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Using Virtual Reality Modelling to Enhance Electrical Safety and Design in the Built Environment.

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Using Virtual Reality Modelling to Enhance Electrical Safety and Design in the Built Environment

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Abstract

Martin Barrett

Using Virtual Reality Modelling to
Enhance Electrical Safety and Design
in the Built Environment

This thesis presents a prototype desktop virtual reality model entitled 'Virtual Electrical Services', to enhance electrical safety and design in the built environment. The model presented has the potential to be used as an educational tool for third level students, a design tool for industry, or as a virtual electrical safety manual for the general public. A description of the development of the virtual reality model is presented along with the applications that were developed within the model. As part of the VR development process, this research investigates the cause and effects of electrical accidents in domestic properties. This highlights the high-risk activities, which lead to receiving an electric shock in a domestic property and identifies at-risk groups that could most benefit from electrical safety interventions. It also examines the theory of transfer touch voltage calculations and expands on it to show how to carry out a sensitivity analysis in relation to the design parameters that are being used by designers and installers. The use of Desktop Virtual Reality systems for enhancing electrical safety and engineering design is a novel prospect for both practicing and student electrical services engineers. This innovative approach, which can be readily accessed via the World Wide Web, constitutes a marked shift in conventional learning and design techniques to a more immersive, interactive and intuitive working and learning environment. A case study is carried out to evaluate the users' attitudes toward VR learning environments and also the usability of the prototype model developed. From the completed case study, it appears that there is sufficient evidence to suggest that virtual reality could enhance electrical safety and design in the built environment and also advance training methods used to educate electrical services engineers and electricians. The thesis includes a discussion on the limitations of the system developed and the potential for future research and development.

Declaration:

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any Institute.

The work reported on in this thesis conforms to the principles and requirements of the Institute's guidelines for ethics in research.

The Institute has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

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Publications Arising from Thesis

Journal Papers:

Electrical safety and touch voltage design, Barrett, Martin; O'Connell, Kevin J; Sung, Tony *BSERT*, vol: 31, issue: 4, pages: 325 - 340, 2010

Analysis of electrical accidents in UK domestic properties, Barrett, Martin; O'Connell, Kevin J; Sung, Tony ; Stokes, Geoffrey *BSERT*, vol: 31, issue: 3, pages: 237 - 249, 2010

Analysis of transfer touch voltages in low voltage electrical installations, Barrett, Martin; O'Connell, Kevin J; Sung, Tony *BSERT*, vol: 31, issue: 1, pages: 27 - 38, 2010

Using Virtual Reality to Enhance Electrical Safety and Design in the Built Environment, Barrett, Martin; Blackledge, Jonathan; Coyle, Eugene; *ISAST Transactions on Computers and Intelligent Systems*, vol: 3, issue: 1, pages: 1 - 9, 2011

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Development and Evaluation of a Desktop VR System for Electrical Services Engineers, Barrett, Martin; Blackledge, Jonathan; *International Association of Engineers: ICEEE12*, London, 2012

Using Quest3D to Develop VES: A Tool for Enhancing Electrical Safety and Design in the Built Environment, Barrett, Martin; Blackledge, Jonathan; *Theory and Practice of Computer Graphics 2012 Conference (TP.CG.12)*, Rutherford Appleton Laboratory, 2012

*All publications can be downloaded from http://eleceng.dit.ie/martinbarrett/index.php

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Glossary of Terms

Low Voltage	A nominal voltage exceeding 50 V a.c. or 120 V d.c. but not exceeding 1000 V a.c. and 1500 V d.c.
Prospective Touch Voltage	The highest touch voltage liable to appear in the event of a fault of negligible impedance in the electrical installation.
TN-C-S	Earthing system in which the neutral and protective conductor functions are combined in a single conductor in part of the system.
Touch Voltage	Voltage appearing between simultaneously accessible parts, during an insulation fault.
Virtual Environment	Virtual Environment, the visual representation of the "virtual world" viewed by the participant, and produced by the VR system.
Virtual Reality	Virtual Reality, the technology or system on which the virtual environment is displayed.
Virtual World	The environment created and displayed to the user.

List of Abbreviations

cpc	Circuit protective conductor
GUI	Graphical User Interface
I_f	Prospective fault current
MET	Main Earthing Terminal
R_1	Phase-conductor resistance
R_2	Circuit-protective-conductor resistance
U_{oc}	Open circuit voltage of the mains supply
U_t	Touch Voltage
VE	Virtual Environment
VES	Virtual Electrical Services
VR	Virtual Reality
Z_e	Earth-fault-loop impedance external to the faulty circuit

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Chapter 1

Introduction

1.1 Background

Electricity provides one of the fundamental cornerstones upon which world economies prosper and plays a significant role in driving the engine of economic stability. In recent decades electricity has become pervasive in modern society to an extent where it has become an intrinsic part of our daily lives. World trends in electricity consumption clearly demonstrate this point suggesting total final consumption has risen approximately 330% in the period 1973-2008 [**95**]. However the same electrical forces that operate our lighting, motive power and communications systems along with an innumerable number of other devices are also capable of interacting with the human body. The biological effects of which can be beneficial when utilised correctly in a controlled medical environment or alternatively can be destructive as with inadvertent exposures that are commonly referred to as electric shock. Consequently, since the widespread electrification of our homes and workplaces, man has consistently attempted to safely harness the power of electricity.

With the benefit of hindsight, society has come to realise just how dangerous electricity is. Ever since the first recorded electrical incidents which date back as far as 1879 [**114**], electrical safety has generated much debate amongst electrical engineers and medical physicians. However it has taken decades of research to enhance our understanding of the harmful effects to a point where useful thresholds of reaction and commonly upheld protection measures are utilised in modern electrical installations. In general, electricity can create serious hazards that provide the potential for exposure to electric shock, electrocution, burns, fires and explosions. According to the Health Service

Executive (HSE) in the UK, contact with electricity is the fifth leading cause of workplace fatalities [**93**] and in the U.S., electricity is the sixth leading cause of injury-related occupational death (1992-2002) and the third in the construction sector [**33**]. Regrettably, when one examines fatal and non fatal statistics it becomes apparent that many of the incidents are repetitive and very often preventable. It is in this light that the considerable benefit of collecting and analysing information from previous electrical incident case histories is of significance. Therefore continued energy and focus on electrical safety issues and the development of methods to enhance our understanding and improve electrical safety design to prevent incidents is vitally important.

Today, modern industrial, commercial and domestic buildings contain an increasing amount of electrical equipment. This is a direct consequence of the technological explosion which has occurred in recent times and of course the economic relationship that exists between electricity and GDP. The net effect of which is an increased demand for electrical power to support the use of this equipment which have become integral to the way we live and conduct our business. In developed countries, buildings utilisation voltage is generally less than a 1000 V a.c. and hence electrical services engineers use the relevant national wiring rules to design and install the electrical installation to be safe for ordinary persons to use and electrically competent persons to maintain. When carrying out an electrical design, a professional engineer has a duty of care to perform faithfully and diligently any service undertaken in the manner a reasonably prudent engineer would under the same or similar circumstances. To adhere to this, electrical services engineers must produce designs that will ensure the protection of people and livestock. They must also ensure the protection of property and allow the client or owner to provide a duty of care to employees or occupants by ensuring an electrically safe working or living environment along with negating as far as reasonably possibly the financial consequences of an inadequate electrical installation.

There is ample evidence to highlight the dangers associated with the use of electricity. However what is of obvious importance is our continued commitment to put electrical safety at the forefront of our engineering decisions. Research into this area will serve to highlight the growing concerns, aid regulatory decisions in the development of standards and promote methods and techniques to enhance our understanding and reduce the number of fatal and non fatal electrically related incidents and it is within this context that this research is motivated.

1.1.1 Virtual Reality and Electrical Services Engineering

Virtual reality (VR) is an emerging technology, which employs the increasing power of computers to simulate real or imaginary scenes and environments with a high level of interactivity and realism [**130**]. The benefits of which have increasingly gained recognition from researchers, developers and numerous commercial organisations. Potential applications have been identified and developed in areas such as maintenance, simulation, planning and testing and verification. Virtual reality technology has also been used for training applications and applied to a wide range of problems in fields such as military, medicine, aircraft and business. One of the key advantages to virtual reality is the potential it offers to expose users to simulated hazardous environments in a highly visual, safe and interactive manner. In doing so, users can familiarise themselves with a potential work environment, technology or a decision making process and immediately evaluate the consequences of tasks undertaken giving the user time to become more competent in a virtual real world setting which can be experienced at the users own pace.

Virtual reality simulation systems allow users to navigate in any direction within a computer-generated environment, decide what actions to take and instantaneously view the impact of those actions [**130**]. The concept of applying virtual reality simulation systems to the electrical services field will allow users to walk around an electrical installation, view and inspect equipment, simulate designs, have the possibility of operating equipment, view current wiring regulations, receive maintenance assistance and advice and undertake design decisions without causing any damage to the equipment or injury to themselves. Depending on the system developed users can interact with the virtual world using various hardware devices such as mouse, joystick or data gloves.

Although virtual reality is an impressive tool and has received much recognition, the need for high end computer systems, expensive head-mounted displays and user interface devices such as gloves has somewhat limited its use. However, today virtual reality systems can run on affordable personal computers and interaction with the virtual environments can be afforded using the mouse and keyboard without introducing any additional peripherals. As a result, desktop virtual reality systems have opened VR to a much wider audience. Due to these characteristics just mentioned, it would appear that this non-immersive technology is becoming more mature and ubiquitously used than its more immersive counterpart. Moreover, with the ongoing development of virtual reality systems on the World Wide Web, the potential to engage users on a mass scale is possible along with the integration of other online tools.

This thesis describes the theoretical foundation, development and evaluation of a desktop virtual reality-based system aimed at improving electrical safety and design in the built environment. It provides an elaboration on current electrically related concerns in this field, investigates how electrical accidents occur and carries out a touch voltage analysis. All of which form the basis of an electrical safety concept which the author puts forward as the foundation on which to develop the VR model. The concept and structure of development used in applying virtual reality to electrical services should provide a framework that can be used to guide the design and development of other virtual reality systems. This current model can be seen as an initial structure from which subsequent augmentations in this area can be developed. The potential of using virtual reality for enhancing the field of electrical services should be embraced and by affording users the ability to visualise; the three-dimensional representation of a problem, abstract concepts, dynamic relationships in a system and interact with scenarios that are unfeasible due to distance, time, or safety factors should only serve to improve electrical safety in the built environment.

1.1.2 Proposed Electrical Safety Concept

Electrical safety in the built environment can be defined as the process of eliminating the risk of incident or injury from electrical installations. To achieve this, an approach must be taken that encompasses all of the elements that influence the outcome. In chapters 2-5 of this thesis, three predominant factors related to preventing electrical accidents in the built environment can be clearly identified. These are *design*, *maintenance* and *persons.* Using the concept of three overlapping circles an electrical safety model is proposed which forms the foundation on which to develop the VR model. From Figure 1.1 below the three factors can be seen to overlap, the importance of the overlap being critical. The section common to *design* and *persons* highlights the potential danger to a person where the design is poor or the person is careless. The section common to *maintenance* and *persons* highlights the potential danger to a person where there is poor maintenance or the person is careless while the section common to *maintenance* and *design* highlights the potential danger to a person where there is poor maintenance or where the design is poor. The section common to all three circles yields the greatest risk of danger. The sections which are not common to any part of the circle can be viewed as good design, good maintenance and a safe person. The person can be an ordinary person, skilled or instructed person.

The intent of electrical safety is to eliminate as far as reasonably possible the potential of electrical accidents occurring. One potential method of addressing each of these elements outlined is to use virtual reality. Through the virtual environment designers can investigate the impact of their designs, persons can become more aware of the dangers of electricity by virtue of the collected accident scenarios, while a skilled person can become more informed or virtually instructed before carrying out maintenance. By providing a format to develop and address each of these elements will only serve to heighten awareness and encourage people to use safe electrical practices.

