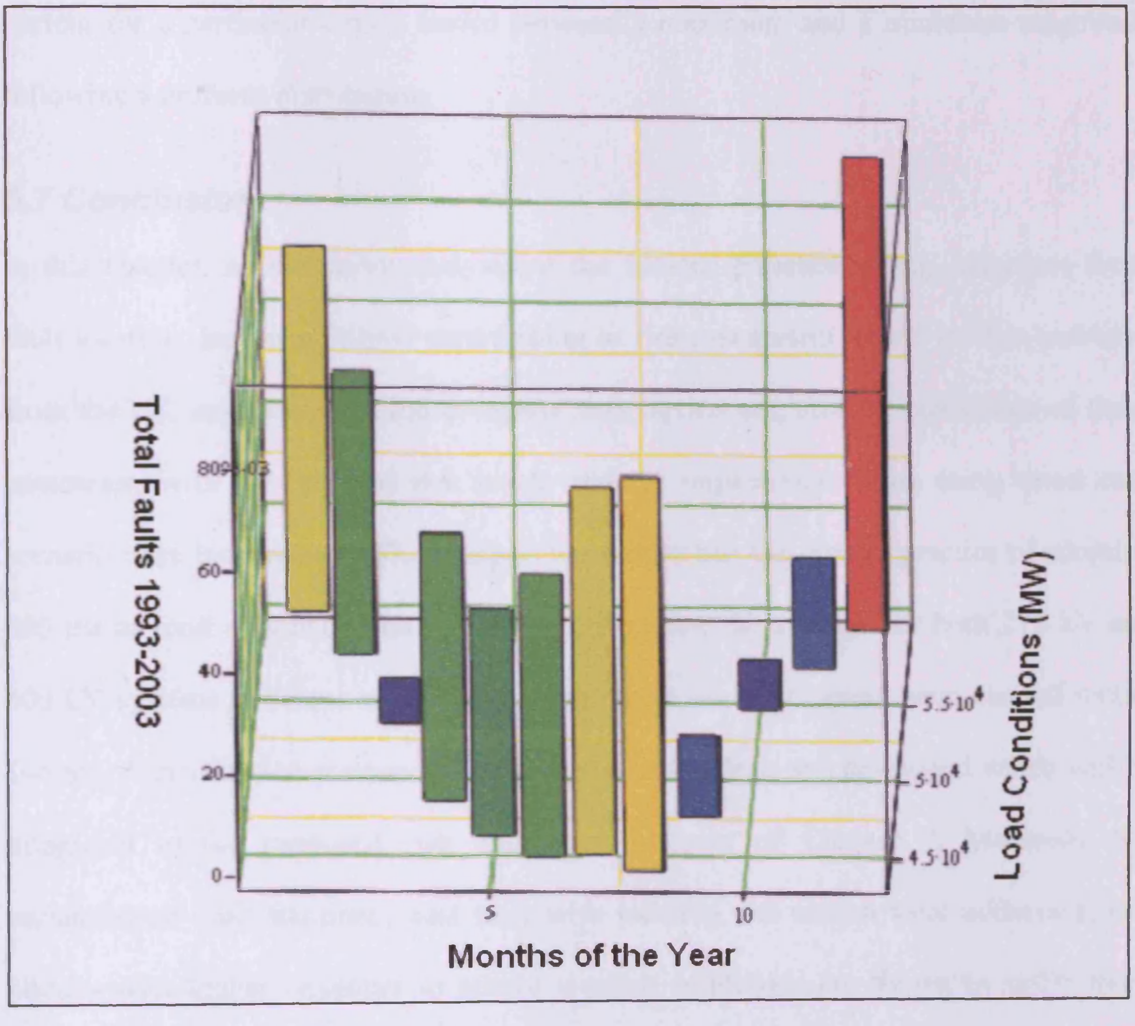


Figure 5.25: Total faults against maximum load conditions per calendar month.

Figure 5.25 shows that only 16% of the faults occur under maximum load conditions generating maximum fault current, and these faults occur in December. However, 53% of all faults, which occur during spring and summer months are expected to have fault currents that are at least 25% lower compared with the maximum possible magnitude. In summary, because of the variability during the month and even the day, it is expected that only a very small percentage of the recorded faults would actually generate maximum fault current magnitude as used in current practice.

In a probabilistic risk assessment, the worst case scenarios i.e. maximum load condition will be included in the assessment but with its frequency of appearance in practice. In the proposed probabilistic risk assessment process described in Chapter 7, the fault current for a particular circuit varies between a maximum and a minimum magnitude following a uniform distribution.

5.7 Conclusion

In this chapter, an extensive analysis of the various parameters (e.g. clearance time, fault location, load conditions) contributing to risk assessment, based on data provided from the UK main transmission company was carried out, and the correlation of these parameters with the imposed risk levels and the implications when using worst case scenario were investigated. The analysis has shown that the current practice of adopting 200 ms as fault clearance time is conservative since the average for both 275 kV and 400 kV systems is 80 ms and 99% of faults for a ten year period were cleared within 146 ms. A distribution corresponding to the recorded time was developed which will be integrated in the proposed risk assessment process of Chapter 7. Moreover, the variability of fault frequency and time with location and season were addressed, and circuits with higher exposure to severe weather conditions are shown to suffer more faults while circuits with higher fault clearance times were linked to protection systems of earlier technology. Also, the fault current magnitude was investigated in relation to location of fault on the transmission line and load conditions of the system. The study showed that only a very small number of faults actually occurred under maximum fault conditions. Finally, by simulating a generic network, it was found the fault current can vary by up to 40% depending on the location of faults on the transmission line, which account for 80% of the total faults.

CHAPTER 6. DEVELOPMENT OF NEW RISK ASSESSMENT PROCEDURE: THE CARDIFF RISK ASSESSMENT FACILITY FOR TRANSMISSION SYSTEMS (CRAFTS)

6.1 Introduction

Having examined the various factors that govern earthing systems and their safety, it was realised that Risk Assessment of earthing systems is still in need of further development and structuring. In this chapter, a new approach is developed to facilitate such investigations and help engineers and asset managers to make informed decisions with regards to safety of earthing systems. Within the time of this thesis, the extensive background to safety requirements and parameters on electrical systems was explored in detail which allowed a clear vision of the process to be developed. This is now implemented through the development of a computerised routine for risk assessment. The developed software problem named Cardiff Risk Assessment Facility for Transmission Systems and referred to here as CRAFTS is already a significant improvement on existing practice. Further refinement of the probabilistic assessment is proposed in Chapter 7.

In this chapter, the developed CRAFTS program is presented. It performs probabilistic risk assessment and integrates the latest developments of the relevant standards [6.1-6.4]. The Interface was built using Matlab V 7.0 and is a standalone application. The aim was to create a user friendly tool which would allow engineers to either perform analytical calculations on the earthing system or use simulation results to conduct a risk assessment of the site.

Following discussion with engineers from the sponsoring companies, it was agreed that the analytical calculations of the earthing system characteristics would comply with

British Standard BS 7354:1990 recommendations [6.1]. In addition, the software incorporates all the latest international developments adopted by IEC 60479 standard [6.4] concerning the accidental circuit, as well as the probability surface of ventricular fibrillation as developed in Chapter 4.

6.2 Capabilities of Developed CRAFTS program.

CRAFTS performs the following calculations and safety assessments:

- Analytical calculation of Earth Resistance of Grid, Earth Wire Chain Impedance and Earth Impedance of Cable Sheath based on BS 7354 [6.1].
- Calculation of EPR based on earth fault current distribution in overhead lines and cables according to BS 7354 [6.1].
- Calculation of prospective Touch/Step voltages in case of earth fault.
- Calculation of Body Impedance taking into consideration its voltage dependence and current path according to IEC 60479 [6.4].
- Allows for the inclusion of additional resistances in the calculation such as contact resistance, footwear and gloves.
- Calculation of allowable Touch/Step voltages based on the IEC 60479 curves of allowable body current, taking into consideration the current path and associated heart factor.
- Determines whether the step and touch voltages generated by fault currents are safe or not.
- Allows a second stage safety assessment performed through probabilistic risk assessment.
- Finally, determines whether the individual risk is acceptable by comparing it against the ALARP criteria.

6.3 Total Earthing Impedance

The total earth impedance is further reduced when the overhead line earth wires and the earthed cable sheaths are connected to the grid. The approximate equations described in BS 7354 [6.1] are used to calculate the grid resistance, the chain impedance of lines and the impedance of cable sheaths. The total impedance is given by:

$$Z_T = \left[\frac{1}{R} + \left(\frac{1}{Z_{L1}} + \ldots \frac{1}{Z_{Ln}}\right) + \frac{1}{Z_{C1}} + \ldots \frac{1}{Z_{Cn}}\right]^{-1} \tag{6.1}$$

Where: R is the resistance of grid to earth (Ω)

Z_L is the line earthwire chain impedance to earth (Ω)

Z_C is the cable sheath impedance to earth (Ω)

Figure 6.1 shows the dialog box for the calculation of the substation earth impedance.

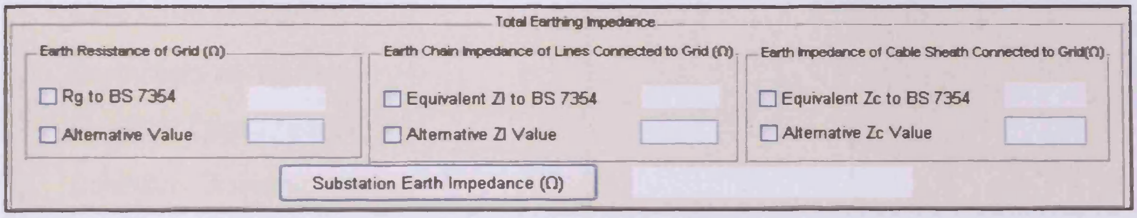


Figure 6.1: Input and Calculated Substation Total Earthing Impedance.

For each of these impedances the option to use alternative values is also provided which may come from experimental measurements or simulation.

6.3.1 Earth Resistance of Grid

The electrode resistance is given by the following equation:

$$R = \rho\left\{\frac{1 + \left(\frac{r}{r + 2.5h}\right)}{8rK_R} + \frac{1}{L}\right\} \tag{6.2}$$

Where: ρ is the soil resistivity (Ωm)

r is the equivalent circular plate radius (m) given from $r = \left(\frac{GridArea}{\pi} \right)^{0.5}$ (6.3)

h is the depth of burial of grid (m)

L is the total length of buried grid conductors

K_R is a constant which is dependent on number, position and length of earth rods connected to the grid, given by: $K_R = \left(\frac{1 + n_R (l_R)^2}{10r^2} \right)$ (6.4)

Where: n_R is the total effective number of rods and l_R is the length of the earth rods (m). Figure 6.2 shows the dialog box for the analytical calculation of the grid earth resistance.

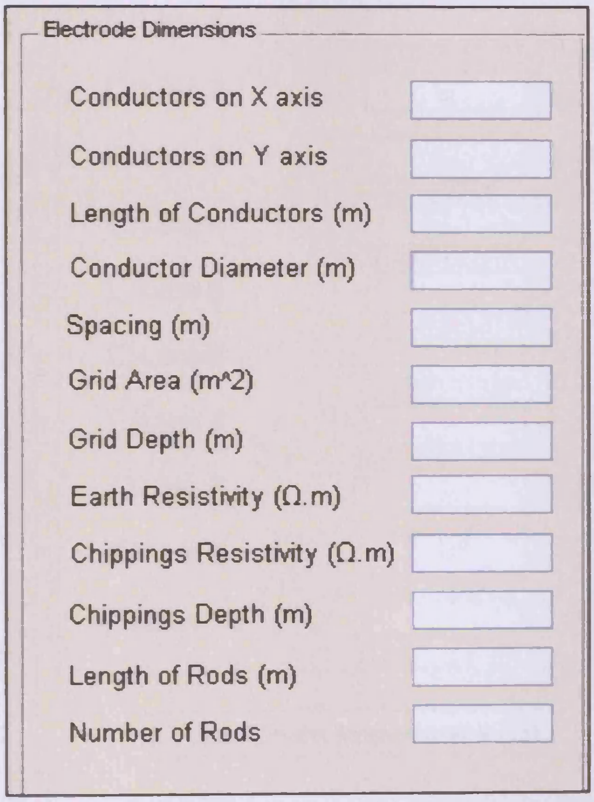


Figure 6.2: Input Box for Grid Parameters for Analytical Calculation of Electrode Resistance.

6.3.2 Earth Chain Impedance of Lines

In the following box, the earth chain impedance of the lines connected to the grid is calculated using:

$$Z_L = 0.5Z_g + \left(Z_g R_T\right)^{0.5} \tag{6.5}$$

Where: Z_g is the earthwire impedance to ground per span (Ω) and R_T is the footing resistance (Ω). Figure 6.3 shows the dialogue window for the calculation of earth chain impedance of the overhead lines connected to the substation.