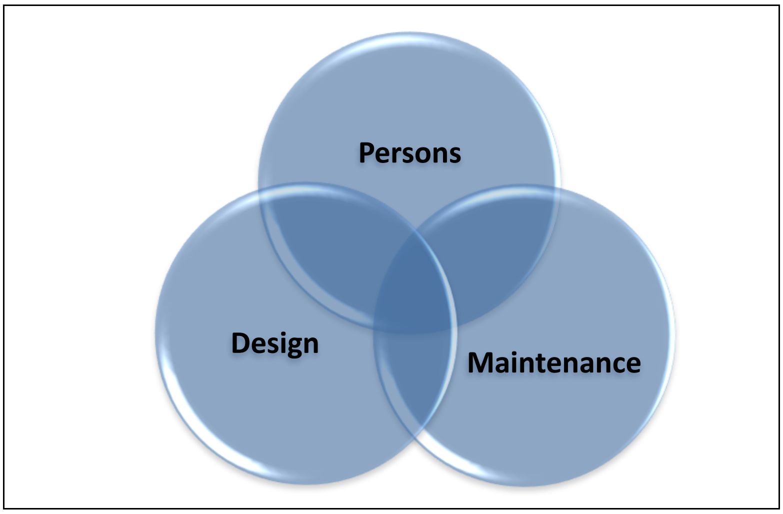


Figure 1-1 Proposed Electrical Safety Concept

1.2 Statement of research problem

It is believed that virtual reality can be successfully applied to improve electrical safety and hazard awareness issues in the field of electrical services engineering. Virtual reality can offer the potential to immerse users into an interactive and well controlled virtual world containing the main components of an electrical installation. This may operate as an enhancement to existing training and design methods. The primary issues of this research will be the implementation of a novel virtual reality system, which will have been developed and tested based on actual accident data and field measurements. This system may offer the ability to view many of the components and simulate many of the circuits in an electrical installation obtaining an adequate level of realism but which is still capable of performing satisfactorily on a personal computer based system.

1.3 Research Aims and Objectives

The aim of this research is to develop and build a novel virtual reality model to improve electrical safety in the built environment that will be used to simulate the dynamic operations of an electrical installation in the built environment. Based on collected data and controlled measurements of electrical circuits designed to ET101 (National Rules for Electrical Installations in Ireland), the expected responses will be examined; compared and critically analysed in a holistic manner. The study will mainly focus on meeting the ET101 requirements and produce a model that is capable of producing simulated outputs and realistic responses.

The virtual model will be used as an educational tool for third level students in Dublin Institute of Technology but can equally be applied to design engineers, electricians or the general public wishing to enhance their understanding of electrical installations. Users who familiarise themselves with the virtual model will quickly immerse themselves in electrical safety and installation design. Adopting the use of the virtual model as an educational tool is a more student centered approach and shifts away from conventional learning techniques to one where students can self learn by investigating the installation for their own inputted data

The provision of safe and reliable means to afford protection against electric shock in the built environment is deemed one of the most important design elements for electrical services engineers who design low voltage electrical installations to conform to ET101 and BS7671: 2008 (17th edition IEE Wiring Regulations). The fact that the built environment ranks as one of the leading locations for electrical injury and death, and electrical installations lack routine inspection and scheduled maintenance in a European environment where an ageing building stock exists in many countries highlights the growing concerns for electrical safety.

However, by performing a value-engineering design through the implementation of the virtual reality model, users can attain a higher level design while also becoming aware of the current issues surrounding electrical safety in the built environment. The 'virtual reality model' can be a powerful tool for designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters. It can also be used to identify the sensitivity of resulting touch voltages to any variations in the main design parameters.

1.3.1 Objectives

To achieve the main aim a number of the key individual objectives can be classified in the following manner:

- To investigate the development of electrical safety standards and from this determine the background that formed the basis of the development of the main threshold levels associated with electric shock.

- To identify the main reasons for concern currently in the electrical services industry by formulating a body of evidence highlighting the major concerns related to domestic electrical safety throughout Europe.

- To identify the main causes of electrical accidents in domestic properties and highlight the at-risk groups that could benefit from improvements in electrical safety, the main risk activities in domestic properties and the products involved.

- To investigate the potential risk associated with touch voltages in electrical installations and outline the underpinning basic theory of a safe touch voltage design. From this develop a set of touch voltage sensitivity calculation equations which can be used by installation designers and installers to investigate and identify the range of resulting touch voltage values that might be the consequence of variation of the four main design parameters.

- Develop a touch voltage simulator that can be used by designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters.

- Carry out an on-site touch voltage case study to verify the validity of the touch voltage simulator as a credible design tool.

- Identify and test a range of virtual reality applications suitable for the development of the VR model.

- Build a novel prototype VR model to demonstrate the potential of using virtual reality in the electrical services industry

- Evaluate the virtual model developed using a cohort of students from Dublin Institute of Technology

1.4 Research Methodology

In order to investigate the objectives outlined a research methodology was developed. A visual overview of the research design by virtue of a flow diagram is given in Figure 1-2. For individual sections of research undertaken a specific methodology element or research method is included in each chapter where it is required. A general overview is given here.

1.4.1 Research Methodology Flow Diagram

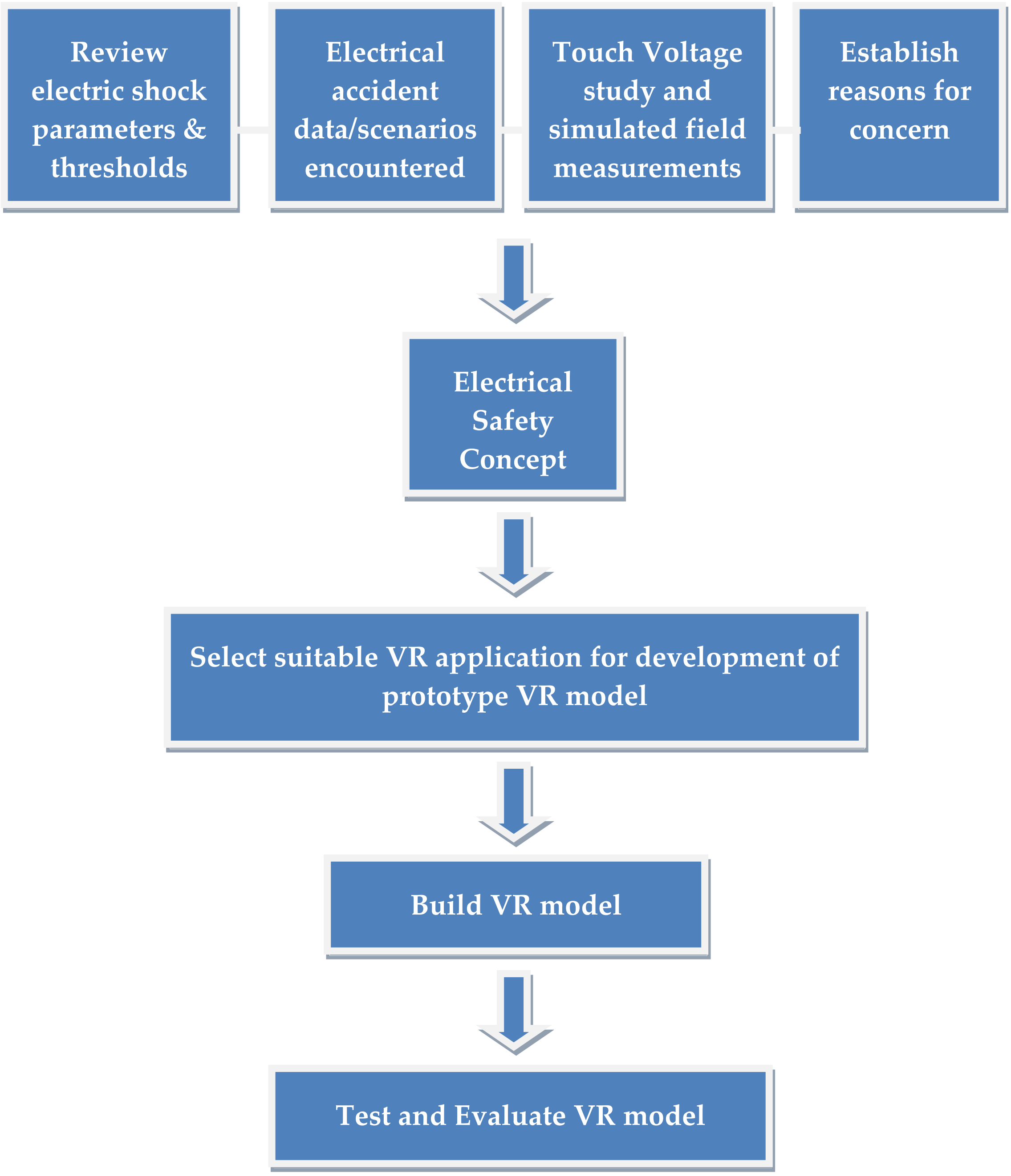


Figure 1-2 Research Methodology Flow Diagram

In order to establish clear justification and motivation for the development of this research, a thorough literary search investigating the current concerns associated with electrical safety in the built environment across Europe was carried out. Inclusive in this search was a review of all available electrical accident data in order to obtain the frequency and depth of the problem. Additionally, to establish the threshold of reactions to electric current and investigate the validity of the published standards in relation to the effects of electric current on humans, a wide variety of published standards, scholarly journals and texts are consulted. The findings of which provide a strong foundation on which to carry out the touch voltage case study. An investigative analysis into touch voltages allow the development of a touch voltage simulator which is verified by on site measurements.

The accumulated knowledge gleaned from the literature search, analysis of the accident data which will provide a range of accident scenarios in addition to the development of the touch voltage simulator verified by field measurements will provide the fundamental basis on which to generate an electrical safety concept from which a prototype virtual reality computer model can be developed. Finally, using a cohort of students from Dublin Institute of Technology the VR model is tested and evaluated.

1.5 About This Thesis

This thesis has been prepared in such a manner that each individual chapter can stand alone as a unique entity that can be read individually. Equally, the considered integration in an intelligible manner of each chapter in a collective group forms the structure of an orderly coherent thesis. Of the seven main chapters (2-8), five peer reviewed journal papers have been published.

The purpose of Chapter 2 is to introduce the reader to the basic themes associated with electrical safety and particularly electric shock from both a historical context and a modern idiom. The analysis provided should prove useful in understanding the establishment of published electric current and voltage limits and levels of concern and aid in the development of the virtual reality model and also in the touch voltage design and electrical accidents discussion which will take place in later chapters. Chapter 3 aims to set out to the reader the electrical standards currently in place and outline the main methods of protection generally employed to provide protection against electric shock in the built environment. Following this a body of evidence is documented which aims to demonstrate the current concerns regarding electrical safety and provide justification for the development of a virtual reality model to feed into the ongoing effort to improve electrical safety levels. Chapter 4 investigates fatal and non-fatal electrical incidents from electric current causing shock or burn in domestic properties. Chapter 5 carries out an analysis of touch voltages in low voltage electrical installations. In this chapter a unique sensitivity equation was developed in order to aid designer and installers in addition to a touch voltage simulator. The purpose of Chapter 6 is to set out the justification for the selection of the software chosen and to outline the software process behind the development of the prototype model titled 'VES' (Virtual Electrical Services). Chapter 7 presents the design process of "VES", which was developed to demonstrate how VR technology can be applied to the electrical services industry and used to enhance electrical safety and design in the built environment. Chapter 8 evaluates the prototype desktop virtual reality model using a cohort of students from Dublin Institute of Technology. Finally, Chapter 9 provides a conclusion to the work and considers an example of further developments that can be undertaken.

1.6 Original Contributions

The principal hypothesis upon which this thesis is based concerns the use of virtual reality for the enhancement of electrical safety and design in the built environment. In the context of this hypothesis, the principal contributions that are new and innovative as reported in this thesis are compounded in the following:

- ❖ Design and implementation of a prototype virtual reality application designed to enhance electrical services design and safety in the built environment using a desktop VR system.

- ❖ Application of independent analysis for the evaluation of the VR model. This analysis makes a significant contribution to understanding the potential of desktop VR technology to support and enhance understanding in engineering. This analysis can guide the future development efforts of desktop VR-based learning environments applied to the field of electrical services engineering.

- ❖ A study of original unpublished data investigating fatal and non-fatal electrical incidents from electric current causing shock or burn in domestic properties is conducted. The electrical incident data was used to trend electrical injury for various categories and groups. This determined at-risk groups that could benefit from electrical safety interventions and highlighted the high-risk activities, which lead to receiving an electric shock in a residential home. The benefits of the narrative reports that accompany each individual incident is also exploited to forge an insight into incident causes that may indicate where specific types of remedial action can be implemented (engineering controls, safety awareness campaigns, etc.) which may temper the number and severity of domestic electrical incidents. The outcome of this study may be used by regulatory bodies in the development of standards in this field.