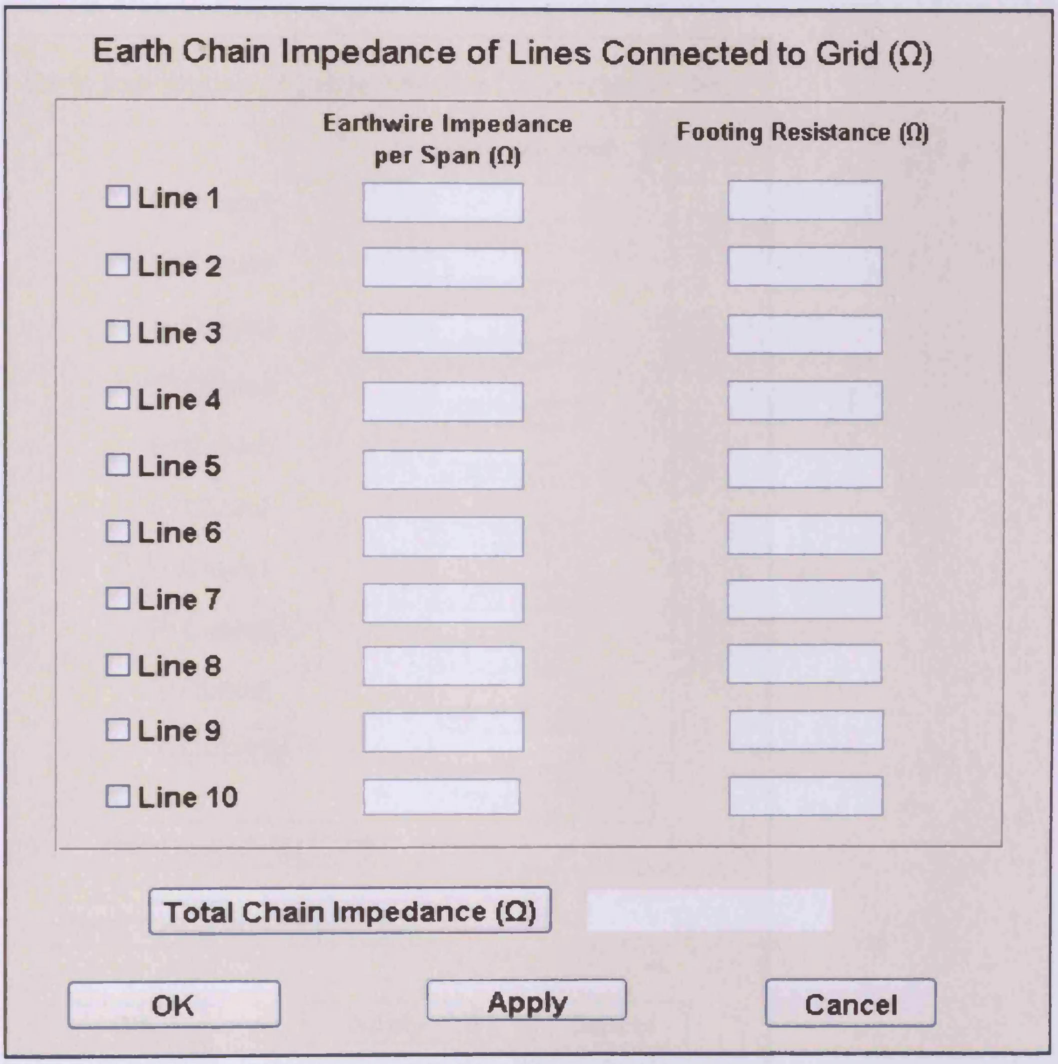


Figure 6.3: Input and Calculation of Earth Chain Impedance of Lines Connected to the Grid.

6.3.3 Impedance of Cable Sheath to Earth

The impedance of the cable sheath depends mainly on the length of the cable rather than the size of the cable or how deep it is buried [6.1]. Based on published analytical derivations, the impedance is given by:

For $l < 60\sqrt{\rho}$ from $$Z_C = \frac{1.2\rho}{0.85l} \tag{6.6}$$

For $l \geq 60\sqrt{\rho}$ from $$Z_C = 0.4\rho^{0.55} \tag{6.7}$$

Figure 6.4 shows the dialog box for the calculation of the impedance.

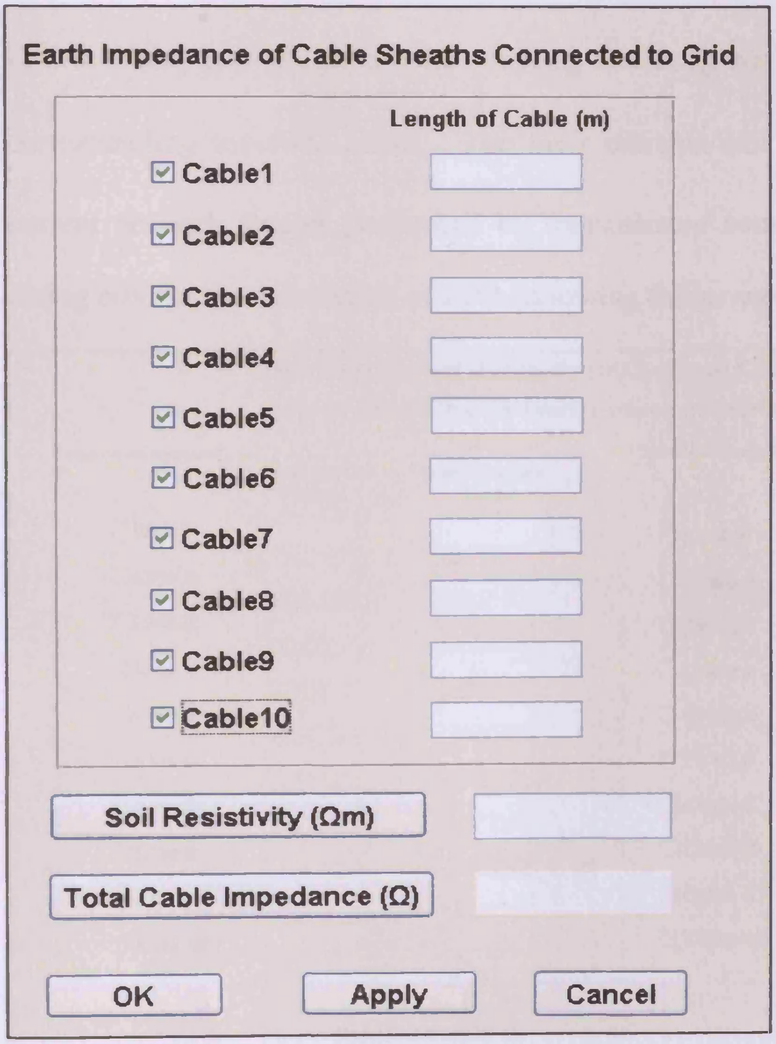


Figure 6.4: Input and Calculation of Earth Impedance of Cable Sheaths Connected to the Grid.

6.4 Calculation of EPR & Prospective Safety Voltages

Once the total impedance is calculated, then for a given fault current, the earth potential rise can be calculated. The EPR is calculated as the product of the total impedance Z_T and the sum of all currents from overhead lines and cables according to the following Equation (6.8):

$$EPR = Z_T\{I_{L1}(1-\mu_1)+...I_{Ln}(1-\mu_n)+I_{C1}\beta_1+...I_{Cn}\beta_n\} \qquad (6.8)$$

Where I_L and I_C is the current induced in each overhead earthwire and cable sheath respectively. Also, $\mu_1...\mu_n$ are the coupling factors (typical value of 0.3) corresponding to $line_1..line_n$ and $\beta_1...\beta_n$ are the coupling factors (given by Table 7 in BS: 7354 [6.1]) corresponding to $cable_1...cable_n$. The fault currents can be obtained from earth fault current network studies performed by transmission companies. Figure 6.5 shows the dialog box for the calculation of EPR following this procedure.

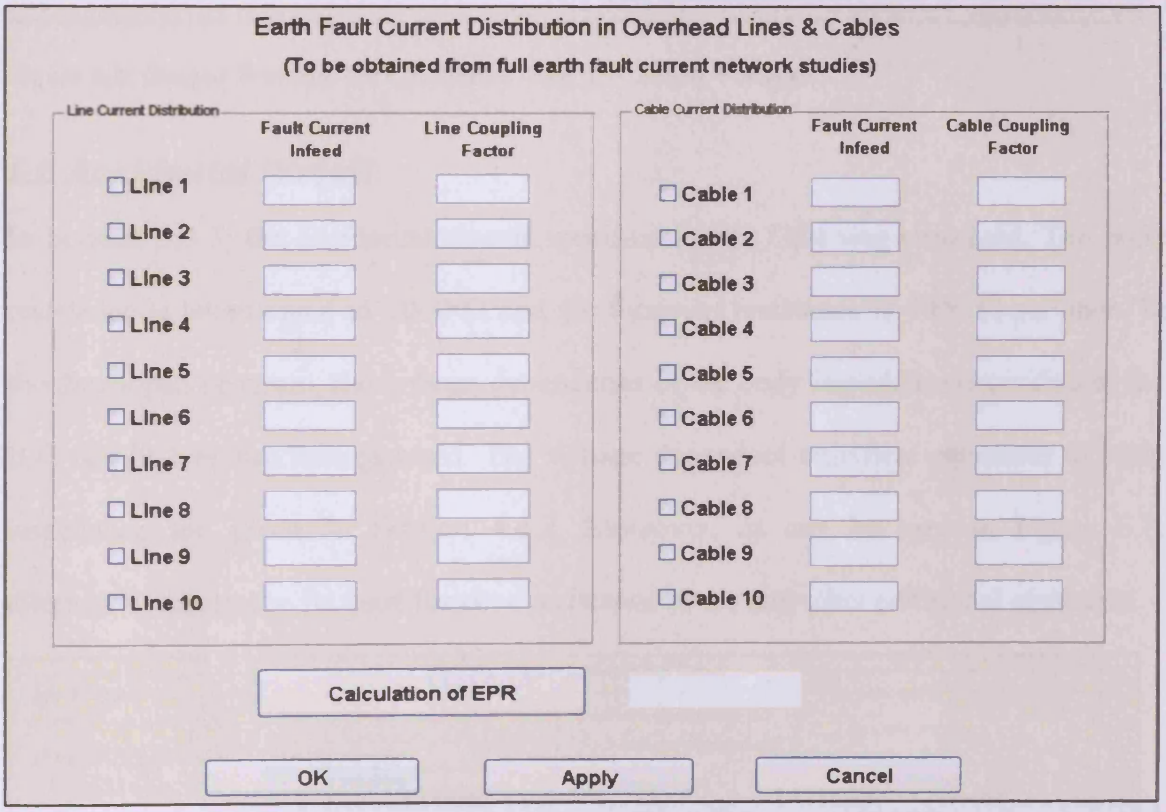


Figure 6.5: Input Box for Line and Cable Parameters for Earth Potential Rise Calculation.

As seen in Section 3.3.2, equations for the calculation of touch and step voltage are:

$$V_T = \frac{\rho V}{\pi R L}\left\{\ln\left(\frac{h}{d}\right)^{0.5} + \left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1-0.5^{n-2}}{D}\right)\right\}K_i \tag{6.9}$$

$$V_S = \frac{\rho V}{\pi R L}\left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1-0.5^{n-2}}{D}\right)K_i \tag{6.10}$$

Where V is the EPR, h is the grid depth, d is the diameter of the conductors, L is the total length of the conductors and the rods, D is the spacing of the conductors and n the number of parallel conductors. The corrective factor K_i is given by:

$$K_i = (0.15n + 0.7) \tag{6.11}$$

Alternatively, the option to enter the grid current (I_{gr}) for calculating the EPR is provided. Figure 6.6 shows the output window for the safety voltages.

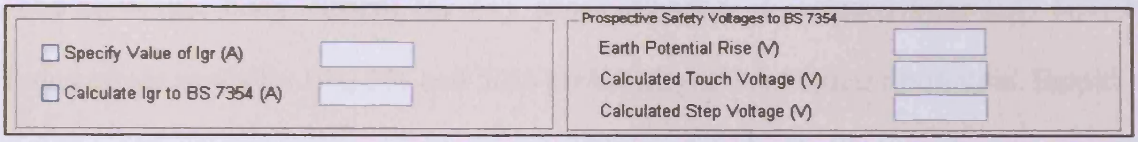


Figure 6.6: Output Window for Calculated Step and Touch Voltages

6.5 Accidental Circuit

In Section 3.3.3, the accidental circuit specified in BS 7354 was presented. The body resistance is taken equal to 1000 Ω and the footwear resistance is 4000 Ω per shoe. In the developed program, the voltage dependence of the body impedance according to the IEC 60479-1 is also incorporated. The voltage dependent empirical equations of body impedance are given in Section 4.4.2. Moreover, as can be seen in Figure 6.7, alternative values can be used for shoe resistance or for any other additional resistance.

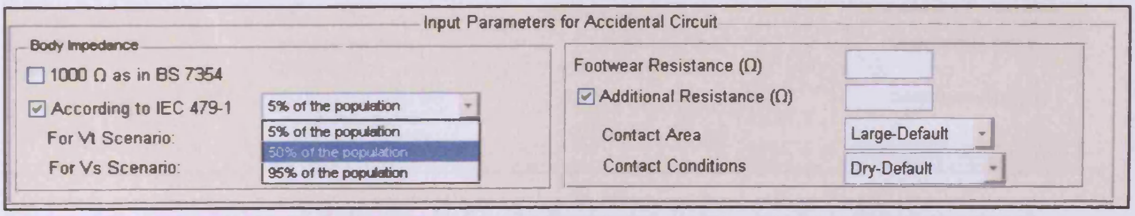


Figure 6.7: Window for Input Parameters for Accidental Circuit.

6.6 Calculation of Tolerable Safety Voltages

The following part of the developed program (see Figure 6.8), calculates the allowable step and touch voltages for a given fault duration and then compares the values with the generated step and touch voltages following injection of fault current into the grid to determine whether the system is safe or not, which forms the deterministic approach.

The allowable step and touch voltages are calculated using the threshold allowable current and body impedance as detailed in Sections 3.3.3 and 4.4.3 respectively.

Therefore, the permissible voltages are:

For touch voltage equivalent circuit: $V_t = I_t\left\{R_B + \frac{(R_{fw} + R_c)}{2}\right\}$ (6.12)

For step voltage equivalent circuit: $V_s = I_t\{R_B + 2(R_{fw} + R_c)\}$ (6.13)

The allowable body current for any shock duration is deduced from IEC 60479-1 time/current zones for 0%, 5% and 50% probability of ventricular fibrillation. Empirical equations for these curves were derived in this work and were given in Section 4.3. The calculation of safety voltages of a particular grid using the different levels of allowable body current, allows the user to compare easily the safety limits suggested in different standards. An option to account for the body impedance and the heart-current factors depending on the path that the current will take through the human body is also implemented. Details of these factors are described in Section 4.4.1. This allows the investigation of different scenarios of electrocution and the automatic determination of safety voltages, corresponding to each scenario.