- A set of original touch voltage sensitivity calculation equations are developed, the author has demonstrated that the equations can be used by installation designers and installers to investigate and identify the range of resulting touch voltage values that might be the consequence of variation of the four main design parameters

- The 'Touch Voltage Simulator' application developed is a powerful tool for designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters.

Chapter 2

Understanding the Effects of Electricity on the Human Body

2.1 Introduction

Our understanding of electricity and its effects on humans has advanced significantly since the first recorded accidental electrocution which took place in France in 1879 [**114**]. In the intervening period, electricity has become an intrinsic part of our daily lives providing us with one of the most convenient forms of energy. However, the inherent dangers associated with the use of electricity will always exist. As a consequence, our awareness of these dangers and our willingness to determine the pertinent thresholds is of the utmost importance. Experimental investigations of electric shock pre date all commercial uses of electricity, tests on the effects of frictional electricity on birds, beetles and other organisms were made during the eighteenth century [**77**]. However experiments from then to approximately the 1930's, a time which marks a watershed with regard to research in this field leave a lot to be desired in terms of relating this information to mankind. Since this time much has happened, which has led to the development of heightened protective measures and a safer built environment for us to work and live in emphasising the practical importance of experimental investigations.

The aim of this chapter is to review the literature on human and animal responses to a.c. 50/60 Hz along with a review of the standards and documents that presently have published values for voltage, current, and resistance. This analysis should prove useful in understanding the establishment of published limits and levels of concern and aid in the development of the virtual reality model and also in the touch voltage design and electrical accidents discussion which will take place in later chapters.

For designers it is important to appreciate factors which influence the severity of an electric shock, these include the physical condition of the subject, the duration and path of the current flow, the frequency of the supply, the magnitude of the current and also the magnitude of the voltage causing the shock. This chapter will attempt to outline these issues and will also examine the information behind the development of a safe level of touch voltage for an electrical installation along with identifying issues of concern and areas where further research would be valuable.

2.2 Underlying Principles

The underpinning theory outlining the relationship between electricity and excitable cells is well documented in [**144**], [**23**]. A general summary of these findings suggest that the effects of electric current can be calculated provided detailed information is available on the cell geometry/biophysical properties and the electrical potential along this geometry [**22**]. However under accidental conditions the aforementioned data is not often readily available for various exposure conditions and each cell affected. As a result the general approach has been to assume a uniform electric field across the tissue concerned leading to a simplification of the effects of electric current. Nevertheless, this approach allows for the establishment of safe values of exposure using a single number e.g. uniform electric field strength [**22**].

Touch and step voltages are electrical potentials that develop under fault conditions in an electrical installation which humans or animals may be subjected to. From an engineering design viewpoint the ability to predict unwanted physiological effects giving only information about the voltage levels is advantageous. On a cautionary note, electrical injury or death can result when these voltages exceed certain threshold values. In humans the internal electric field will depend on the contact voltage along with the geometry of contact and tissue properties. Hence a 'safe' touch or step voltage will vary depending upon the exposure conditions and also upon the subject [**22**].

A significant proportion of the parametric sensitivity to electric shock can be best appreciated when considered in the light of the basic principles of bioelectricity. Reilly [**144**] deals with such matters admirably. For the purposes of this chapter some of the more pertinent principles will be outlined.

From the preceding discussion the bulk impedance properties of biological material is of obvious importance when electric shock is considered. These properties often determine the current densities and pathways that result from electric shock.

Hence for a cylindrical block of biological material having length l, the total path resistance R, which is determined by the ratio V/I will be directly proportional to the length of the material and inversely proportional to the cross sectional area of the material in accordance with

$$R = \frac{\rho l}{A}\ (\Omega) \tag{2.1}$$

where ρ is the uniform resistivity

Electric Field Strength is defined as the force per unit charge that would be experienced by a stationary point charge at a given location in the field

$$E = \frac{V}{D}\ (V/m) \tag{2.2}$$

Current Density (J, A/m^2) is the amount of current flowing through a conductor/tissue per unit of cross sectional area. If a homogenous volume resistivity is assumed current density can be related to electric field by $E = J/\sigma$ where σ is conductivity [**22**]. Current (I, A) across the biological material can be linked to the current density, provided information on the geometry of the material and the entry and exits points are known and voltage *(V)* across a biological material can be related to current I passing through that material with a total path resistance R by $V= I*R$

Finally knowing that a (biological) material presents a resistance to electron or current flow flags another important phenomenon for electrical safety. The conductor temperature will increase as the current passing through it increases. This results in heat energy being transferred to the surrounding environment via conduction, convection and radiation. This process is called Joule heating and the amount of heat produced can be determined from Joules law.

$$P = I^2R\ (\mathrm{W}) \tag{2.3}$$

where, P is power in watts

2.3 Basic Effects of Electricity on Humans

On an annual basis humans worldwide are injured or killed as a result of hazardous defects in electrical systems or because they adopt unsafe working practices on electrical systems. In general, electrical injuries can be categorised into three main groups: electric shock, burns and falls due to an electric shock. Injuries such as falls due to electric shock and injuries which could technically be classed 'electrical injuries' such as fires or explosions resulting from the malfunction of electrical equipment which although serious are beyond the scope of this chapter.

A human body will conduct electricity if it comes in contact with an electrically energised object while simultaneously in contact with another object at a different potential. If such an event were to happen an electric current would flow through the body entering at one point of contact and exiting at the other. The magnitude of the current will increase as a function of the potential difference between these two points. However, this relationship is not linear as the impedance of the human body varies with the change in potential (touch voltage or step voltage). There are two standout reasons why our bodies are so susceptible to electric shock. Firstly our nervous system makes us very sensitive to even the smallest of currents. Secondly, our resistance to the flow of current through our bodies results in energy dissipation through Joule heating [**85**] as defined earlier. The result of each of these exchanges can have severe consequences for the human body.

For engineers to fully appreciate the effects of electric shock, requires an understanding of the physiology of one's body. Central to this, is the human nervous system which endows humans with sensory perception, processing power and motor control, all of which are primary functions which allow us to exist with some useful purpose. Human senses such as touch, taste, sound etc. along with pain receptors provide the sensory input via bio-electric signals to this system. Motor control of our voluntary muscles, like our limbs and our involuntary muscles such as our heart and lungs is controlled by the output of these bio-electric signals. The incoming and outgoing signals for these various functions are processed and executed by the brain. Neurons are the electrically excitable cells that process and transmit this information by electrical and chemical signalling. Neurons regulate the contraction of the cardiac, diaphragm and muscle cells. The level of these signals is typically in the micro amp range.

Electric shock as defined by [**31**] is the physical stimulation that occurs when electric current flows through the human body. Humans range and scale of reaction to this stimulation can be quite varied ranging from mere perception/tingling sensation at low levels of alternating current to muscle contractions, to pain, to one which can have severe effects on the sensory and control functions of the nervous system leading to death. In general, the effects of electricity are commonly characterised by reference to the current flowing. Figure 2-1 [**144**], outlines various categories of reaction and presents an informative approximate scale of reaction for an adult gripping a large electrode in one hand, while a foot is in contact with the return electrode. The applied alternating current is in the 50-60 Hz range and the duration of exposure is approximately 5 seconds. Knowing these thresholds of reaction for the various effects of electricity is vitally important for the development of safety standards.

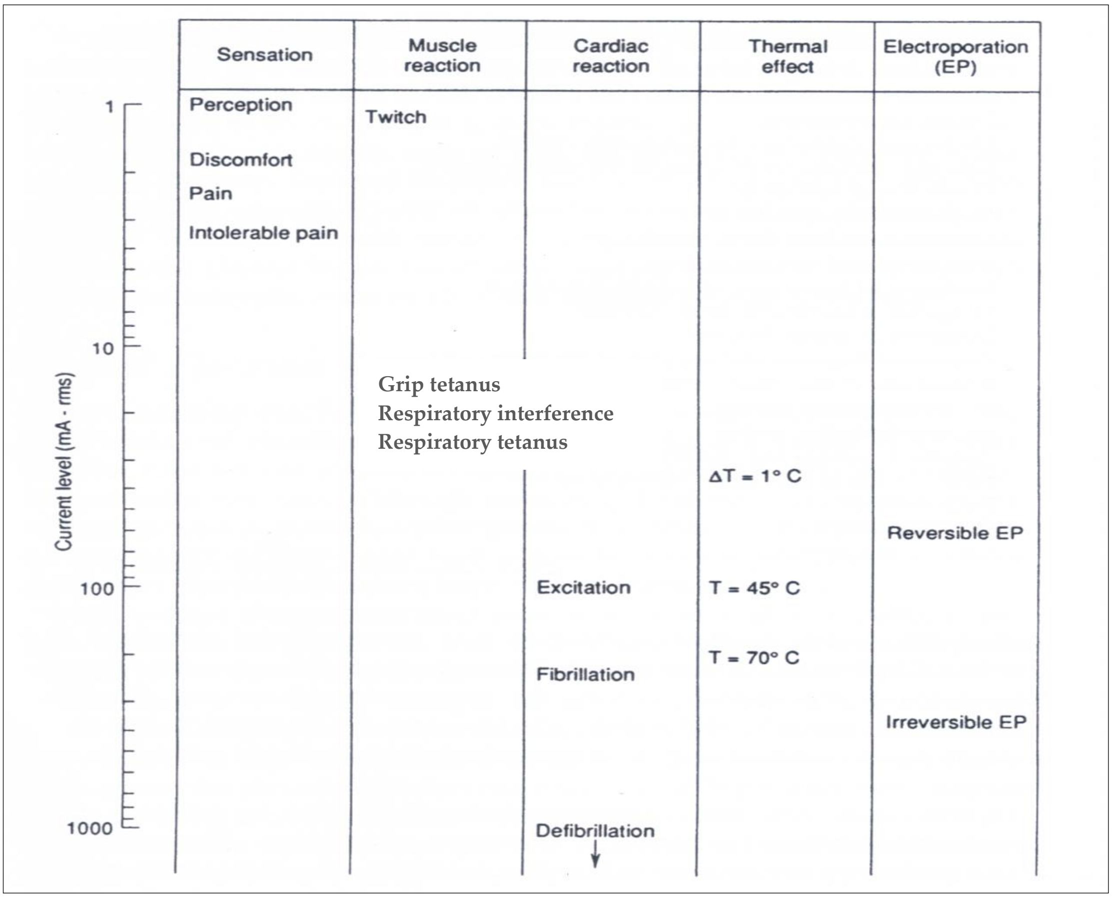


Figure 2-1 Adult human scale of reaction to short term exposure to alternating current [144]

Electric shock should not be considered as a singular phenomenon as it can lead to the activation and disturbance of many muscles including those involved in respiration. Electric shock is usually painful, and can affect cell functionality. However cell or tissue damage is not necessarily always a direct consequence. A tingling sensation is generally the result of currents in the very low mA range. As the current increases the sensation quickly transcends into one of severe stabbing at the points of entry and exit and can sometimes be felt along the current path [**43**]. These sensations are very often accompanied by severely painful involuntary contractions of the muscles along the current path. It is also not uncommon where a person has a grasp of a conductor or the frame of a class I appliance that it proves impossible to let go. Alternatively if the person was touching a live conductor as opposed to having a grasp of it, there may be a violent contraction of the back and leg muscles causing the person to be thrown backwards.

2.3.1 Common causes of death associated with low voltage electricity

Low voltage deaths are generally attributed to one of three causes.

1) Asphyxia
2) Respiratory arrest
3) Ventricular fibrillation (most common)

Muscles of the chest, diaphragm and glottis subjected to tetanic contraction may prevent breathing and this can result in death from suffocation if the current goes uninterrupted or the victim fails to gain release from the live part. Under these conditions the person would lose consciousness after approximately a minute followed by death a few minutes later. This is commonly referred to as death from ***asphyxia***.

Death due to ***respiratory arrest*** is also associated with electric shock. Current passing through the respiratory control centres of the central nervous system may cause a prolonged contraction of the chest muscles upsetting the breathing function thereby suspending the flow of oxygen to the lungs. Very little is known regarding the parameters of time and current to produce this effect.

The most common mechanism of death related to electric shock is associated with direct interference with the heart. This is generally attributed to ***ventricular fibrillation*** and hence this topic is of great practical importance when developing safety standards. Ventricular fibrillation of the heart results in the uncoordinated contraction of the cardiac muscle of the ventricles, making them quiver rather than contract properly. This prevents the heart from acting as an effective pump and death follows quickly. As a result, research in this area has been extensive. Papers by Lee [**119**], Dalziel and Lee [**54**] and Geddes [**27**] successfully summarise this research and from these sources amongst others it is possible to ascertain a good insight into research trends and opinion.

2.3.2 Electrical burns

Aside from the problems associated with the sensory and control functions due to electric shock, electric current may heat both external and internal tissue sufficiently to cause structural damage through ***electrical burns***. This is caused by the flow of current through the body and the resultant dissipation of energy. In the case where an energised conductor is gripped the greatest temperature rise will occur in high current density areas such as around the wrist or in the hand at the edges of the conductor. The heating depends mainly on the r.m.s. value of the current rather than the waveform. The delivered energy can damage the excitable cardiac and nervous tissues along with the non-excitable skin and blood vessel tissues [**22**]. Damage can vary from third degree burns to severe internal organ damage [**85**]. The rate at which energy is delivered to the body can be ascertained by determining the instantaneous power (W) which can be calculated using the equation $P = v(t)i(t)$ or alternatively using the formula $P = i^2(t)R$ where the values for (P) power, (V) voltage and (I) current are the instantaneous values. The integral of this equation will determine the energy delivered to the body in a certain time.

Electroporation can result in an increase in cell membrane permeability when the electric field is sufficiently large. It is reversible at less intense levels of electric fields but at higher levels it becomes irreversible [**144**] leading to complete cell damage. Severe consequences are generally thought to be linked to high voltage accidents.

2.4 Important Parameters for Electrical Safety

When considering prevention of electric shock in an electrical installation, there are several important parameters that need to be considered to fully appreciate the vulnerability of humans under various conditions. Generally, the physiological effects are predominantly determined by the magnitude and frequency of the current, the type of waveform (whether it is a continuous sine wave, rectified sine wave, or pulsed etc), the path it takes through the body and its duration. The response of the human body will vary depending on these parameters. Due to the significance of this topic, widespread research has resulted in an effort to determine the minimum thresholds for the various body responses and exposure conditions. Thresholds of note range from the minimum perception threshold, to muscular reaction, to the inability to let go, to ventricular fibrillation/death. Ultimately, from a European perspective the time/current zone graphs outlined in IEC 60479 *Effect of Current on Human Beings and Livestock* [**97**] evolved, which outlines the minimum permissible current thresholds for various body responses to electric current. However these graphs are not directly applicable in practice for design measures in relation to protection against electric shock in an electrical installation. The touch voltage limit is the necessary criterion. Importantly though, the relationship between current flow through humans and voltage is not linear, as the impedance of the human body varies with the potential placed across it. Therefore to appreciate how much current could possibly flow, requires analysis of the impedance of the human body and how it varies with touch voltage.

It will be useful at this stage to review the development of the important parameters which are vital to understanding human's interaction with electricity. This in turn can be used to appreciate the development and effectiveness of various standards in the protection of humans against electric shock and will aid in the development of the touch voltage simulator in the virtual reality model.

2.4.1 Electric Current type, waveform and frequency

Stimulus parameters such as, wave-shape, polarity, duration, repetition pattern, and whether the stimulus is mono-phasic or bi-phasic can significantly affect sensory sensitivity [**144**]. Although our major focus will concentrate on alternating current in the 50-60 Hz frequency range due to its widespread use in the distribution of electricity, it is worth observing the contrasting effects of alternative stimuli due to the growing number of electronic products on the market that produce markedly different waveforms than those distributed by utility suppliers.

Electrical accidents associated with direct current (d.c.) are far less prevalent than those associated with alternating current (a.c.). In fact if a fatal d.c. accident does occur it is generally under very unfavourable conditions. Generally d.c. effects on humans are more closely related to a burning rather than a tingling sensation [**85**]. With d.c., a severe feeling of shock is felt when the circuit is made or broken while in contrast there is much less pain when the current is maintained [**17**]. The let-go phenomenon of an object which is gripped is also much less difficult and there is no definable threshold for this phenomenon [**97**], while for exposure times greater than one cardiac cycle the threshold of fibrillation remains notably higher than for alternating current. However, for shock durations less than 200ms the fibrillation threshold is approximately equivalent to the a.c. value. Data derived from animal and electrical accidents also outline that the threshold for fibrillation for a downward current is twice that for an upward current. Lower thresholds (23% lower) for monophasic stimuli of negative polarity compared to positive polarity, is also cited in [**144**]. As far back as the 1880's when Edison and

Westinghouse infamously battled it out over which system was most suitable for the distribution of electricity, a.c. or d.c. Edison rightly claimed at that time (without any experimental data it must be noted) that a.c. was more dangerous than d.c. and hence d.c. (the system he was promoting) should be used for the distribution system. Edison also acceded to the request of the New York state to support the drive to replace hanging with legal electrocution using a.c [**145**].

Ultimately, the main difference between a.c. and d.c. can be highlighted by the excitatory effects of the current i.e. stimulation of nerves and muscles, induction of ventricular fibrillation etc. which are related to the change in the magnitude of the current particularly when making or breaking the current. Therefore for d.c. current to produce an equivalent excitatory effect as a.c., the magnitude of d.c. would need to be several times that of a.c. [**96**]. Table 2-1 provides a comparison of a.c. to d.c. based on the findings of the IEC [**97**] for various physiological effects.

	a.c.	d.c.
Perception	0.5 mA	2 mA
Involuntary muscle contractions (5 sec)	0.5-5 mA	2-25 mA
Strong muscle contractions (5 sec)	5-40 mA	25-150 mA
Min. fibrillation level (20 msec)	500 mA	500 mA
Min. fibrillation level (5 sec)	40 mA	150 mA

Table 2-1 Comparison of a.c. to d.c. for various physiological effects.

In contrast to studies on 50-60 Hz shocks, studies concerning the dangers surrounding pulse or impulse shock are limited [**17**]. Reilly [**144**] and Geddes [**83**] however provide some detailed analysis on our sensory responses to various forms of electrical stimuli (for an in depth study these sources should be consulted). In terms of waveform dependency, the relationship between the threshold of reaction and the intensity of a monophasic current has received greatest scrutiny [**144**]. Obvious from previous research related to monophasic currents is the striking sensitivity of the neural excitation thresholds to the duration of the monophasic currents. Weiss and Lapicque are the forefathers of the S-D relationships for neural excitation dating back to the beginning of the 1900's.

Exposure to a transient electric shock is a common occurrence. Our bodies regularly act as a capacitor that stores an electric charge, subsequently when in close contact with a grounded object, the stored charged is discharged through a spark that may be felt and heard. Of course, inadvertently discharging a charged capacitor through one's body while carrying out maintenance on a machine maybe more serious. Capacitive energy storage can lead to an impulse discharge shock resulting in high voltage and currents with the possibility of significant energy transfer to the victim. Deaths have been recorded to impulse shocks but in far fewer numbers than other types of shock [**85**]. From electrical accident data related to discharging capacitors type shocks and from animal experiments used in developing the defibrillator, it is believed that in regard to pulse type shocks, it is the electrical energy in the discharge which presents the hazard [**17**]. Bernstein [**17**] cites energy content above 50 J as probably hazardous while Gordon [**85**] cited a study which demonstrated fibrillation resulting from a shock as low as 30 J. Swiss and Austrian groups developed capacitor discharge thresholds which form the basis of acceptability criteria published by the IEC [**98**].

Many studies have been carried out on monophasic and biphasic stimuli, in many cases for the benefit of medical science rather than electrical safety. Experimental data demonstrates a single biphasic stimulus has a reduced efficacy for neuromuscular stimulation in contrast to monophasic stimulus of the same phase duration [**144**]. However, this is not to suggest that thresholds for all biphasic stimuli are elevated above monophasic stimuli of the same duration. Indeed, repetitive oscillatory biphasic stimuli may decrease to the monophasic value.

In general repetitive stimuli may enhance sensory response if many action potentials are generated and it may also reduce the threshold for exciting a single action potential in contrast to a single stimulus pulse. To fully understand our response to repetitive stimuli, it is important to recognise the role of the refractory period (period during excitation and early recovery during which a cell cannot be excited) and the capability of a cell to be re-stimulated which depends on the duration of its action potential and refractory period [**83**]. Hence if the frequency of the stimulus is greater than the reciprocal of the refractory period, each pulse will not excite the cell [**83**]. Therefore the current required for stimulation should rise with frequency.

Sinusoidal stimulus which is a repetitive biphasic waveform is of special concern when electrical installations are concerned. For electric shocks, the waveform of the current can have a significant influence on current efficacy. From our earlier discussion on d.c. it is evident that a.c. in the 50-60 Hz range is considered more likely to induce hazardous electric shocks than d.c. current. Indeed our perception and tolerance to this type of current at various frequencies gained much attention in the early 1900's when it was necessary to choose the frequency for distributing electrical energy [**83**]. From this time onwards there has been extensive research on the influence of frequency in relation to electric shock. Analysing these findings, it is evident that the human body is particularly susceptible to sinusoidal currents with frequencies ranging from 15 to 150 Hz. At these values the heart and muscle response is much more susceptible than for higher frequencies.

D'Arsonoval [**44**] a pioneer in terms of the effects of frequency demonstrated this very point by passing current with increasing frequency through the human body, in these studies as the frequency was increased beyond 2500-5000 Hz the current could not be perceived. Experiments on dogs by Geddes and Baker [**83**] to determine the threshold current for ventricular fibrillation using sinusoidal current of varying frequencies clearly indicated that as the frequency was increased the current required to induce ventricular fibrillation also increased. Of note from this research is the fact that the fibrillation threshold between 20-100 Hz is almost independent of frequency, while above 100 Hz the current required to produce fibrillation is notably higher. Data from 1936 obtained by Kouwenhoven et al [**113**] using interrupted direct current is in general agreement with Geddes and Bakers findings suggesting that the threshold for fibrillation current at 1260 Hz is 12 times that at 60 Hz. Previous to this in 1900, Prevost and Battelli [**139**] found the threshold voltage for fibrillation at 2000 Hz was 10 times that for 200 Hz. More recent studies analysing the effects of frequency are also in general agreement, Dalziel and Lee [**52**] in 1969 found 20-100 Hz induced involuntary hand muscle contractions most effectively, while Kugelberg [**115**] in 1976 determined that frequencies in the range of 12-60 Hz induced fibrillation of the heart most effectively.

Concluding from the above, it is evident that currents in the 50-60 Hz range which are the commercial electric power frequencies used throughout the world are among the most dangerous in terms of electrical stimulation, however if electrical burns are considered, tissue heating depends on the RMS values of the current and not on its waveform/frequency [**22**].

2.4.2 Body Impedance and Current Path

As illustrated in Figure 2.1 the scale of reaction to the effects of electricity are commonly characterised by reference to the current. However, for designers a much more convenient method to apply safety standards is to determine a safe voltage level. Ohms law amalgamates these two factors *(V= I.Z)* and also establishes the significance of total path impedance in developing a safe working voltage. Of note here of course is the fact that the relationship between current and voltage is not linear as the impedance of the human body varies with touch voltage. Hence, for designers to determine safe design measures, impedance data for various touch voltages under various conditions is required.

During electrocution current is predominantly introduced to humans via contact with a metallic conductor. The limiting impedance under such conditions will be defined by the phasor sum of contributions from the energy source, the electrode interface, the skin and the internal body tissue. From this list and for low voltage accidents in general, the skin is the primary current limiting component provided the touch voltage is approximately 200 V or less and the skin remains undamaged (The level of voltage being significant due to abrasion of the skin at higher voltages). However skin impedance can be difficult to characterise as it is non linear, time variable and dependent upon environmental and physiological conditions [**144**].

To allow examination of the flow of current for various exposure conditions many analyst have developed equivalent circuit models to represent the skin and body. Complex models have been developed by Edelberg [**68**] and more simplistic models by Yamamoto et al in 1977 [**173**] where the skin impedance is represented by a parallel capacitor and resistor followed by a series resistor which is used to represent the internal body resistance. However due to the properties of the skin and body, the models developed are only approximations that may be useful in studying the effects of electricity on humans. In general the overall current path impedance is the value reported when we consider the impedance of the human body. In doing this, tissue inhomogeneity is ignored and the total impedance is inclusive of the resistance of the electrodes.