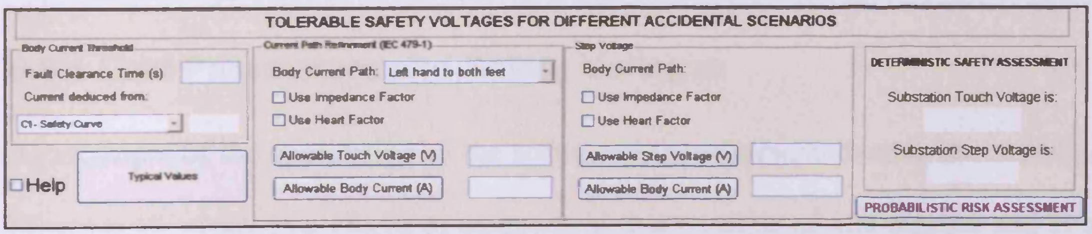


Figure 6.8: Calculation of Tolerable Safety Voltages and Deterministic Safety Assessment.

6.7 Probabilistic Risk Assessment

The probabilistic risk assessment in the developed program can be applied either for step or touch voltages. This interface uses the information for the system and accidental circuit that were entered in the previous steps and calculates initially the probability of ventricular fibrillation (P_{VF}). The probability P_{VF} is calculated through the developed probability surface (Cardiff Probabilistic Model), described in Section 4.3, which allows accurate readings of the probability of VF. The same probability can also be calculated by the stepwise probability model, discussed in detail in Section 2.6.5, according to which the probability of VF can be either 0%, 5%, 50% or 100%.

The Probability of Presence (P_{Pr}) is calculated by the number of working days per year and the individual exposure per day, while the Probability of EPR (P_{EPR}) is retrieved from historical system data. Finally, as shown in Figure 6.9, the individual risk is calculated, and depending on its value, it is ranked according to the ALARP criteria, as discussed in Section 2.7, to determine whether the risk is acceptable or not.

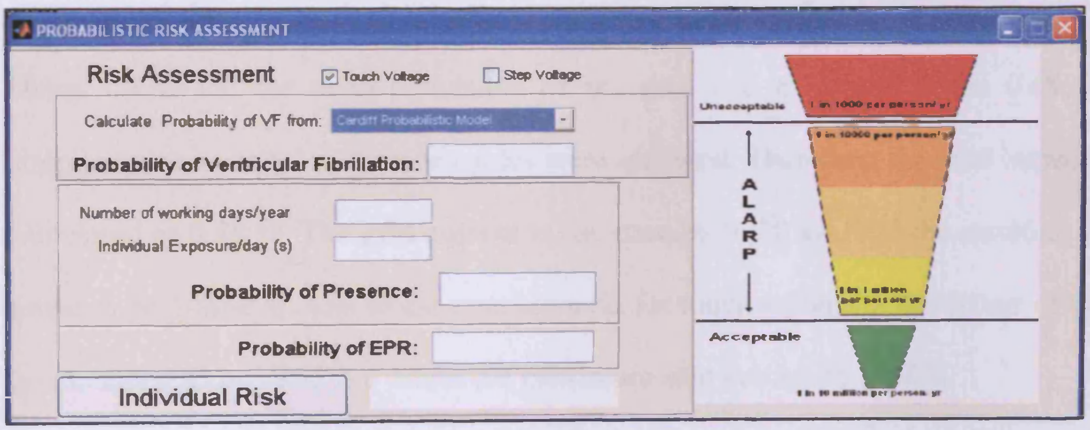


Figure 6.9: Probabilistic Risk Assessment Window. Application of Developed Cardiff Risk Assessment Facility of Transmission Systems (CRAFTS) to a Generic Typical Grid.

6.8.1 Grid Parameters and Safety Voltages

An example of the application of the software is now presented using the model grid of Figure 6.10 which is a 10x10 m square grid that consists of 100 meshes and is buried

0.6 m under the ground surface. The diameter of the conductors is 0.1m and they are equally spaced every 10 m.

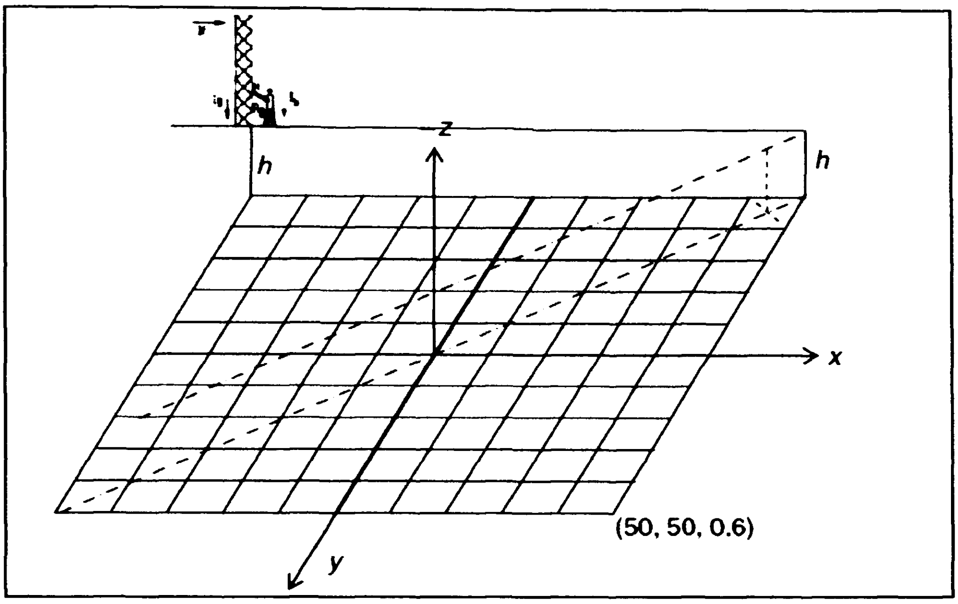


Figure 6.10: Layout of Model Earth Grid.

The soil resistivity is assumed to be 100 Ωm, and the surface is covered with a layer of chippings. The thickness of the layer is assumed 0.08 m and the chippings resistivity is taken as 300 Ωm.

Using CRAFTS, the earth resistance of the grid was calculated to be 0.48 Ω. For simplicity, no connected lines or cables were included. Therefore, the total impedance is calculated as 0.48 Ω. The grid current is assumed to be 30 kA, and the resulting EPR is found to be 14484 V. The worst case scenario for touch voltage at the corner of the grid is calculated to be 1961.9 V while the maximum step voltage is 1048 V.

The voltage dependency of the body impedance is taken into consideration, and it is calculated according to the statistical values corresponding to the 50% of the population. Hence, the body impedance is 870 Ω and the footwear resistance is assumed to be 4000 Ω per foot. Figure 6.11 shows an overall screen display of the developed graphical user interface for CRAFTS. The input data described above together with the calculated parameters are shown.

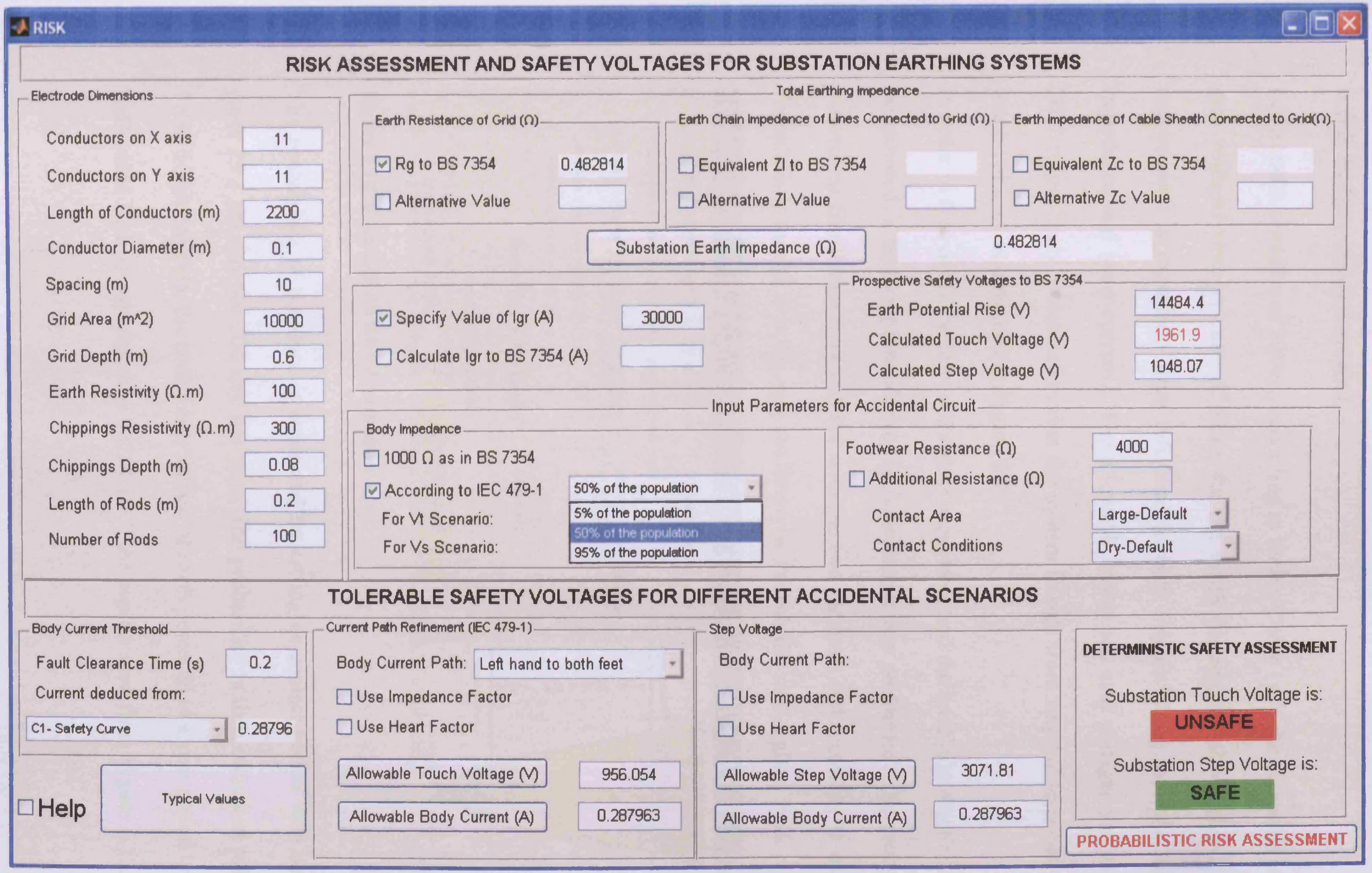


Figure 6.11: Risk Assessment and Safety Voltages of a Model Grid.

6.8.2 Safety Assessment

For a shock duration of 200ms, according to Safety Curve (c_1), the allowable touch and step voltages were calculated. Here, for the touch voltage, the allowable value for a current path is examined from left hand to both feet including the path factors for impedance and heart-current. The allowable touch and step voltages are 956 V and 3071 respectively which infers that the system is safe from step voltages but not from touch voltages as indicated in Figure 6.11 .

In order to find out if the imposed risk is acceptable and the level of mitigation that may be required, a further probabilistic risk assessment was performed. The probability of ventricular fibrillation is calculated with the two methods and according to the Cardiff Probabilistic model, it is 9%, and the Stepwise Probability model gives 50%.

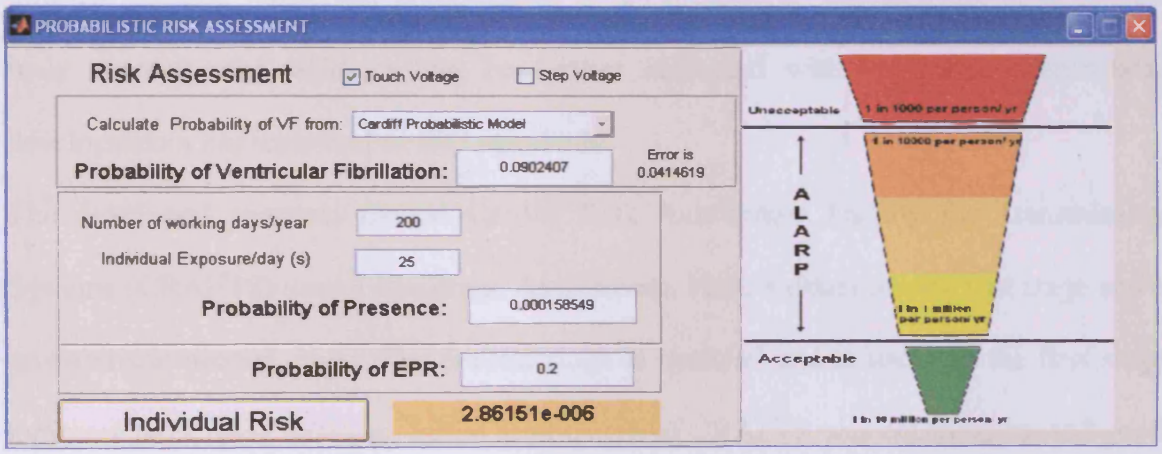


Figure 6.12: Probabilistic Risk Assessment.

The probability of presence is estimated by setting as contact period with conductive parts 25 s per day for 200 day per year. The probability is then estimated to $1.5 \cdot 10^{-4}$. From historical data, the probability of rise of earth potential in a year period is 0.2. The Individual Risk is calculated to be $2.8 \cdot 10^{-6}$. As can be seen from Figure 6.12, the risk falls in the ALARP area which means that a cost benefits analysis will show whether it is worth applying mitigation measures to the assessed grid.