For the purpose of this review, clothing and footwear which would provide added resistance and hence increased protection against the dangers of electric shock will be ignored as the intention here is to determine from the available research the worst case scenario.

As one might expect human impedance varies across multiple subjects. Indeed body impedance is dependent upon multiple factors including location and size of the contact electrodes, applied voltage, current path, frequency, surface area of contact and the skin condition whether it be, dry, moist or wet. In addition, impedance gradually falls over time as Mason and Mackay [**128**] (1976) demonstrated when an electrode was placed against dry skin for 30 minutes. The drop of impedance under such conditions was asymptotic in nature and perhaps can be attributed to the hydration of the skin due to sweat build up at the electrode [**144**]. From this it is clear that the presence of moisture due to the environment or the subject's physiological condition which may result in perspiration may decrease the value of the contact resistance between the electrode and the skin. In experimental studies, non dry conditions are usually achieved using NaCL or saline solution [**97**].

Human skin consists of a series of layers which can provide considerable insulation against the flow of current. The corneum which is the outer most layer of the outer layer structure (the epidermis) is a poor conductor when dry but if bypassed by abrasion or if it is wet or sweaty, the skin resistivity can drop by a factor of 300 [**144**]. Sweat ducts or pores create electrical weak points in the epidermis. These act as conductive tubes to the more conductive dermis and tissues below. Skin impedance is dependent upon frequency (skin impedance decreases as frequency increases), voltage, duration of current flow, surface area and pressure of contact, degree of moisture present and the temperature and type of skin [**97**]. Camps et al [**32**] noted if hands are conditioned by manual labour, dry skin resistance may reach 2000 kΩ. DiMaio et al [**61**] concluded dry and hardened skin may have a resistance of 1000 kΩ, dry skin 100 kΩ, moist skin 1 kΩ, and thin moist skin as little as 100 Ω. Generally for lower touch voltages skin impedance can vary widely even within the same subject with a variety of contact areas, condition of skin, temperature etc. However for larger touch voltages and the passage of significant current the impedance of the skin can decrease significantly and become almost negligible if the skin breaks down. Freiberger [**79**] describes breakdown at voltages above 100 V while Biegelmeier and Miksch [**21**] pointed to breakdown above 200 V.

The internal impedance of the human body can be considered as mostly resistive. Its value depends mainly on the current path and to a lesser extent on surface area of contact [**97**]. Knowledge in this area has been greatly contributed to by the work of Freiburger (1934) whose measurements were mainly made on cadavers [**79**]. Even today reference to his work is still made in the IEC standard [**97**]. Freiberger concluded that roughly 50% of internal impedance for hand to hand and hand to food contact resides in the wrists and ankles. (these are poor conductors due to bone and ligaments forming the majority of these parts) He attributed less than 10% of the internal body resistance to the trunk.

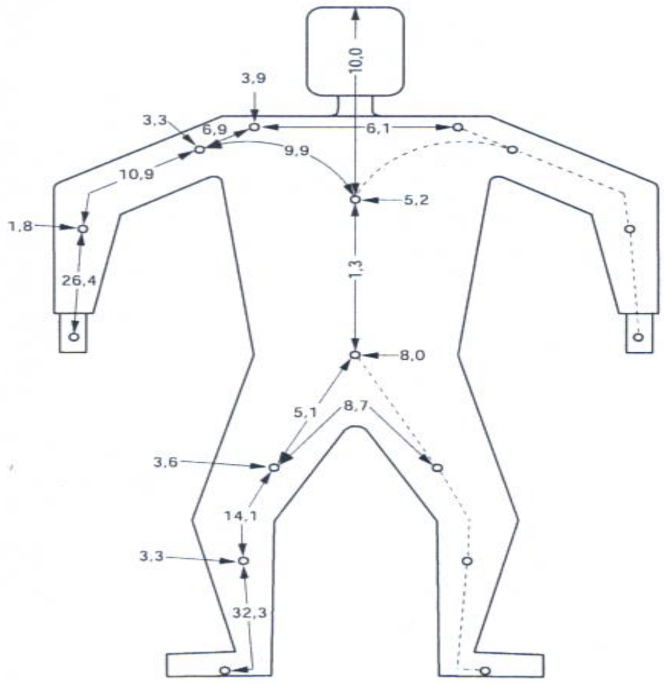


Figure 2-2 Distribution on Internal Impedance of the Human Body [97]

Figure 2.2 details the percentage impedance for a hand to foot path. Using the impedance of hand to hand or hand to foot as a reference, the internal impedance from one hand to both feet is approximately 75% the reference value, while the impedance from both hands to both feet is 50% and from both hands to trunk is approximately 25% [**97**].

Taylors investigations (1985) [**163**] are in large agreement with Freiberger's impedance distribution model as is Biegelmeiers research [**19**]. In terms of actual resistance values for the internal body impedance, Freiberger reported an average of 1000 Ω for 60 cadavers of various age's, sex and body size for hand to hand and hand to foot paths. This value is somewhat larger than values subsequently obtained by researchers in the field (500-750 Ω) and possibly can be attributed to increased impedance values of humans after death.

Biegelmeier one of the main contributing authors to the IEC standard on the effects of electric current also carried out significant studies in this field. Biegelmeier's studies [**19**] demonstrated that at 25 V impedance is almost inversely proportional to contact area, however as the voltage was increased impedance values drop dramatically and area dependence is reduced significantly.

Biegelmeier also reported for electrode contact area of approximately 82 cm^2, internal body resistance only drops slightly as the touch voltage is raised from

25 V to 200 V, dropping to 650 Ω for a hand to hand path and to 550 Ω for a hand to foot path. This is consistent with high frequency low voltage experiments (10 V) made by Osyka [**135**] (1963) who reported a total body impedance of 2 kΩ hand to hand and 500 Ω hands to feet under wet conditions at 60 Hz [**22**]. Taylors [**163**] results for high voltage short duration discharges in living people also agree well with internal body impedance values highlighted above, finding for untreated dry skin a total body impedance of 533 Ω ± 52 standard deviation left hand/left foot, 521 Ω ± 37 standard deviation right hand/left foot and 508 Ω ± 29 standard deviation right hand/left hand. For his experiments with treated skin where conductive electrode paste was applied the impedance values only dropped slightly.

Underwriters Laboratories [**170**] also developed statistical impedance data for adults and children under dry and wet conditions (using a saline solution) for d.c. currents and low voltages up to a maximum of 12 V. In general adult's resistance was less than that for children, the reduced volume of children apparently accounting for this [**144**]. For adults 18-58 years and 64.5± 10.9 kg the resistance variation for two hands/two feet varied from 0.63 at the 5% rank to 1.16 kΩ at the 95% rank. For children 3-15 years and 32.3± 11 kg the resistance variation for two hands/two feet varied from 0.9 at the 5% rank to 2.04 kΩ at the 95% rank.

The current IEC standard [**97**] (4th edition) presents a much more comprehensive picture of the impedance of the human body than did the 3rd edition which contained little information on the dependence of the impedance on the surface area of contact and then only for dry conditions. The current standard presents the most up to date knowledge on the impedance for small, medium and large surface areas for dry, water wet and saltwater wet conditions. The impedance values presented principally result from measurements on corpses, animals but also on results from living persons. Measurements were carried out on 100 people for a touch voltage of 25 V for a large surface area in dry conditions, on 10 people for small and medium contact areas for wet conditions and for voltages ranging from 25 V up to and including 200 V measurements were carried out on one person. For touch voltages from 200 V to 700 V and higher, Freiberger's data was adapted taking account of the different temperature of cadavers and used to estimate impedance values for these higher touch voltages [**97**]. Table 2.2 shows a sample of some of the worst case statistical data adopted by the IEC for total body impedance for a current path hand to hand, for a large surface area of contact in saltwater wet conditions.

Touch Voltage (V)	5% of the population	50% of the population	95% of the population
25	960	1300	1755
50	940	1275	1720
75	920	1250	1685
100	880	1225	1655
150	830	1180	1590
200	790	1135	1530
500	625	850	1150
700	575	775	1050
1000	575	775	1050
Asymptotic value = internal impedance	575	775	1050

Table 2-2 Total body impedance for large surface area in saltwater wet conditions for hand to hand current path. Data from [97]

Concluding from the major research reports and examining the worst case scenarios which generally involve a large surface area of contact and wet conditions, the total body resistance under worst conditions from limb to limb appears to be 500Ω - 600Ω. Bikson [**22**] also reports in his review, that resistance across the chest can possibly be less than 100 Ω. Of course as already outlined, designers should be aware that total body impedance is dependent upon many factors such as current path, touch voltage, frequency, skin condition, surface area, pressure exerted and duration of flow. Hence as less onerous conditions are examined the value for total body impedance can dramatically rise

2.4.3 Electric Current

Many of the very early experimental studies such as Trotters [**166**] in 1902 on the effects of electric shock related to the voltage applied to the subjects under investigation. However, from these studies, no clear relationship developed relating the magnitude of the voltage applied and the effect it produced [**119**]. It was not until the seminal work of Ferris[1] et al [77] in 1936 that it became

[1] Ferris et al determined threshold fibrillating currents for different conditions of pathway, frequency and duration, using numerous anesthetized animals including guinea pig, rabbit, cat, dog, pig, sheep and calves.

apparent that the physiological effects of electric shock are related to the magnitude of the current and not the voltage, citing the wide variations in contact impedance as a major reason. Ferris and his colleagues clearly related the passage of current through a body to the cause of a deranged heart action causing ventricular fibrillation and sought to identify a value of current which if exceeded would be dangerous to humans. Subsequent to this, researchers related various human effects to electric current such as sensory perception [**42**], muscular contraction [**47**], respiration [**122**] along with in depth studies of ventricular fibrillation [**112**].

2.4.4 Electric Current –let go value

Alternating currents, even in the very low mA range can result in a loss of voluntary skeletal muscle control leading to involuntary movements which may result in a victim freezing to a live conductor. As a result, the current level at which this occurs is of interest in establishing safety criteria. The pioneer investigators of this effect defined the current level where a victim could just barely free himself from a hand gripped current source as the 'let go value' [**144**]. However some studies have also used the criteria whereby the victim demonstrates an inability to let go of the grasped object to establish a let go threshold (this occurs when the stronger forearm flexors dominates the extensors during involuntary contraction of the skeletal muscles under stimulation). Shock currents below this threshold can be painful, frightening and exhausting, however they are not considered dangerously hazardous [**8**]. Due to significance of the let go threshold, many experimental studies were performed to determine this value for electric current in the 50-60 Hz range and particularly in the period between 1920 and 1940. A review of the results of these studies [**8**] can be seen in Figure 2-3 below. It is important to note that tetanic peripheral muscle contraction is not directly linked to low voltage electrocutions and death (at the let go value) however loss of mobility with a more hazardous higher current may be fatal [**22**].

Thompson (1931) found an average let go value of 8.35 mA for men and 5.15 mA for women using a rotate handle endpoint. Whitaker in 1939 using the results of a three-year investigation of electric shock exposure related to electric fences published his findings in an Underwriters' Laboratories bulletin. This established an average let go current of 7.8 mA. Gilbert also in 1939 found an average value of 15 mA.

Report	Subjects	Current Path	Active Electrode	Endpoint	Let-Go Current, mA Average	Let-Go Current, mA Minimum/ Maximum	Frequency, Hz
Gilbert, 1939[9]	25 (both sexes)	Hand-to-hand	20-mm brass rod	Release grip	15	NR	50
Whitaker, 1939[2]	13 (UL staff members)	Hand-to-hand	Pliers	Release grip	7.8	6.0/10	NR
Thompson, 1933[10]	42 men 27 women	Hand-to-hand	Rotatable metal handle	Rotate handle	8.35 5.15	NR/20.0 NR/ 8.8	60 60
Grayson, 1931[11]	42 men	NR	NR	Not "serious discomfort"	8	NR	NR
Dalziel, 1938[3]*	56 men	Hand-to-hand	Flat metal disk	Tolerate sensation	13.9	NR/22	60
	18 men	Hand-to-foot	Flat metal disk	Tolerate sensation	13.5	NR	60
Dalziel, 1938[3]**	42 men (20 to 40 years of age)	Hand-to-hand	No. 10 AWG copper wire	Release grip	12.6	NR/18	60

NR = Not Reported   * = First Series   ** = Second Series

Figure 2-3 Summary of early Let go thresholds. Data source [8]

Dalziel and his colleagues are probably the most cited authors on this topic. From 1941-1956 several papers including [**49**], [**55**], [**47**] were published based on the accumulation of human data. Banks and Vinh [**8**] do highlight in their review that some of the statistical methods used by Dalziel would be unacceptable by today's standards, however these reports still mould our knowledge about the let go phenomenon and form the basis of setting safety standards. Indeed Dalziel's results can be found in Figure 23 of the current IEC standard [**97**]. The results of these findings are summarised comprehensively in papers published by Dalziel and Lee in 1969 and 1972 [**52**] [**50**]. In these reviews the results of 134 males who were predominantly aged between 21 and 25 years can be observed along with the results of 28 females largely in their late teens early twenties. The results from a small number of children are also presented. For these experiments the subject's hands were kept moist with a saline solution. A picture of a subject under investigation is shown in Figure 2-4. Dalziel also defined in these studies the let-go current as the maximum current that a subject can tolerate when holding a copper conductor in one hand and yet let go of the conductor by using muscles directly affected by that current. Table 2-3 and Figure 2-5 represent a summary of Dalziel's findings.

Dalziel recognised that the whole experience was very unpleasant for the subjects under test and one would not expect that similar experiments would be allowed today. In terms of the variation of results Dalziel believed that psychological factors including fear and competitive spirit were some of the main contributing factors.

Figure 2-4 Subject under investigation to determine the let go threshold [49]

Capturing let go currents for young children has proven to be extremely difficult [**8**] [**144**]. Dalziel found at higher current levels children tended to cry and also parents had an understandable reluctance to allow children to undergo such testing. Bearing these problems in mind Dalziel reported the findings for three small boys and recommended a 'reasonably safe' current level for children as 50 percent of the safe value for normal adult males which would be 4.5 mA.

Subjects	0.5 percentile rank	Minimum	Average	Maximum
134 males	9 mA	9.7 mA	15.9 mA	22 mA
28 females	6 mA	7.4 mA	10.5 mA	14 mA

Table 2-3 Dalziel's 60 Hz let go current data

In the current IEC standard [**97**] 5 mA for 5 seconds is used as the threshold current after which involuntary muscle contractions may occur. From the findings of the research related to this topic to date, there is little doubt that this standard is well supported, particularly for healthy adults. However as Banks and Vinh [**8**] point out this standard may possibly not be universally applied pointing to its questionable applicability to young children and the infirm. However in general considering low voltage accidents that occur in the home or the workplace it would appear that 5 mA is a practical value for designers to use.

Subjects	Age	Minimum
1	5 years	7 mA
2	9 years	7.6 mA
3	10 years	9 mA
mean		7.9 mA

Table 2-4 Dalziel's let go threshold data for children [8]

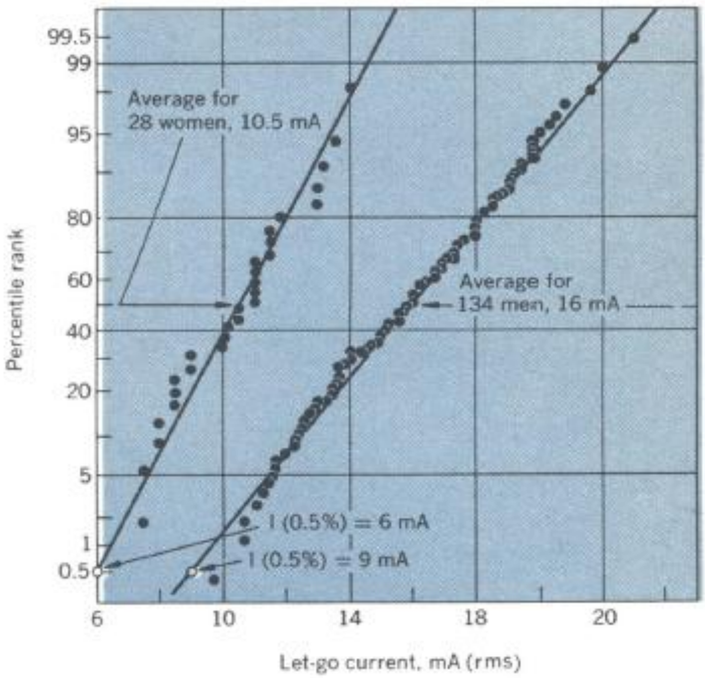


Figure 2-5 Dalziel's let go current data for males and females [50]

2.4.5 Electric Current - Threshold of Ventricular Fibrillation

Ventricular fibrillation leads to a condition of complete asynchronous contraction and relaxation of all the ventricular fibres. Indeed once initiated ventricular fibrillation very rarely spontaneously stops in humans without external intervention. If a current goes uninterrupted for three minutes, irreversible damage may occur to the central nervous system [**83**]. In an average human, a current of low magnitude at the standard power frequency through the thorax will cause ventricular fibrillation. Realising how susceptible we are to electric current it would be hugely beneficial to know the current threshold for fibrillation, however the ability to experiment on humans is not desirable for obvious reasons. To allow development of safety standards for protection against electric shock, studies have mainly been carried out on animals having similar body weights to humans to determine dangerous current levels at various frequencies [**77**], [**82**].

In 1946 Dalziel [**48**] analysed Ferris et al findings to determine a minimum threshold for ventricular fibrillation. In accordance with an original statistical method of analysis already utilised by Dalziel in his investigations of let go currents he sought to establish an acceptable relationship between the three major factors believed to be of concern; body weight, current and duration. Working on the assumption that, the responses follow a normal distribution below the 50 percentile rank, Dalziel defined a straight line, drawn by eye, through the 0.5 percentile rank plotted on a log scale as the danger limit [**20**]. This line had a slope of -1/2, leading to the mathematical expression for the threshold of ventricular fibrillation as shown in Figure 2-6.[2]

$$I = \frac{\mathrm{K}}{\sqrt{\mathrm{T}}}\ \text{(mA) rms} \qquad (2.4)$$

where,
I is the body shock current at the threshold of fibrillation
T is the duration of the flow of that current
K is a constant, which Dalziel determined

[2] The equation of a line in a log scale is given by the expression $y = c.x^m$

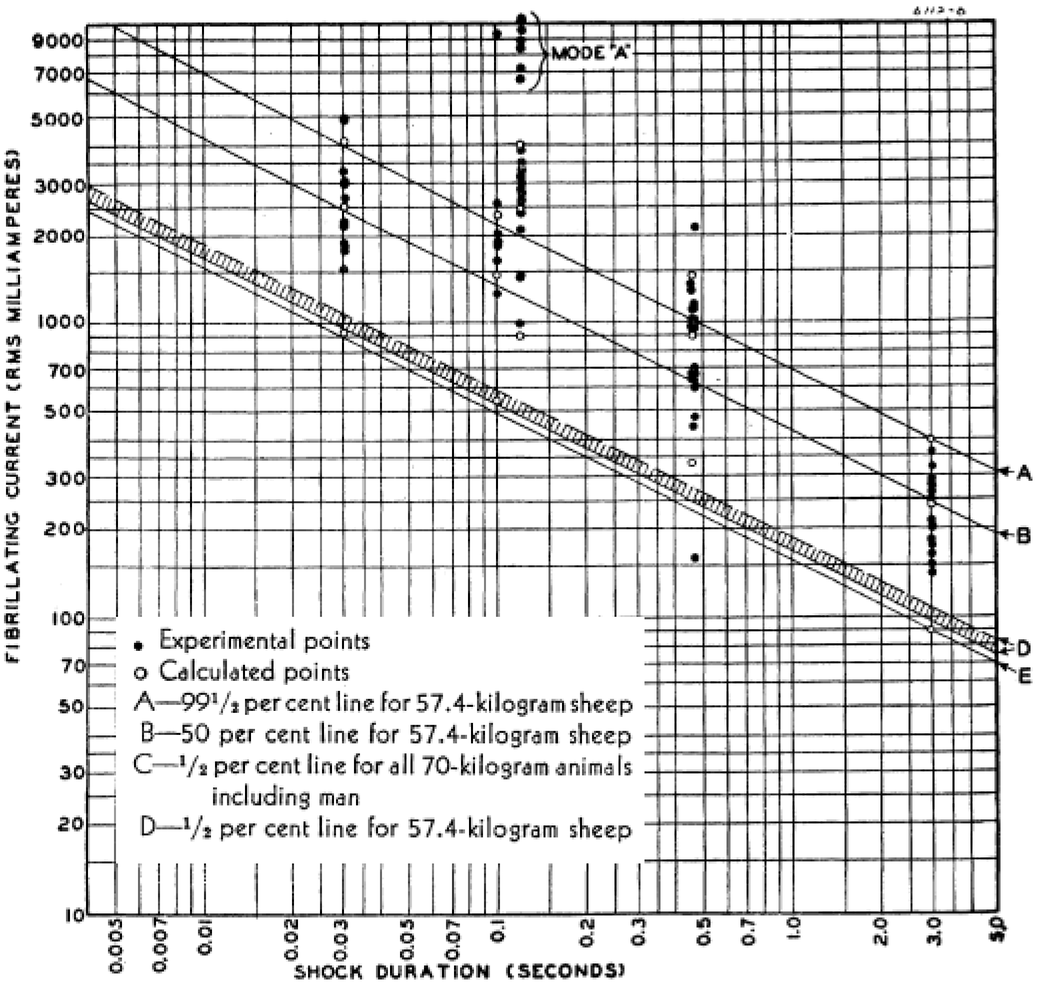


Figure 2-6 Relation of 60 cycle sine wave fibrillating currents to shock duration 1946 [48]

Assuming a weight of 70 kilograms as the average weight for a man, Dalziel proposed a minimum fibrillating current at 60 HZ of I = $165/\sqrt{T}$ for 0.5% of a large population. However, as attractive as this equation is to electrical engineers it is important to recognise that assumptions were made in deriving it. Dalziel's equation is based on probability, by virtue of the points he derived the equation from. Dalziel's constant is derived from a graph shown in Figure 2-7 which relates body weight to the current necessary to cause ventricular fibrillation [**119**]. From this graph it can seen that the points are widely spread and the 0.5% confidence limits are well separated from the regression line.