The interface is proved to be very useful in applying a sensitivity analysis of system parameters and accidental circuit. The probabilistic assessment gives an estimation not only of whether the system is safe or not but also how critical the safety is, which allows engineers and asset managers to make a more effective decision and cost benefit analysis.

6.9 Conclusions

A new risk assessment program with easy to use interface is developed. It uses BS 7354 recommendations for the determination of safety voltages. Moreover, it allows user specified input for earth impedances and safety voltages, that may have been obtained through detailed numerical computation or measurement. The analysis of allowable body currents and voltages can be further enhanced with the latest international developments implemented in IEC standards.

The developed program named Cardiff Risk Assessment Facility for Transmission Systems (CRAFTS) uses a two-stage Assessment. First, a deterministic first stage and a probabilistic second stage. The second stage is optional and is useful if the first stage indicates hazardous voltages. Initial application of CRAFTS was encouraging and good feedback was received from industry. A fuller statistical and probabilistic analysis of the parameters governing safety of earthing system would allow a further refinement of the proposed method.

CHAPTER 7. PROBABILISTIC RISK ASSESSMENT OF ELECTRICAL SUBSTATIONS: A FULL ANALYSIS

7.1 Introduction

Probabilistic Risk Assessment (PRA) involves the quantification of various parameters of a hazard with the aim to evaluate numerical results upon the imposed risks. When a single "best guess" value is used as an estimate for the modelling of each of the contributing parameters, the process is described as single point or deterministic modelling.

Monte Carlo simulation takes into account the statistical variation and the probability distribution of the input parameters for the investigated system. It is a different approach of probabilistic risk analysis, where a large number of possible scenarios is generated in order to account for a large number of values of the contributing parameters. The main advantage of Monte Carlo simulation is that it takes into account the weighting of each possible scenario by including the probability of its occurrence. Therefore, each variable within a simulation process is modelled by its associated distribution. The distribution characteristics may be based either on historical data of adequate size and quality or on expert analysis. For each distribution, the horizontal axis gives a range of possible values that the parameter could take while the vertical axis provides a probability weighting for each value within that range [7.1, 7.2].

As with a deterministic model, in a simulation model, the way the variables are structured and linked remains the same with the only difference that each of the contributing parameters is not represented by a single value but instead is described using a probability distribution [7.2]. This type of variable representation aims at calculating the combined impact of the variability in the model's parameters. In this way, the result will be provided as a probability distribution showing the possible outcomes and their associated probability of occurrence.

7.2 Description of PRA Process in Earthing Systems

Chapter 4, was focussed on the probabilistic nature of the various parameters affecting the accidental circuit (e.g. body impedance, fibrillating current, etc), while Chapter 5 investigated those variables that concern the system and its characteristics (e.g. fault current magnitude, clearance time, fault location).

The diagrams of Figures 7.1 and 7.2 provide an outline of the proposed probabilistic risk assessment for a transmission substation as it has been modelled using a platform simulation software, @Risk [7.3]. As can be seen, the first block concerns the earth fault current levels. The National Grid Seven Year Statement [7.4] provides tables with the maximum predicted fault current for each substation based on computer simulations of the system [7.5, 7.6]. However, as it was seen the fault current magnitude can vary significantly. For the risk assessment process different fault currents will be sampled during the simulation, from a uniform distribution shaped by predetermined maximum and minimum fault current values.

In the developed method, summarized in Figures 7.1 and 7.2 (flowcharts), fault current levels are used to compute the voltages appearing in and around a substation compound in case of an earth fault. CDEGS Software [7.7] was used to carry out the numerical computations. The earthing system geometry of a substation is modelled, and an earth fault current is injected for which the touch and step voltages are computed throughout the substation. Instead of assuming a worst case scenario that a person will be exposed to the maximum possible voltage, a person can be located anywhere in the substation and, therefore, he/she will be exposed to the voltage at the location.

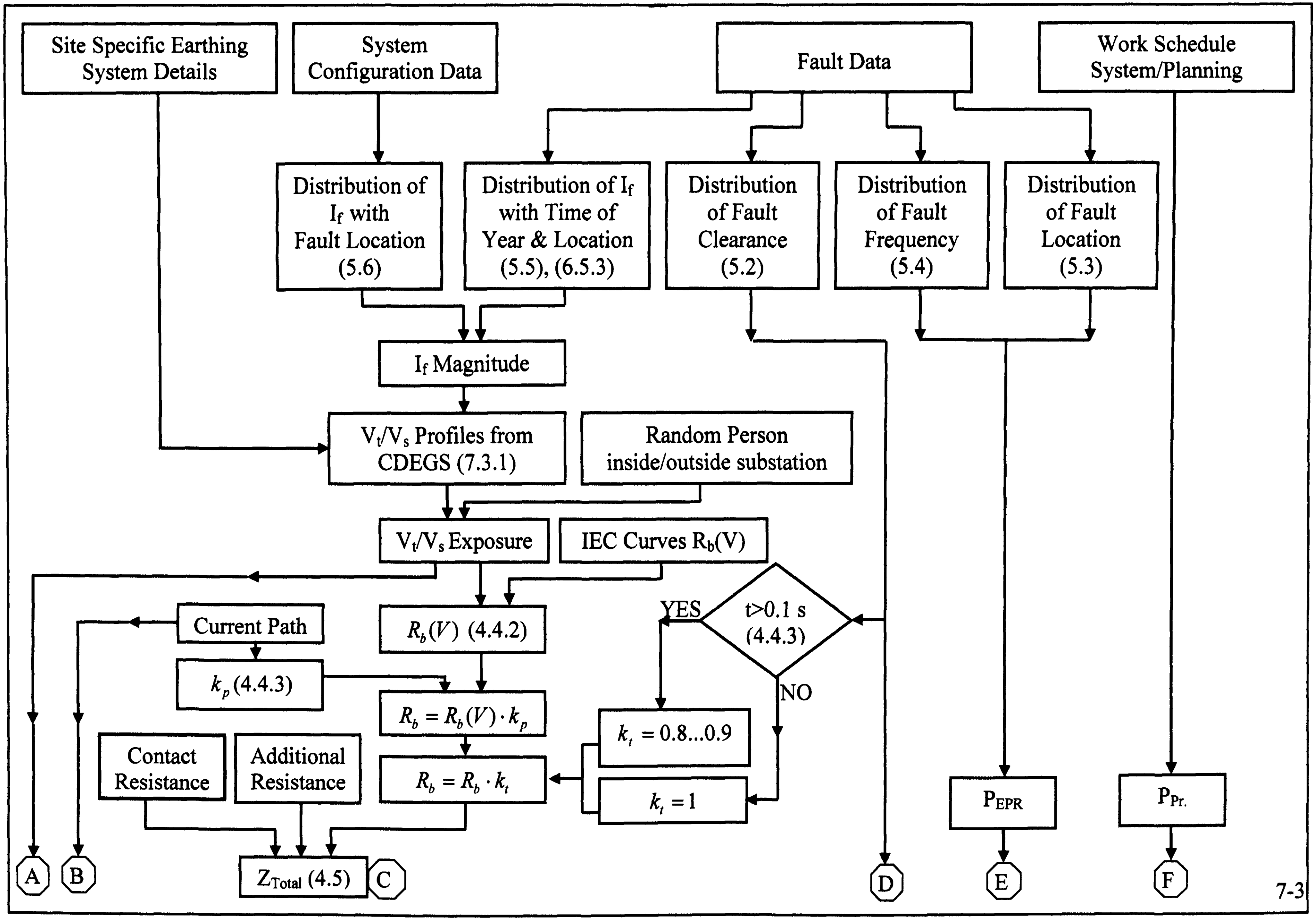


Figure 7.1: Probabilistic Risk Assessment Outline (continued to next page).

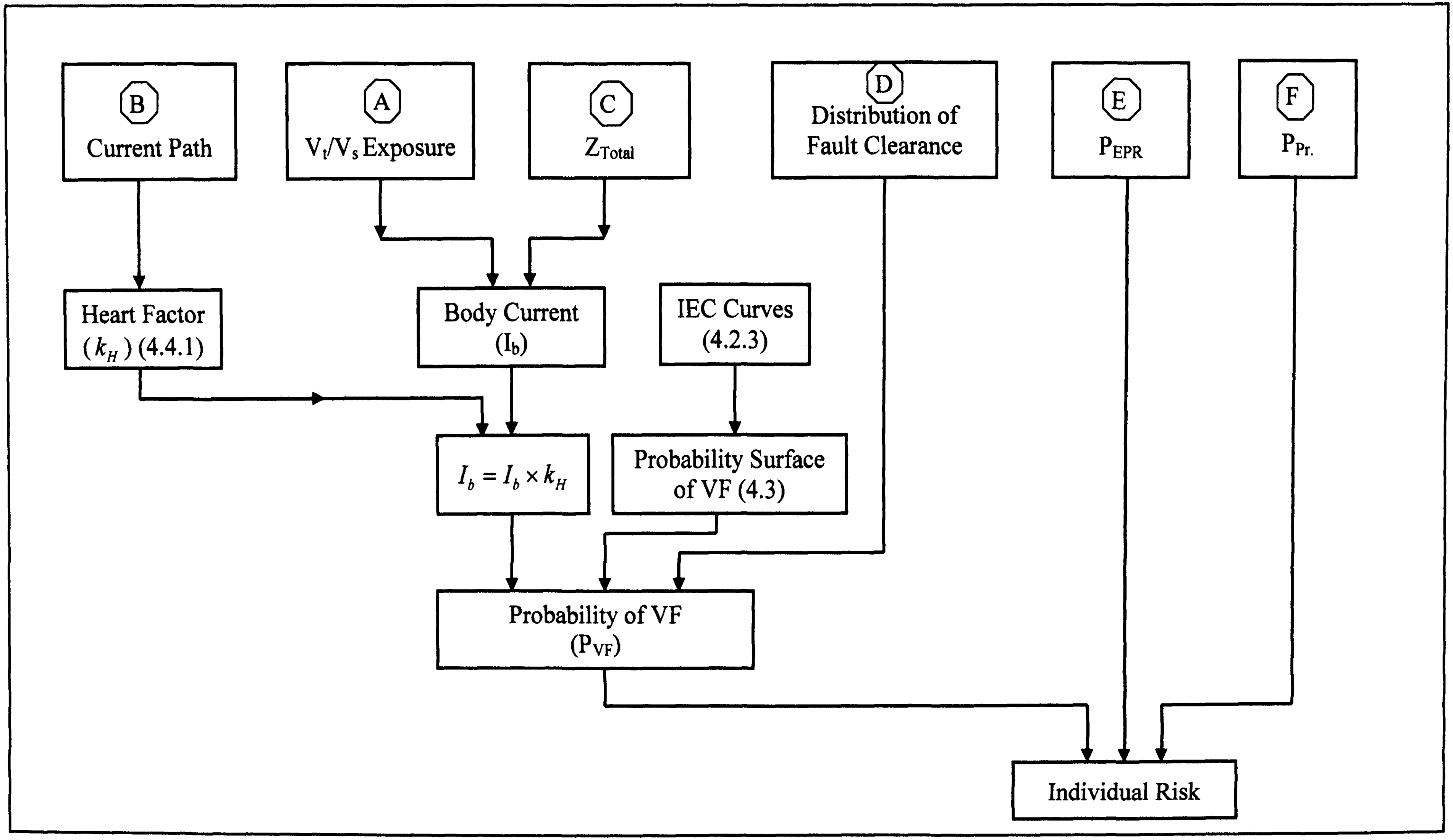


Figure 7.2: Probabilistic Risk Assessment Outline.

CDEGS software offers the option of extracting the results of the investigated profiles in Excel files which can then be integrated in the @Risk model to assess the Individual Risk. Moreover, the model makes use of the CDEGS facility along with the touch/step voltages to provide the exact coordinates in the substation where these voltages appear.

For the investigation of risk caused by touch voltages, it was assumed that throughout the substation, there is a possible touch voltage hazard scenario. The sampling of locations is made randomly within the substation and two meters outside the perimeter of the substation to include cases of contact with the fence. In addition, the model allows different visiting frequency for each area, which can be based on the local knowledge of the site. In this way, areas such as the gate, offices or pathways can be treated as busier than other locations at the substation. If an area is out of reach and presents no realistic hazard, then it could be ignored.

For each touch/step voltage scenario the corresponding body impedance is calculated. In Sections 4.4.2 and 4.4.3, the body impedance was shown to be not only voltage dependent but also its magnitude varies for different body current path, and for shock durations longer than 0.1 s, the value of body impedance may decrease by about 10% to 20% because of the skin rupture [7.8]. These factors, as can be seen in the diagram, are taken into consideration.

In order to calculate the magnitude of the body current, it is necessary to include any other resistances of the accidental circuit (See Section 4.5). The next block of the diagram concerns the calculation of the Probability of Ventricular Fibrillation for a given scenario. In Sections 4.2 and 4.3, safety criteria based on IEC 60479-1 criteria [7.8] were further processed to develop a probability surface for ventricular fibrillation which allows determination of the probability of VF for any given scenario of body current, specific current path and shock duration. The shock duration is sampled from a distribution which was generated using the historical fault clearance records of a ten year period as it was described in Section 5.2.

As far as the Probability of Presence is concerned, the site locations, scheduled work activities and the presence of people in the hazardous area, control the time during which a person will be in contact with conductive parts in the substation within a year. The Probability of Presence is calculated over a year's time. For the calculation of the Probability of EPR, the fault frequency of a substation can be site specific based on the complexity of the system as shown in Section 5.4. Once the Probability of VF is calculated, the Individual Risk is obtained from the product of the three probabilities; Presence (P_{Pr}), EPR (P_{EPR}) and VF (P_{VF}).