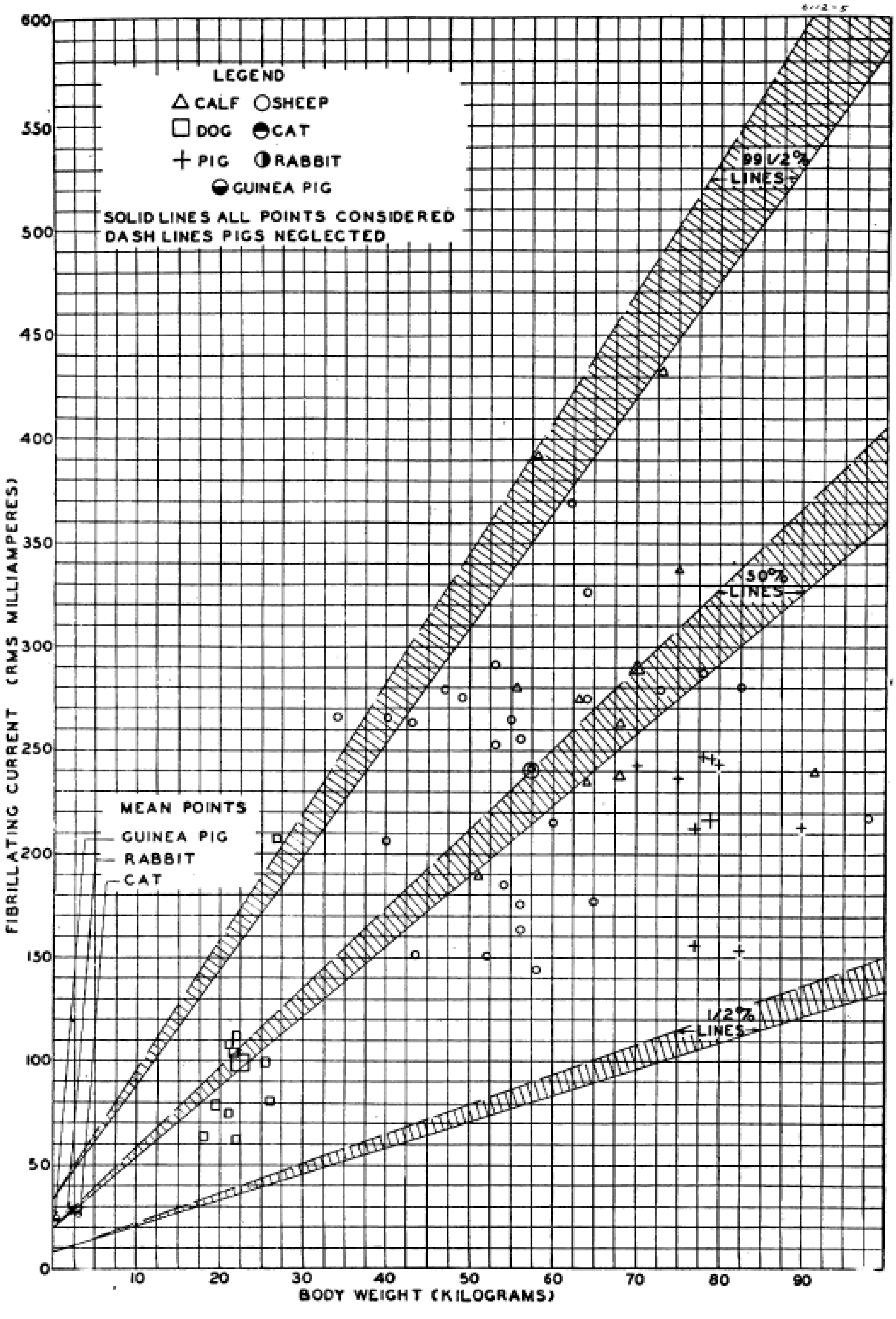


Figure 2-7 Relation of fibrillating current and body weight 1946

Subsequent to Ferris et al studies, Kouwenhoven and his associates in 1959 at the John Hopkins University carried out another classic series of animal experiments [**112**]. The results of which were analysed by Dalziel in 1960 and which in Dalziel's opinion corroborated with the original threshold 60-cycle currents for fibrillation proposed in his 1946 paper [**51**]. Dalziel was careful to stress at the time the time range over which these experiments were based which was 8ms to 5s. Dalziel's paper from 1946 was reprinted in most corners of the world and received much criticism, in many cases due to basing his conclusions on limited data. Criticism of his proposed equation by Biegelmeier and Kouwenhoven in his 1959 paper was largely based on the physiological arguments relating to the nature of ventricular fibrillation and the indication from various other investigations that the mechanism for ventricular fibrillation varies when the shock duration covers an entire heart cycle in contrast to covering only part of the cycle [**51**]. This is an important observation and will be dealt with later in this chapter.

Lee [**120**] in 1965, made a detailed case analysis of deaths due to electric shock over a two year period (1962/63) in England and Wales. From this study Lee gained an insight into victims of electric shock and realised a significant number of victims were female (25%) and many were under the age of twenty (20%). As a result of these findings, Dalziel's minimum fibrillation threshold current equation which used a weight of 70kg (average body weight for a man) was questioned. Lee asserted in a paper the following year [**119**] that there was a case for selecting a lower body weight of around 50kg and suggested it would be prudent to alter Dalziel's equation such that I = $121/\sqrt{T}$ which is a more conservative figure based on the lower body weight. Following these findings of Lee and also the findings of Kiselev [**110**] from the Academy of Medical Sciences in the former U.S.S.R. who performed a detailed study of threshold current in dogs, Dalziel and Lee [**54**] re-evaluated the threshold for lethal electric currents. Here the authors clearly recognised the prudence in selecting a more conservative body weight for evaluating K and from this concluded that the maximum non fibrillating current and the minimum fibrillating current are:

$$I = \left[\frac{116\ to\ 185}{\sqrt{T}}\right]_{8.3\ ms}^{5\ s} \quad (mA)\ rms \tag{2.5}$$

This equation is still very much in use today and forms an integral part of the safety aspect of IEEE Guide for Safety in AC Substation Grounding IEEE-Std 80 [**104**].

From the above, one could question the regard given to the vulnerability of children to electric shock. From the authors own findings on the analysis of electrical accidents in domestic properties [**12**], young children rank highly in terms of presenting at Accident and Emergency units as a result of receiving a shock from electric current. Hence, they are worthy of detailed analysis. Dalziel and Lee did consider children in their 1969 paper [**52**] noting that there was no direct evidence available on the threshold fibrillation currents for children and determining such a value would require even more assumptions than what was required to derive the above equation. However, using Ferris's data which related to tests on calves weighing between 51kg and 103kg Dalziel attempted to determine if there was a difference in the reaction of a young heart to a mature heart. On examination, the points for calves fell close to the current versus body weight lines providing at least some evidence to suggest that a child's heart would not exhibit an alternative response to a mature human. Further to this, taking a body weight of 18kg and a height of one metre, Dalziel produced an equation for children such that

$$I = \left[\frac{\sqrt{3}(30\ to\ 40)}{\sqrt{T}}\right]_{8.3\ ms}^{5\ s} \quad (mA)\ rms \tag{2.6}$$

Concluding from this it is evident that the extant of research related to the effects of current on children is limited and it is suggested that the current thresholds and the resistance of children's bodies (bearing in mind the difficulties of such research) be the subject of more detailed analysis. This could perhaps lead to an individual set of thresholds for children. It must be noted however in the IEC report [**97**] it is emphasised that the values used are so conservative that the standard applies to persons of normal physiological conditions including children.

As we already have acknowledged a knowledge of fibrillation currents as a function of body weight, current and duration was instrumental in the development of standards (indeed Dalziel's equation was used in the first IEC standard 1974 related to the effects of electric current). However Dalziel is not the only researcher to put forward a view concerning the shock parameters for the initiation of fibrillation. In fact there is some variance among prominent researchers concerning the electrocution equation.

Dalziel's and Lee's equation (1969) based on animal studies concluded that constant energy (I^2t) was required to fibrillate the heart over the time span studied (8.3ms-5s) and fibrillation is linearly related to weight. In contrast, Osypka [**135**] maintained that it is the total charge (It) which determines the hazard. Osypka achieved this by rearranging some of the previously published data and including this with some newly developed results. He found that for a period of 8ms-5s, the fibrillating current was proportional to

t^{-1}. It should be noted however that both Dalziel and Osypka derived their results from studying current and duration parameters and are not from a physiological basis [**53**].

Geddes et al [**84**] using data from 104 various animals (ponies, rabbits, goats, monkeys) including 71 dogs, concluded that the current required to produce ventricular fibrillation varies approximately with KW^{α} where K is a constant which depends on the current pathway, W is the body weight and α is approximately 0.5 for the right fore limb to left hind limb. This demonstrates a fibrillation threshold that varies with the square root of the body weight.

Bridges [**27**] suggested that when scaling results from small animals to humans, a current density criterion would be more appropriate and also suggested that scaling is only reasonable for small and large animals of the same general proportions and where there is control of the position of the subject's heart under test. Bridges proposed a 2/3 power weight relationship e.g $I_f \propto W^{2/3}$.

In 1980, Biegelmeier and Lee [**53**] undertook a further evaluation on the threshold of ventricular fibrillation. This study considered all notable animal studies up to this date. These included in addition to the ones already previously outlined (i.e Ferris et al, Kouwenhoven et al and Kiselev); Scott et al study on the threshold for a.c. shocks of long duration on dogs, Osypka [**135**] research on this subject and Jacobsen et al study on the threshold of fibrillation for pigs. From these studies an unusual discontinuity of the threshold for shock durations in the vicinity of one cardiac cycle could be observed. It is interesting to note that this significant point had already gained attention in 1960 and was discussed by Biegelmeier and Dalziel [**51**]. Also, Ferris et al had invoked extrasystoles in his studies and commented on this in his pioneering paper [**77**].

In general the animal measurements recorded by the above researchers tended to follow a log-normal distribution as shown in the left diagram in Figure 2-8 below. However at approximately half a cardiac cycle which is approximately 0.167s in a dog, the curve appears skewed as can be seen in Figure 2-8 (right). This suggests that two different physiological mechanisms are involved. These are; if the shock occurs during the vulnerable period of the hearts cycle, ventricular fibrillation will occur immediately and the threshold will be closely related to any other shorter duration shocks occurring during the vulnerable period, alternatively if the shock occurs during diastole (which is the period when the heart is in a state of relaxation and the ventricles are filling) a premature heartbeat is initiated and if this goes uninterrupted continuing on to the vulnerable period the threshold for ventricular fibrillation will be significantly lower.

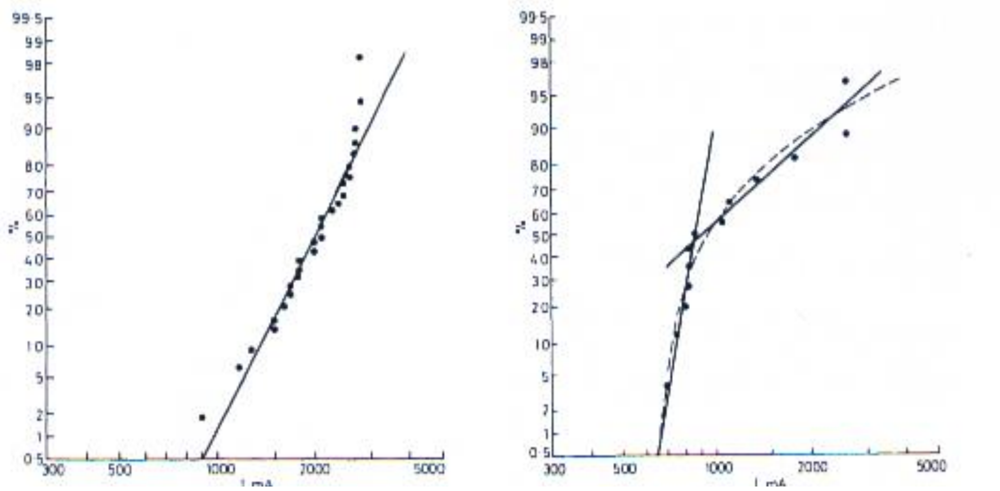


Figure 2-8 Kouwenhovens experiments - minimum fibrillating current distribution for dogs (8.3ms shock duration on the left and 0.167s on the right)

A variety of experimental studies have verified this point and when the ventricular fibrillation thresholds are plotted against the duration of the shock current a Z shaped curve results. The ratio, R, between the plateau thresholds and the period between the transitions t_1 to t_2 vary with the experimental conditions including the test species, see Figure 2-9 [**144**]. Biegelmeier and Lee argued when interpreting animal data and applying it to human's consideration should be afforded to the difference in heart rate such that the ratio, R, and the upper part of the transition should be increased relative to an animal with a faster heart beat. Ultimately Biegelmeier and Lee (1980) proposed an inverse relationship between the ventricular fibrillation current threshold and the shock exposure time for periods between 0.2 and 2 s with a threshold value above and below these times. Subsequently in 1987 Biegelmeier revised these values to 0.1 and 2 s and this was used to represent the recommendations of the International Electrotechnical Committee (IEC) on the Effects of Current on Human Beings of which Biegelmeier was a contributing author. More recent standards take into account the s-shaped curve rather than straight legged transitions shown between (2) and (3) in Figure 2-9.(see chapter 5)

In general Dalziel's, Gedde's and Bridge's linear, square root rule and power rule respectively are in reasonable agreement over a wide range of body weights [**22**]. However, a body weight relationship is not universally accepted for ventricular fibrillation in human safety applications. Biegelmeier argued successfully at a specialist panel meeting (1985) against a body weight formulation, pointing out that when the VF thresholds of many species are plotted against body weight, there is an apparent body weight relationship. However when the threshold's of a single species is plotted against body weight, the statistical correlation largely disappears [**144**].