7.3 Case Study of Probabilistic Risk Assessment

The purpose of this study is, on the one hand, to explore further all the probabilistic parameters of the process making use of the available data provided from the transmission company and, on the other hand, to identify the studies that need to be conducted or the data that need to be recorded for the future support of risk assessment processes.

The quantitative risk assessment method proposed in the previous section is applied here to a real case study of a 400/275 kV substation located in South Wales. The site of the Cilfynydd substation has been used for various experiments and measurements conducted by the High Voltage Energy Systems Group (HIVES) of Cardiff University, therefore, data concerning the earthing system design and circuit specifications are readily available. Some parameters which were necessary for the modelling of the system were derived from previous risk assessment reports [7.9, 7.10].

The studies carried out in this work include both analytical calculations according to British standards and numerical simulations of the substation earthing system under fault conditions.

7.3.1 CDEGS Simulation

The model shown in Figure 7.3, represents the original earthing system of the substation and the fence is also included in order to investigate shock scenarios of fence touch voltage.

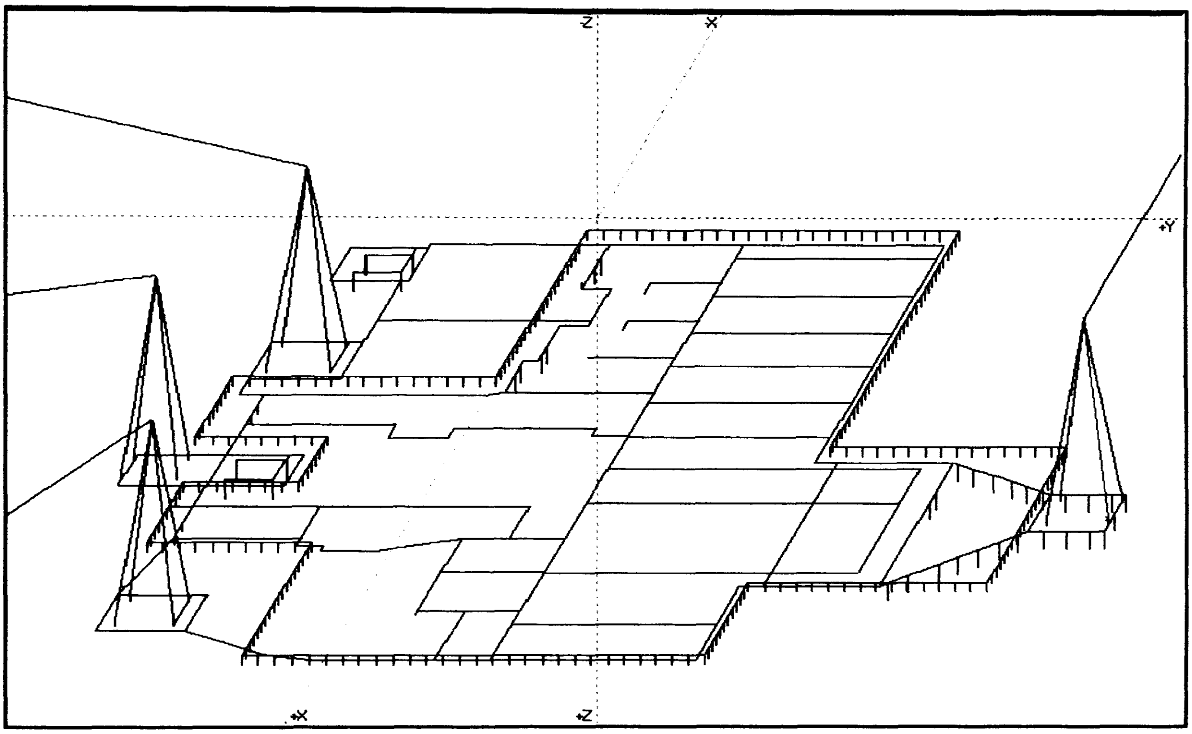


Figure 7.3: Simulated System Layout for Cilfynydd Substation.

The touch profiles were set to two meters from each other in order to avoid extremely large result files. On the other hand, the points of each profile were set to every meter so that a detailed enough analysis of touch/step voltages could be obtained across the substation. The results are presented in Figure 7.4 and Figure 7.5 showing areas where the touch voltage can be as high as 50% of the EPR. As can be seen, the highest potential difference appears at the corners of the meshes. As expected, step voltages are much lower than touch voltage ranging between 1.3% and 13% of the EPR.

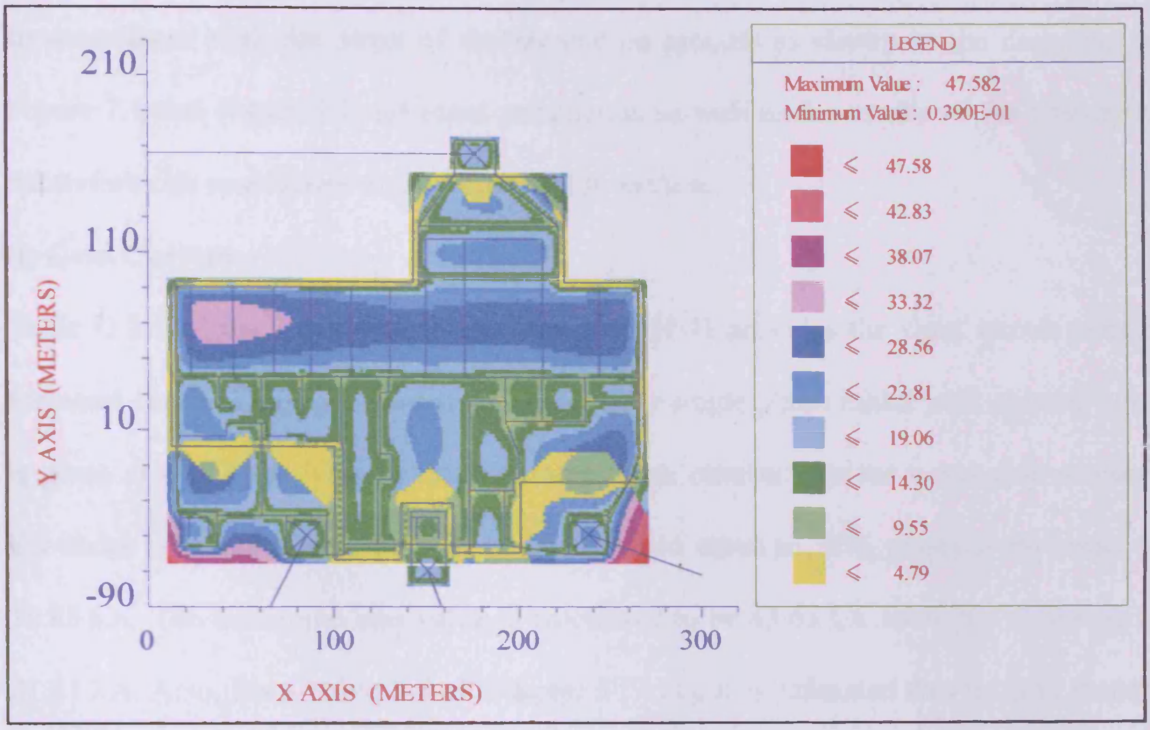


Figure 7.4: Computed Touch Voltage Profiles provided as percentage of EPR.

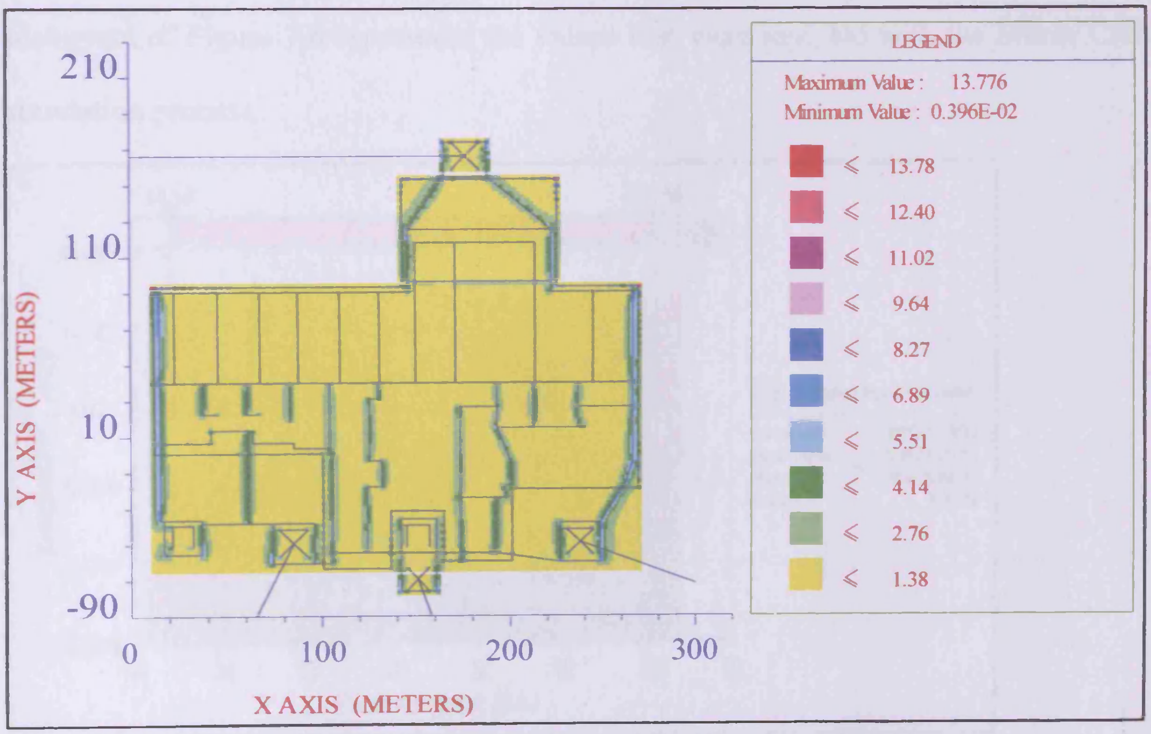


Figure 7.5: Computed Step Voltage Profiles provided as percentage of EPR.

7.3.2 Risk Assessment Results

7.3.2.1 Touch Voltage Risk

In accordance with the steps of the simulation process as shown in the diagrams of Figure 7.1 and Figure 7.2, all input parameters as well as the results of the Cilfynydd substation risk assessment are detailed in this section.

(i) Grid Current

Table D.3.1 of the NG Seven Year Statement [7.4] provides the short circuit current forecasts for the Cilfynydd substation where the single phase initial peak current value is given at 61.71 kA. This is the maximum value obtained for the worst case scenario but under favourable conditions, it can be reduced down to 50%, giving a minimum of 30.85 kA. The maximum rms value is calculated to be 43.63 kA while the minimum is 21.81 kA. Also, from Table 5.2 of Chapter 5 [7.11], it is estimated that the grid current (I_{gr}) is a percentage of the return current (I_r) where for Cilfynydd it is 69.2%. Therefore, the maximum grid current is 30.1 kA and the minimum is 15.05 kA. The histogram of Figure 7.6 represents the values that were sampled with the Monte Carlo simulation process.

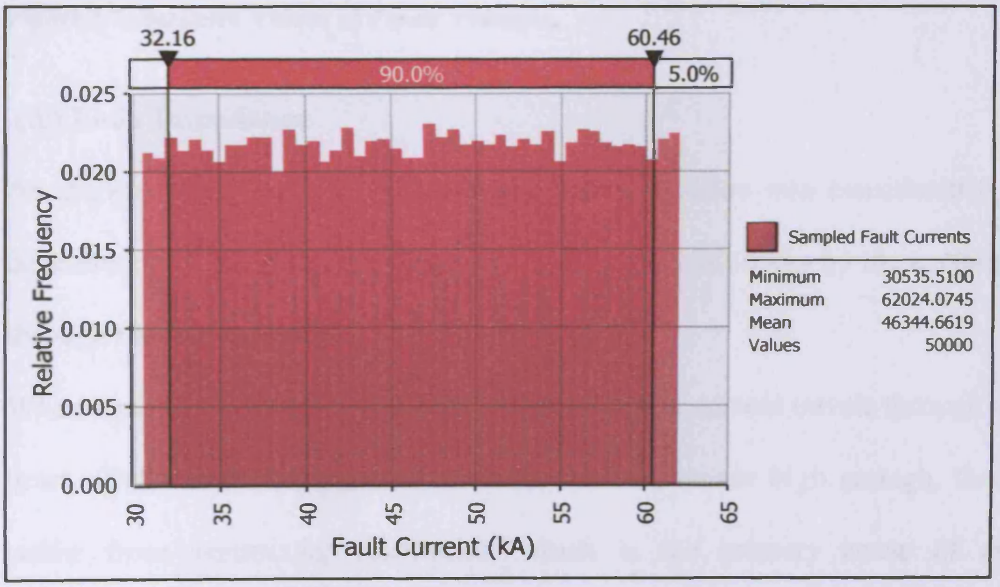


Figure 7.6: Sampled Values of Fault Current.

(ii) Touch Voltages

Since for every iteration and associated grid current (I_{gr}), the touch voltage is determined, the magnitudes of these voltages, not only depend on the grid current but also on the exact location within the substation.

By randomly sampling different locations of presence throughout the substation and for different possible fault currents, a distribution of touch voltage magnitudes ranging from 5V to 12854 V was calculated and reported in Figure 7.7.

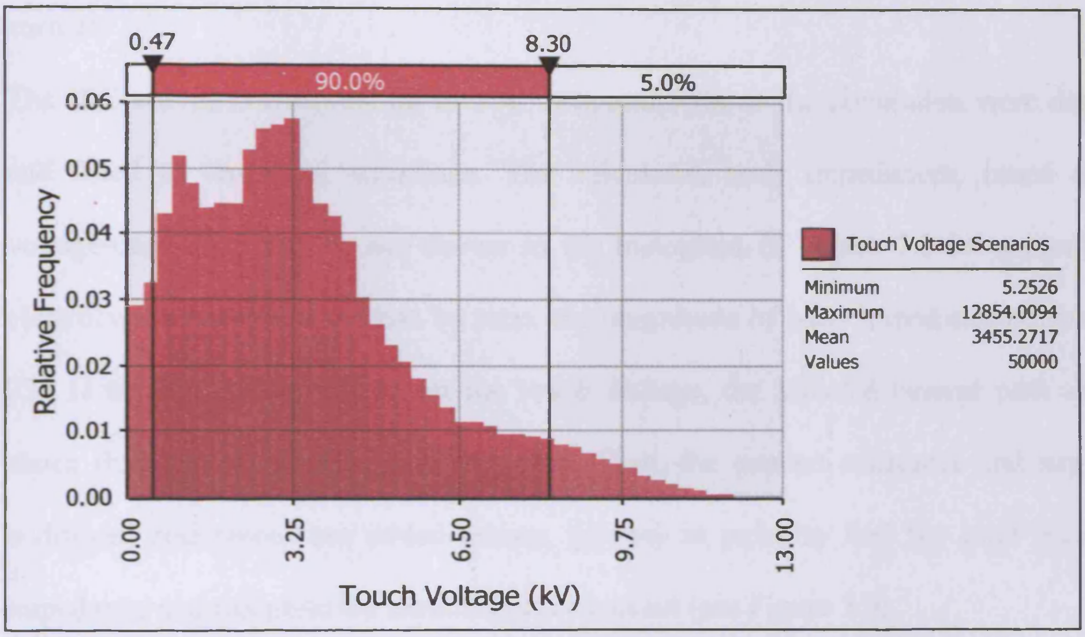


Figure 7.7: Sampled Values of Touch Voltages.

(iii) Body Impedance

As shown in Figure 7.1, the proposed approach takes into consideration the voltage dependency of the body impedance as well as the path taken by the current as it travels through the human body.

When a person is exposed to a hazardous voltage, a current travels through the body and heart. If the current magnitude and shock duration are high enough, the person will suffer from ventricular fibrillation which is the primary cause of death during electrocution. The magnitude of the body current depends on the accidental circuit whose main parameters are the body resistance, the contact resistance, footwear resistance and any other additional resistances (gloves, etc.) In this study, BS 7354 was adopted for which $R_F = 4000\ \Omega$ per foot, but no chippings were considered.

For the body resistance, BS 7354 specifies a single value of 1000 Ω. On the other hand, IEC 60479-1 suggests that the body impedance is voltage dependent and, therefore, provides curves of body resistance against the applied voltage. In Section 3.7.6, it was shown that a relatively small change in body impedance can affect the allowable grid current.

The IEC curves corresponding to 5%, 50% and 95% of the population were digitized and fitted to empirical equations. The calculated body impedances, based on the voltage-dependent model, are shown in the histogram of Figure 7.8 for a number of electrocution scenarios. As can be seen, the magnitude of body impedance ranges from 237 Ω to 6354 Ω depending on the touch voltage, the selected current path and the shock duration sampled in each iteration. Then, the contact resistance and any other additional resistances are added (shoes, gloves) in order to find the total accidental impedance and calculate the resulting body current (see Figure 7.9).

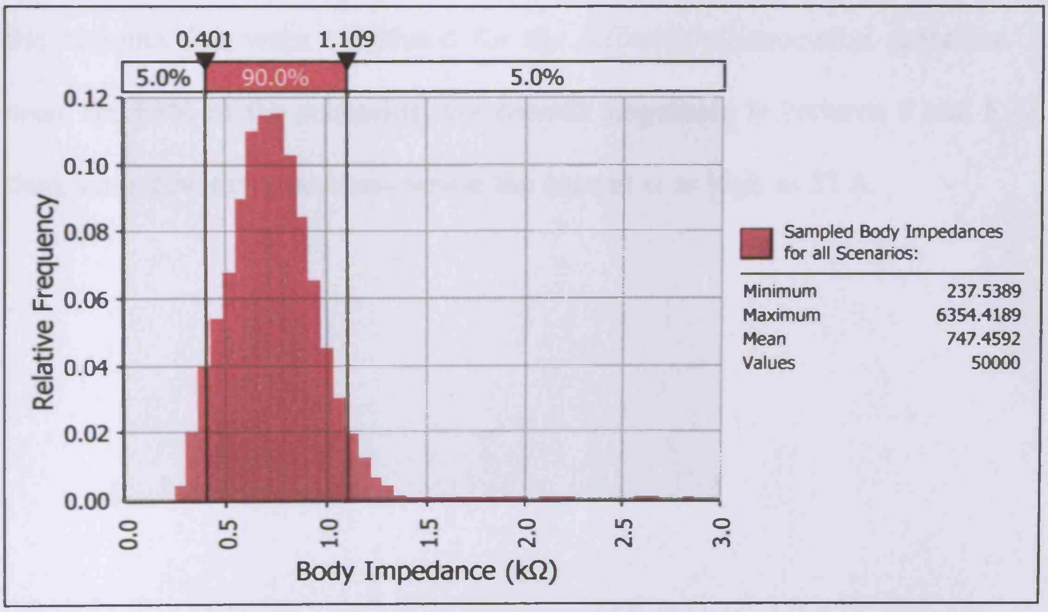


Figure 7.8: Calculated Body Impedances for Touch Voltage Scenarios.

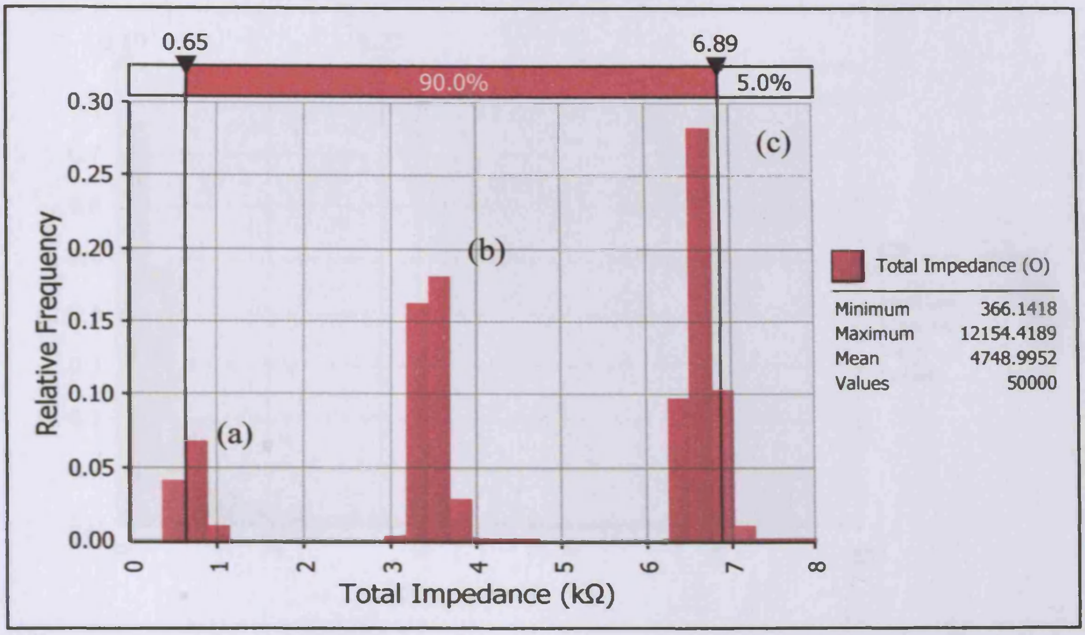


Figure 7.9: Calculated Total Impedance for Touch Voltage Scenarios.

The three different parts of the histogram from left to right correspond to current paths, (a) hand to hand (no shoe resistance included), (b) hand to both feet and (c) hand to foot.

(iv) Body Current

Once the accidental impedance is calculated, the magnitude current that will travel through the human body is calculated for any given touch voltage. Figure 7.10 shows the currents that were calculated for the different electrocution scenarios. As can be seen, for 95% of the scenarios, the current magnitude is between 0 and 5.27 A, while there are a few extreme cases where the current is as high as 27 A.

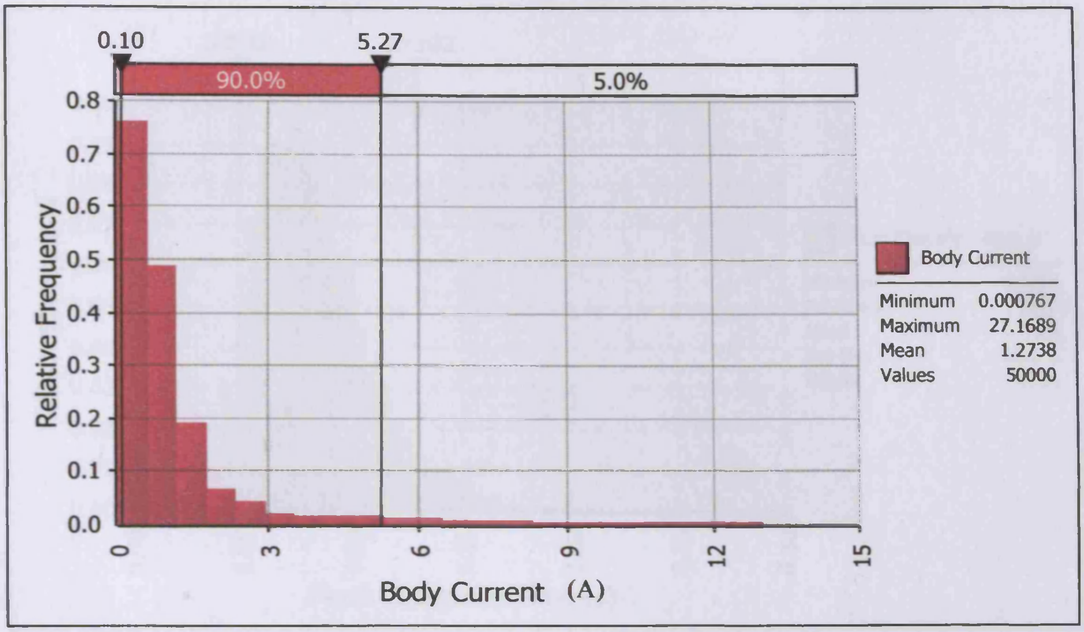


Figure 7.10: Calculated Body Currents for Touch Voltage Scenarios.

(v) Clearance Times

The measured fault clearance times provided by National Grid were fitted using a Gamma Distribution. During the simulation, the distribution was used to include scenarios with various combinations of applied voltage and shock duration. Figure 7.11 shows the sampled clearance times used for the 50000 iterations of the study. The minimum sampled clearance time is 31ms and the maximum is 247 ms, while the mean value of clearance time is 82 ms.

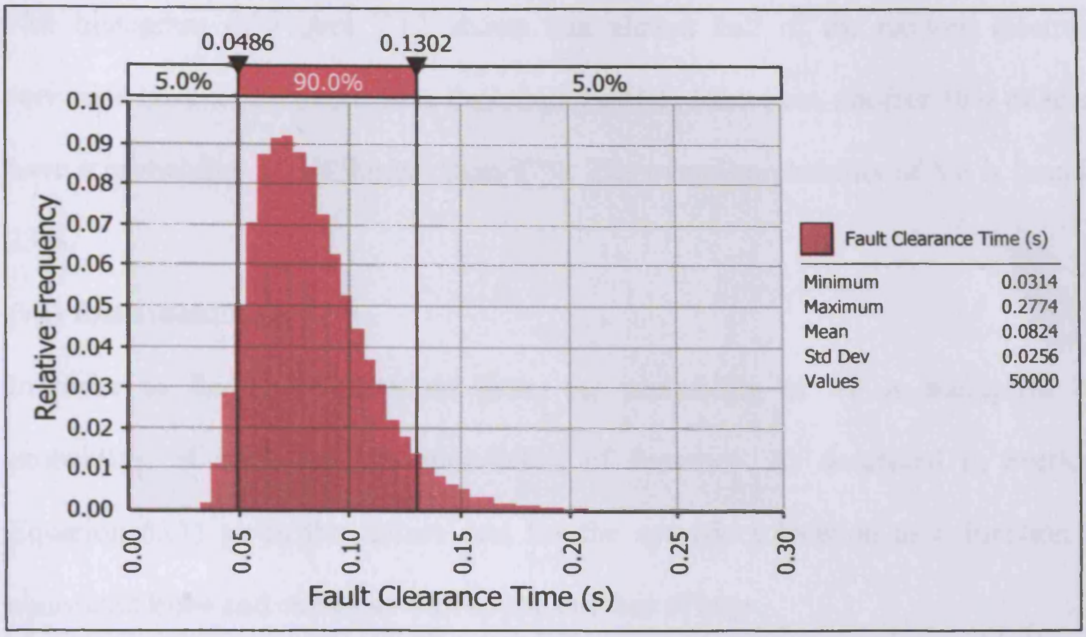


Figure 7.11: Sampled Fault Clearance Times.

(vi) Probability of Ventricular Fibrillation

Making use of the probability surface of ventricular fibrillation developed in this work (Section 4.3), for every combination of body current and shock duration, the corresponding probability of fibrillation is calculated taking also into consideration the body current path, (Figure 7.12).

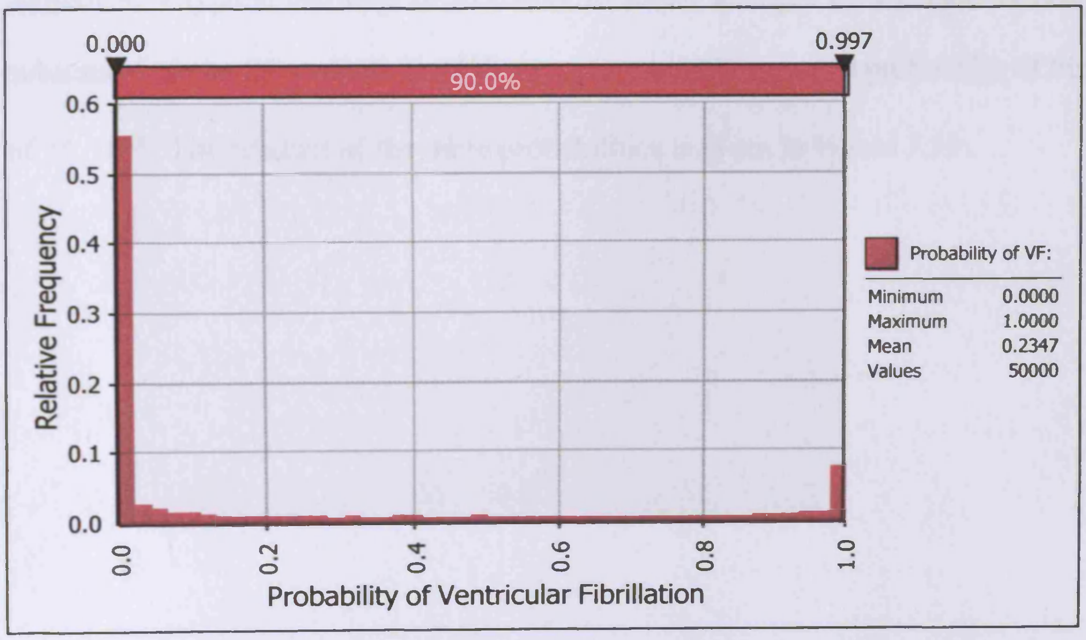


Figure 7.12: Calculated Probability of Ventricular Fibrillation for Touch Voltage Scenarios.

The histogram of Figure 7.12 shows that almost half of the random electrocution scenarios have a maximum 10% Probability of VF. Moreover, another 10% of scenarios have a probability of VF higher than 97%. The overall probability of VF is found to be 23%.

(vii) Individual Risk

In order to find the Individual Risk, the probability of VF is multiplied by the probability of EPR and the probability of Presence. As described in Section 5.4, Equation (5.1) gives the failure rate for the specific substation as a function of the connected lines and cables as well as the number of bays.

Cilfynydd substation has 11 switchgear bays, and 4 double circuit lines are connected to the substation but there are no underground cables routes. According to Equation 5.1, the fault rate is 0.475 faults/ year i.e. one fault every couple of years is expected. However, only 25% to 50% of the faults result in significant fault current and rise of earth potential [7.10]. Assuming the worst case, the Probability of EPR in a year period for the Cilfynydd substation is estimated to 0.2375 or 24%.

Moreover, a typical estimate of exposure to touch voltages of a person working at a substation can be 25 seconds for 200 days per year. This gives a probability of Presence of $15 \cdot 10^{-5}$. The product of the three probabilities is given in Figure 7.13 .

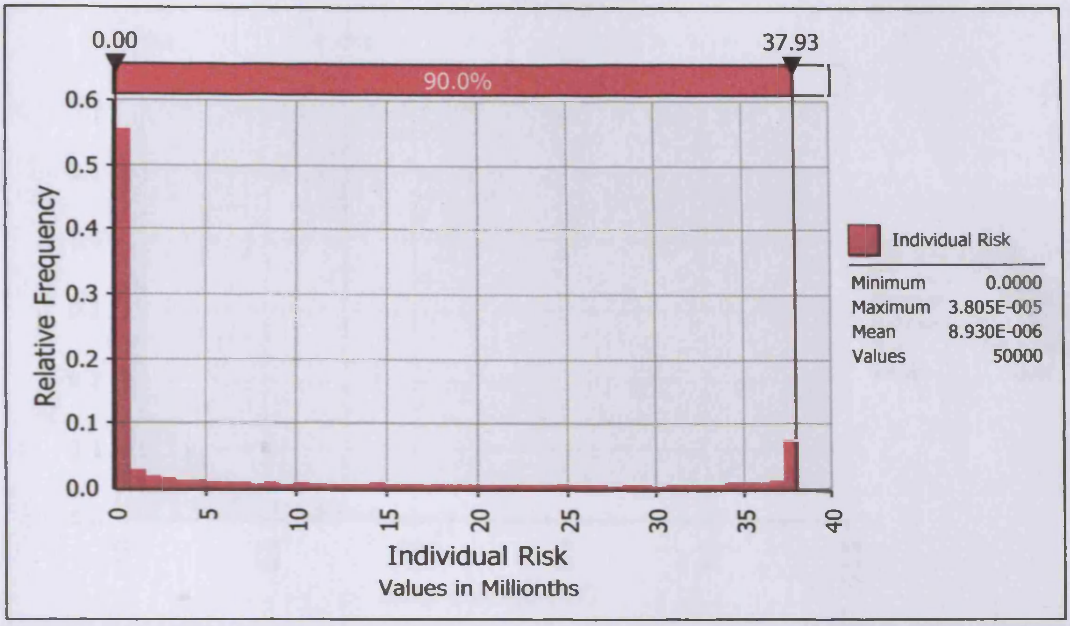


Figure 7.13: Calculated Individual Risk for Touch Voltage Scenarios.

The Individual Risk is estimated to be $8.93 \cdot 10^{-6}$ and is compared against the HSE criteria introduced in Section 2.7. The risk falls within the ALARP region which means that although the risk is controlled, further mitigation is advisable. Usually, a cost benefit analysis will follow to determine the level of expenditure necessary to have a sufficient impact on the reduction of risk.

7.3.2.2 Step Voltage Risk

Similarly, the risk from the step voltages that a person maybe exposed in case of a fault is also assessed. As seen in CDEGS simulation results, shown in Figure 7.5, the step voltages is not higher than 13% of the EPR. However, it is important to note that the step voltage profiles were calculated using as reference the worst EPR of the system and therefore, overestimating their magnitude.

As with the touch voltage study, different fault currents and locations within the substation were included during the simulation to produce possible step voltage electrocution scenarios. Figure 7.14 shows these values of step voltages.

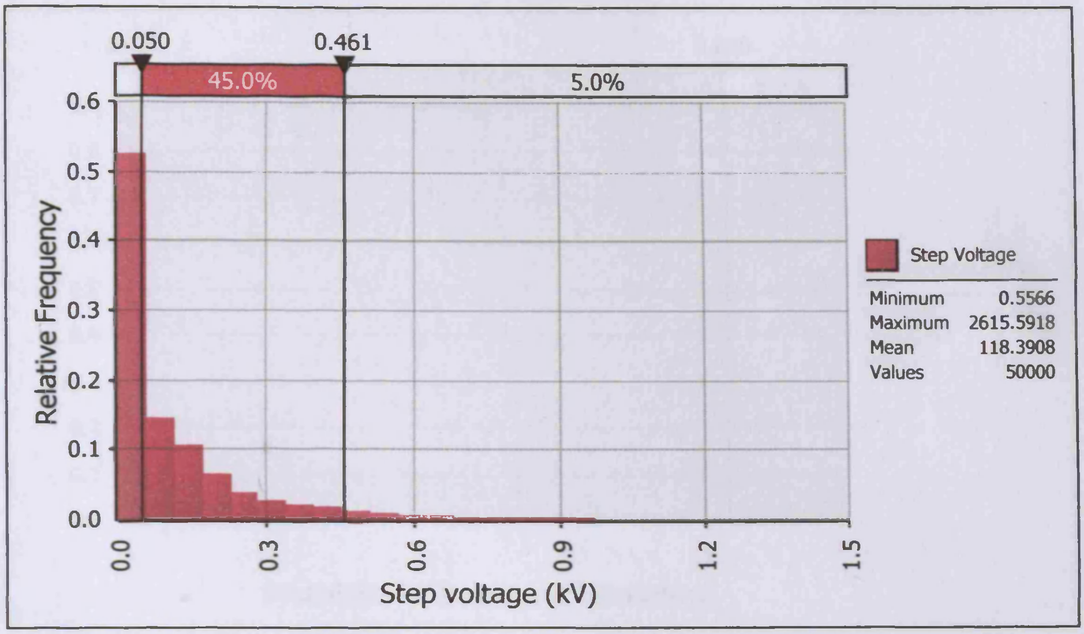


Figure 7.14: Sampled Step Voltages.

The step voltages as expected are of low magnitude, and 50% of the values are less than 50V. Although there are a few values reaching 2.6 kV, the mean value is 118 V, and only 5% of the values are higher than 460 V. It is then expected, that only a small percentage of these scenarios would result in ventricular fibrillation.

Figure 7.15 shows the probabilities of VF for step voltage scenarios. In 83% of the cases, the probability of VF is less than 2%. As can be seen from the figure, for 5% of the scenarios, there is more than 84% probability of VF.

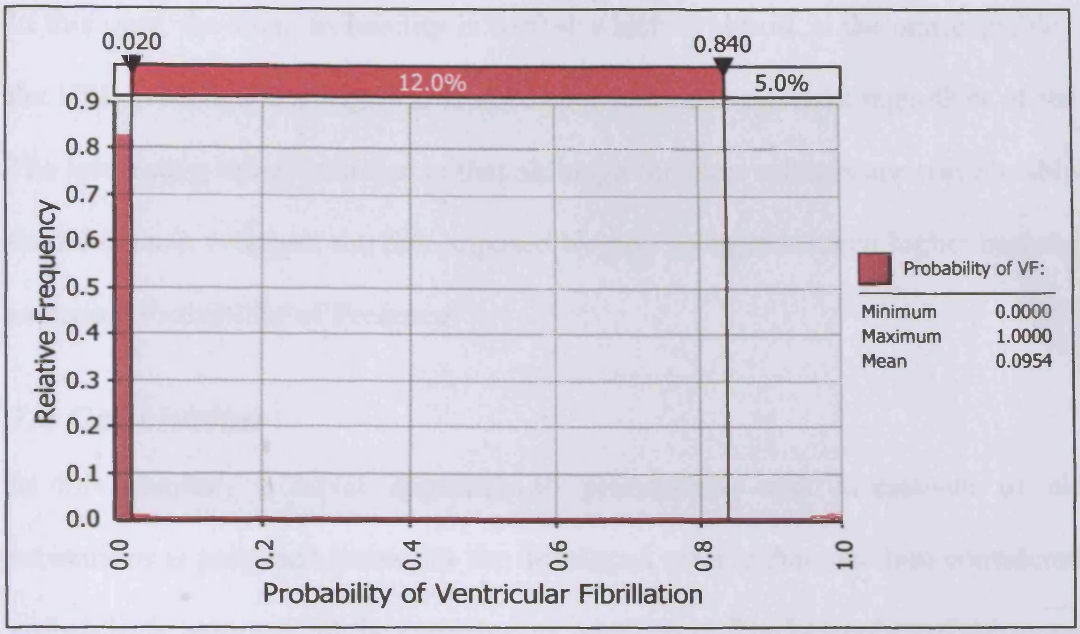


Figure 7.15: Calculated Probabilities of Ventricular Fibrillation for Step Voltage Scenarios.

The mean value of the probability of VF is close to 1% and is much lower than the 33% calculated for the case of touch voltages. However, the probability of someone getting exposed to step voltage hazards is much higher. A person working in a substation is expected to be exposed to step voltage risk for 200 days per year for 8 hours a day. For the same Probability of EPR, the Individual Risk is shown in Figure 7.16.

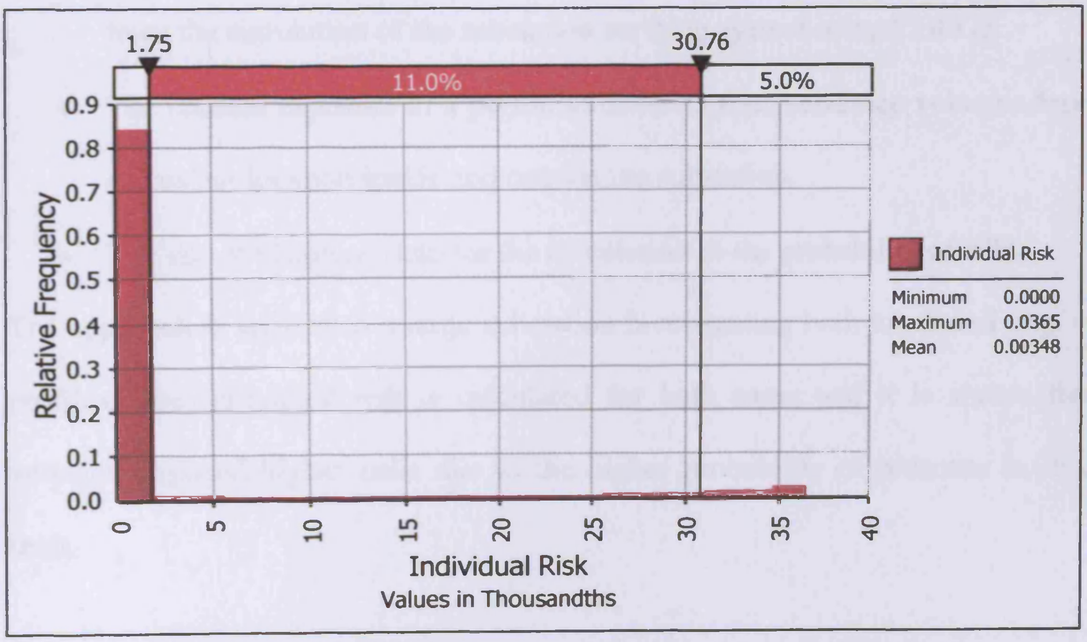


Figure 7.16: Calculated Individual Risk for Step Voltage Scenarios.

In this case, the total probability is 0.0034 which is almost in the unacceptable area of the HSE criteria and mitigation is necessary to reduce the risks regardless of the costs. The interesting thing to notice is that although the step voltages are considerably lower than the touch voltages, the risk imposed by step voltages is much higher because of the increased Probability of Presence.

7.4 Conclusion

In this chapter, a novel approach to probabilistic risk assessment of electrical substations is proposed, based on the developed criteria that take into consideration the probabilistic nature of all the contributing parameters. The key points of the process are:

- The integration in the process of the probability surface of ventricular fibrillation for accurate readings of the probability of VF.
- The voltage and time and time dependency of body impedance.
- The use of historical data for the simulation of various system parameters such as fault clearance time and fault current.
- The integration of computed touch and step profiles in the substation acquired from the simulation of the substation earthing system using CDEGS.
- The random exposure of a person to different touch and step voltages depending on his/her location inside and outside the substation.
- The use of historical data for the calculation of the probability of EPR.

The approach is applied to a large substation investigating both touch and step voltage profiles. The individual risk is calculated for both cases and it is shown that step voltages imposed higher risks due to the higher probability of presence in case of a fault.

CHAPTER 8. GENERAL DISCUSSIONS, CONCLUSIONS AND FUTURE WORK

In this investigation, existing risk assessment practices for power systems earthing systems have been examined closely. A number of key parameters have been studied in detail which lead to the development of a new approach of probabilistic risk assessment. The new proposed method incorporates the recommendations of applicable standards and uses historical fault data for the location and better estimate clearance time of the faults. The new method is further developed and computerised in the form of a software routine to be used by practising engineers.

The extensive literature review carried out primarily aimed at describing the legal framework required for conducting the risk assessment process in order to comprehend its main principles as well as the targets that need to be achieved. It was shown that probabilistic risk assessment is a tool that makes full use of the available data, scientific information and experts' analysis in order to understand the nature and degree of risk imposed to the employees and public during an operation.

Based on the latest findings of investigations on the effect of current on the human body and on the accidental circuit as well as on the recorded data of electricity networks faults, a process that represents closely the real life conditions, minimises assumptions and provides sound risk assessments can be developed. Over the past few years the electrical industry worldwide has started recognising the probabilistic nature of the exposure to rise of earth potential and of the effect of current on the human body.

An extensive review of the suggested processes revealed a range of different approaches, some of which have been recently adopted by various transmission and distribution companies worldwide.

Either because of the lack of historical data to support the various assumptions made or the complexity of the process, probabilistic risk assessment so far has not gained enough confidence, and it is usually employed as a second stage assessment after the use of deterministic criteria implemented in the various standards around the world.

An appraisal of existing standards has shown that due to different assumptions used for calculating the various parameters of a given earthing grid, there are substantial differences between the recommended values of tolerable voltages and, consequently, reinforced the concept of safety limits that are applicable for an earth grid. Significant differences in the safety limit-curves were obtained with different applicable standards. The differences were attributed to a combination of factors: (i) difference in assumed tolerable body current; (ii) differences in the parameters of the electrocution circuit; (iii) differences in the predicted touch voltage; and (iv) differences in the assumed worst-case shock location. The initial studies carried out by previous members of the research group were limited to considering a generic 100x100m earth grid and only the 100Ωm and 1000Ωm earth resistivity cases. In this work, this approach was further extended and developed into a fully computerised process for the determination of the safety-limits for grids of different size and design in terms of the maximum allowable fault current for a given fault duration. The computations allow the construction of safety-limit surfaces, which are the threshold surfaces of maximum permissible fault current magnitude and duration, for the earthing parameter under consideration.

The three representative standards, IEEE 80, BS 7354 and EA-TS 41-24, were considered in this work for a parametric study of the effects of earth resistivity, grid area and mesh density on the maximum allowable fault current for a given fault duration. A wide range of generic grid designs and earth resistivities have been considered and it was demonstrated that:

- Large variations exist between the safety limit-surfaces determined by the different standards.
- Differences found in these comparative studies are attributed mainly to the assumed probability of ventricular fibrillation, shock location and electrocution circuit.
- More extensive overlapping of the safety limits was predicted from different standards than was shown by the initial work through a more comprehensive parametric study of earthing system parameters.
- Safety limit-curves and surfaces could be useful in identifying whether a given standard may have safety and/or cost implications compared with the alternative standards.
- Harmonisation of earthing systems design standards require the inclusion of probabilistic parameters, and may lead to a less subjective approach to design.

As a result, the industry is looking for a more rigorous and comprehensive procedure of probabilistic risk assessment of the earthing systems. In order to achieve this, a detailed analysis of all parameters was undertaken using the accidental circuit and historical fault data provided from the collaborating transmission companies. These parameters were modelled and integrated into the proposed probabilistic risk assessment process.

Work within this investigation on improving accuracy of calculation of heart fibrillation has led to the development of a probability surface of ventricular fibrillation and a computerised process that determines an accurate probability for a given body current and shock duration. This procedure takes into consideration the body current path and eliminates reading errors or assumptions that could result into conservative or optimistic conclusions.

A model for the body impedance was also developed to include dependence of impedance upon voltage and time as well as accounting for the path that the current travels through the body. The resulting accidental circuit includes various additional resistances such as footwear and contact resistance giving an improved model which is as close as possible to real life conditions.

The proposed risk assessment methodology aims to take account of the contributions due to the probabilistic nature of the load, protection system and grid characteristics. In this work, fault data was obtained from the collaborating company for a period of 10 years (1993-2003). The extensive analysis revealed that the mean clearance time is 80 ms, which is much lower than the currently adopted 200 ms. Moreover, such mean is variable with substation location and type of circuit breaker installed. A further important finding is the frequency of faults at given locations. It was demonstrated that some coastal/industrial site have a much higher fault frequency compared with in land substations. The clearance time and fault frequency are two major factors that can affect the risk in a significant way.

Another observation made from the supplied fault data relates to the cause of the fault. Over 80% of the faults were caused by lightning and severe weather conditions, and take place mainly on overhead lines. Current working practice on substations and towers requires no lightning risk and a low humidity which reduces the risk of exposure significantly. Such information is not considered in the existing practice of risk assessment and yet its benefits are enormous for the companies.

The current practice of risk assessment used by the transmission companies uses the maximum possible fault current in order to calculate the generated touch and step voltages. Studies in this investigation have shown that only a very small percentage of faults would result in maximum fault current and, consequently, in maximum touch and step voltages. Since 81% of faults occur on overhead transmission lines due to lightning or severe weather conditions, a double circuit line was modelled, and faults at different points on the transmission lines were simulated in order to investigate the resulting fault currents. It was found that depending on the length of the line and fault location, the fault current could range from 25% to 41% of its possible maximum value. Moreover, by the assumption that the maximum fault current would occur under maximum load conditions, the fault occurrence was investigated using the system fault data, and it was found that only 16% of faults could have occurred under maximum load conditions. It is noted that the load values used are the maximum values of each month, while the real load conditions vary during the day and month between minimum and maximum values. On this basis, it is estimated that only a small percentage of the recorded faults could have actually caused a maximum fault current.

The above fundamental investigations on parameters affecting the risk were implemented in a new computerised risk assessment procedure CRAFTS suitable for transmission systems. CRAFTS allows a full probabilistic risk assessment of the system under investigation. The application integrates the recent developments in the latest standard IEC 60479-1 and the developed probability surface of ventricular fibrillation. A case study performed on a typical grid has shown that the developed program is very useful when applying sensitivity analysis of the various parameters of the system and accidental circuit. It allows a direct visualisation of the effects of these parameters on the magnitude of risk. Furthermore, it estimates the level of risk more accurately indicating how critical the situation is, and consequently, allowing for a more effective decision making and cost benefit analysis.

The different parameters that affect the estimation of the individual risk in the proposed probabilistic risk assessment methodology were included in the process.

It is worth mentioning that the process incorporates the earthing system simulation results performed by specialised software, namely CDEGS. For the case study, the earthing system of an operating 275kV /400kV substation is modelled and an earth fault current is simulated in order to calculate the touch and step voltages throughout the substation. Instead of assuming a worst case scenario that a person will be exposed to the maximum possible voltage, it is considered that a person can be anywhere in the substation and, therefore, he/she will be exposed to the voltage at the point of exposure. For a sufficient number of possible scenarios, the total Probability of VF is calculated for both touch and step voltages. The case study demonstrated that although step voltages were of smaller magnitude than touch voltages and only a small percentage of the simulated scenarios would result in death, they imposed higher risk due the higher exposure of employees.

8.1 Future Work

Areas that this work could be extended to include:

- Further studies on the fault current for the development of algorithms that can describe statistically its magnitude according to load conditions and fault location and their integration on the proposed methodology.
- Investigation of employees' whereabouts in the substation and working habits in order to withdraw safer conclusions on the period of time that they remain in contact with conductive parts and are exposed to hazardous voltages.

Extension of the user's interface to perform the Monte Carlo simulation process as described in Chapter 7.

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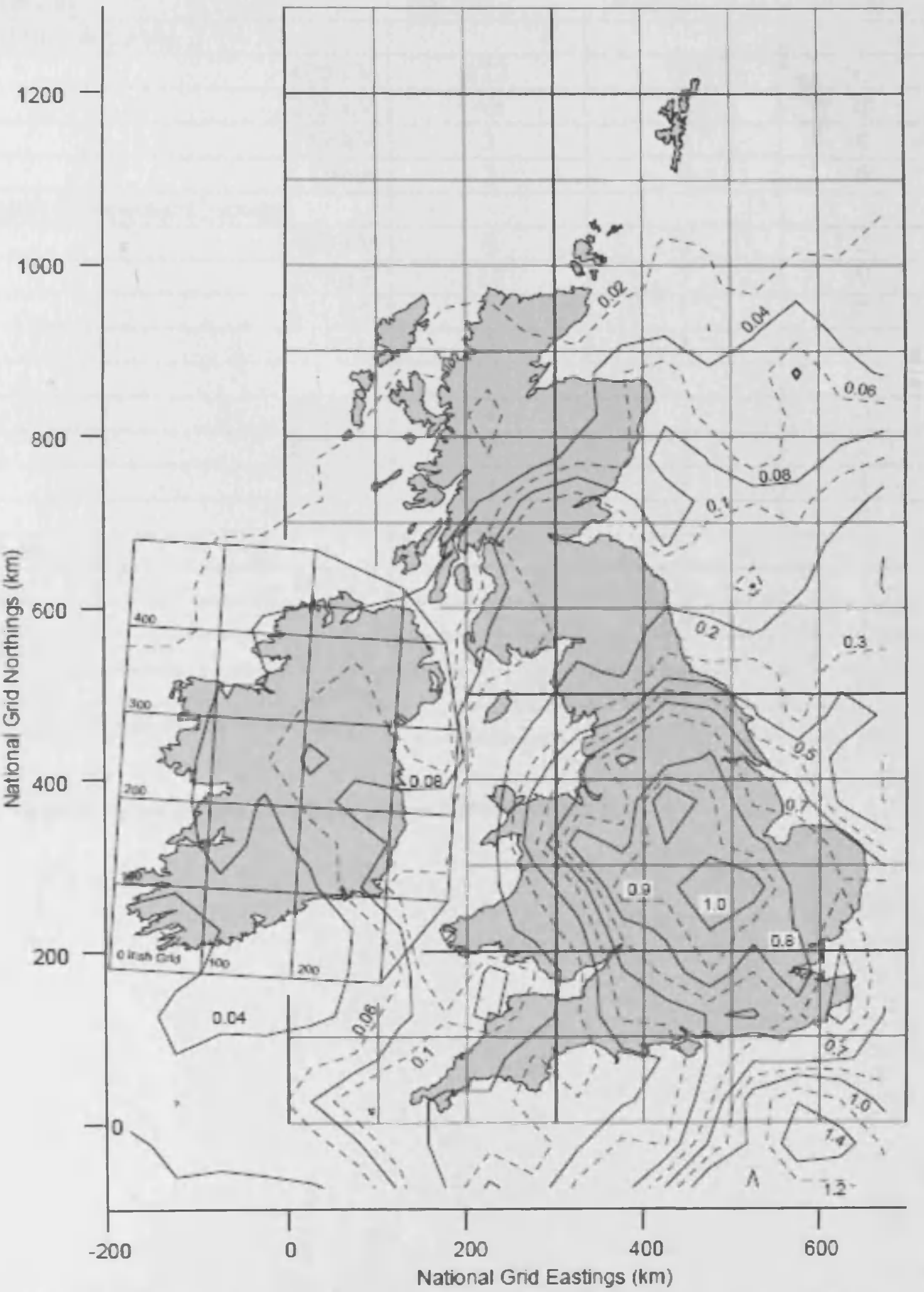
APPENDIX A



NOTE 1 This lightning density map was compiled by E.A. Technology Ltd. from data accumulated over 10 years.

NOTE 2 A linear interpolation should be used to determine the value of the lightning flash density, N_g, for a location b
two contour lines.

Figure A: Lighting flash density to ground per square kilometre per year for the British Isles [5.5].

APPENDIX B

Fault Location	1997/98	1998/99	1999/00
Overhead line & Cable			
400 kV	122	123	93
275 kV	49	20	33
132 kV	3	2	6
Other	2	0	0
Transformer & Reactor Circuits			
400 kV	9	6	2
275 kV	13	7	9
132 kV	3	1	7
Other	3	1	0
Busbars			
400 kV	4	1	0
275 kV	0	2	2
132 kV	3	0	1
Other	0	0	0
Other Plant			
400 kV	1	0	4
275 kV	3	4	1
132 kV	5	5	7
Other	0	0	0
Unknown or external to National Grid	1	6	0

Figure B: Fault Location for the three year period 1997 to 2000 [5.8].