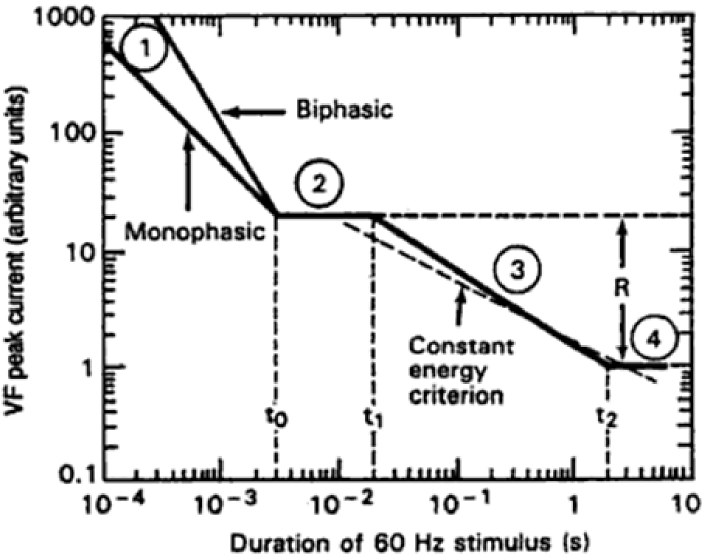


Figure 2-9 Ventricular Fibrillation versus 60 Hz stimulus duration [144]

As a consequence of the above the IEC does not include a body weight law in its safety standard. Instead, the IEC bases its safety criteria mainly on experimental data from dogs. This procedure is considered to be conservative in view of demonstrated lower thresholds in dogs as compared to humans. Especially noteworthy are the experimental thresholds obtained for both dogs and humans using similar electrode arrangements placed in the heart [**144**].

2.4.5.1 Current knowledge on ventricular fibrillation

Dalziel's constant energy fit to the Ferris group's data was not an unreasonable assumption to make at that time. Indeed the $1/\sqrt{T}$ relationship, does provide a reasonable fit when examined over the duration 0.08 to 5s. However upon examination of the Ferris group data using a *log normal distribution* in contrast to a *normal distribution* used by Dalziel, it is clear that Dalziel's equation neglects the rapid decline of the threshold near a shock duration of one heart cycle. In Dalziel's defence, the role extrasystolic excitations play in lowering ventricular fibrillation was not widely known at this time.

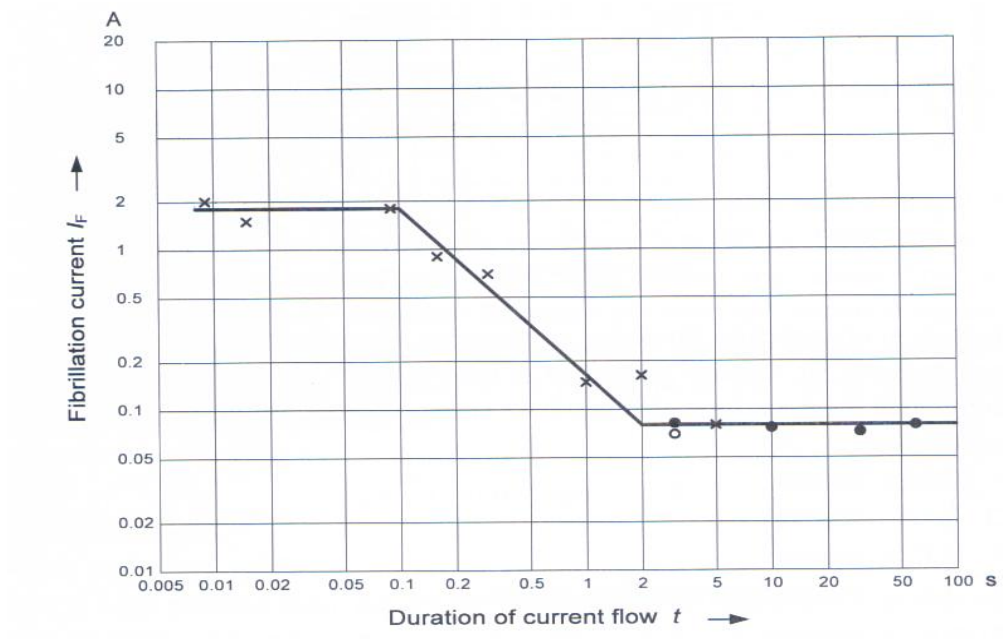


Figure 2-10 Fibrillation threshold as a function of duration of current flow for dogs [6]

Kouwenhoven's [**112**] essential contribution (as already mentioned) to our understanding of ventricular fibrillation using dogs was made in 1959. In this paper it was made explicitly clear, that no clear dependence existed between body weight and fibrillation thresholds [**6**]. Also worth noting is the fact that the Ferris group also found no dependence of body weight within one species on fibrillation thresholds. Figure 2-10 shows Kouwenhoven's results plotted in a log normal distribution. It is evident from this that a sharp decline of the threshold of fibrillation occurs for shock durations of approximately one heart cycle which is caused by premature heart beats. In general fibrillation experiments longer than one heart cycle are more trustworthy than those shorter than one heart cycle due to fibrillation only occurring during the vulnerable period of the heart cycle in the latter. Dalziel and Lee [**54**] did attempt to re-evaluate Dalziel's energy criterion using Kouwenhoven's new data again using body weight calculations, however this procedure is still not considered convincing [**6**]. In essence, Dalziel's work was a first attempt of huge merit to apply statistical considerations to animal data to establish fibrillation thresholds. The inaccuracies in his findings can essentially be attributed to two misjudgements (1) fibrillation thresholds do not depend on body weight and (2) fibrillation thresholds follow log normal distributions and not normal distributions [**6**].

For numerous years fibrillation data from animals have been directly applied to humans, consequently due to the animal's shorter heart cycle the results for shock protection are quite conservative and may result in economical losses in some instances. It was therefore necessary to examine fibrillation thresholds for humans in contrast to data that existed for dogs and hogs. Raftery et al [**142**] [**141**] carried out such studies when they compared the effects of the electrical excitation of the heart muscle of living humans to dogs. From these studies it can be seen that the human heart requires greater excitation currents compared with the hearts of dogs. Using the current required to cause failure of a pumping action of the heart an average factor of 3.5 was determined for human-dog. This factor was then conventionally applied to the fibrillation threshold [**6**]. The Buntenkotter group made more precise measurements in this respect in relation to hogs and this work is considered even more reliable due to the modern measuring equipment and systematic approach used. A factor of 2.8 was found for human-hog.

As outlined in detail in chapter 5 the current zones used in the IEC standard are based on conventional agreements, especially boundaries c1-c3 which are taken directly from measurements on dogs. As a result [**6**] now proposes that the latest knowledge in electro pathology derived from the fibrillation thresholds of dogs and hogs in conjunction with the comparative factors for the fibrillation threshold of persons be used in the development of a new IEC standard. Consequently a new draft is already under discussion [**6**]. The proposed new time/current zones are based on tolerable and non tolerable risk, the statistical probability of ventricular fibrillation below 1% is conventionally chosen as tolerable risk for protection against electric shock. For a detailed explanation on the electro pathological knowledge behind this development, see [**6**] pages 8-18. Figure 2-11 shows the proposed time/current zones Z1 (AC) and Z2 (AC) between tolerable and non tolerable risks of harmful electric shock for fault protection. The time limits for the transition of the Z_L boundary from low to high have been chosen with t = 1.5 heart cycle = 1s and t = 0.75 heart cycle = 0.5s using the duration of a heart cycle of a three year old child (0.6s) for additional safety.

The less conservative new proposals made by [**6**] based on defined risk evaluation and clear mathematical boundaries have considerable advantages in terms of earthing arrangements and discrimination design. However it will take time for these proposals if adopted to be filtered down to the applicable standards. As a result, the situation now exists in North America where the latest IEEE Std. 80 standard (IEEE Std. 80-2000) uses Dalziel’s curves while in Europe Biegelmeier’s curve forms the basis of IEC 479-1 specification. Figure 5 of the latest IEEE Std. 80 standard does however contrast both these fibrillation curves. It appears the reason for doing this was to give the reader a visual comparison between Biegelmeier's Z curve and Dalziel's equations. In doing so it demonstrates that Dalziel's equation (k= 0.116) is more conservative for times between 0.06 and 0.7 seconds which would be considered normal fault clearing times in substations. Hence, this justified the continued use of Dalziel's equation in the IEEE Std. 80-2000 on safety basis at least.

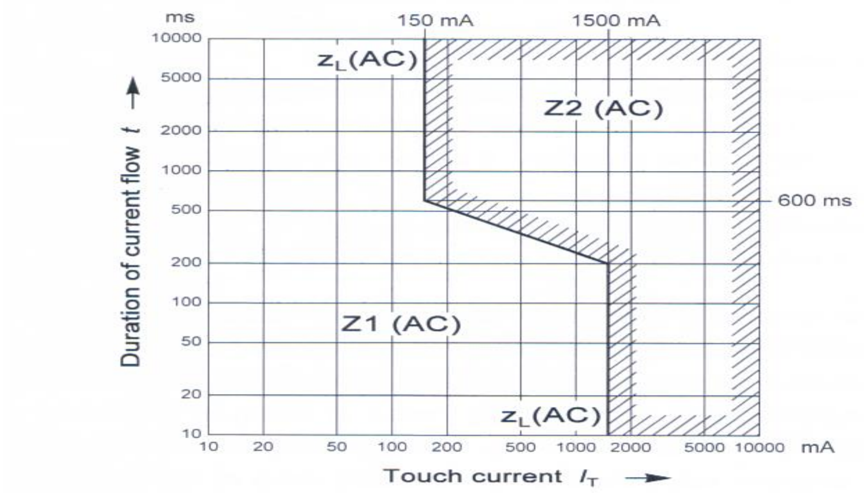


Figure 2-11 time/current zones Z1 (AC) and Z2 (AC) between tolerable and non tolerable risks of harmful electric shock for fault protection [6]

To summarise the findings on the effects of electric current in producing ventricular fibrillation in the 50-60 Hz range, Bikson [**22**] produced a table that reviewed the most relevant reports, reviews and books on the subject. ESF's [**6**] new approach complements this information and gives the latest information on tolerable fibrillation thresholds albeit with safety factors built in. Using this information in conjunction with the well defined human impedance values in the IEC standard [**99**] allows one to develop pretty well defined safe touch voltage thresholds for various environmental and physiological conditions

	DHHS (1998)	Leibovici et al (1995)	Bridges et al (1985)	Camps et al (1976)	DiMaio and DiMaio (2001)	Wright and Davis (1980)	Webster (1980)	Reilly (1998)
Ventricular fibrillation (exposure time)	100	30-50	>70 (0.1s) 40-100(∞)	70(5s)	75-100 (>5s)	120 (0.1s)	75-400	33 (5s) 807 (8.3 mS)

Table 2-5 Estimated electric current required to produce ventricular fibrillation (in mA peak limb contact) [22]

2.5 Summary

Any time a touch or step voltage of sufficient magnitude is present between two conductive points in an electrical installation current will flow if an external impedance makes simultaneous contact. Persons, in an electrical sense, can represent such external impedance and the resulting current flow through the human body can range from little or no perceptible effect to the possibility of electrocution.

In such circumstances, the resultant effect on the human body depends upon:

- path impedance
- frequency of supply
- current magnitude, and
- duration of the current flow

In general, the longer the contact duration, the higher the voltage and the lower the impedance of the body, the chances that the electric current will exceed the level necessary for human perception is enhanced [**63**]. Knowing this, one can appreciate the importance in establishing the relevant impedance characteristics and the current and voltage thresholds particularly for the most onerous situations where humans are most vulnerable. From a designers point of view the ability to predict whether an unwanted physiological condition will result based on voltage values would be advantageous. However this is not just as straightforward as applying ohm's law. The impedance of the human body is determined by the magnitude of the touch or step voltage (an inverse relationship exists between impedance and voltage) and other factors, such as the physiological and environmental conditions, the cross-sectional area of contact with the energised conductors, and whether or not there are abrasions on the skin.

The impedance ranges that are useful for the characterisation of humans are variable and very much depend on whether or not the person is dry, wet or immersed in water. Generally speaking, at applied voltage of 230 V 50 Hz, conservative total body impedance for a hand-to-feet path will be in the range 1000 Ω to 2500 Ω for the majority of the population. This value can fall to around 750 Ω at voltages in excess of about 1000 V. In the reports examined in this chapter concerning low voltage installations assuming large contact area between two limbs and wet conductive contact, resistances maybe as low 500-600 Ω. If the person is immersed in the case of a swimming pool or hot tub, 200 Ω may apply.

As outlined in this chapter, it is the current level through the body that will determine the physiological effect. Most reports identify a key number of current thresholds such as *perception*, *startle*, *let go* and *fibrillation*. The fibrillation threshold being arguably the most important as it is generally viewed as the most prolific in causing death in low voltage electrical installations. Tetanic peripheral muscle contractions while painful are not directly linked to death while respiratory paralysis may lead to death but requires a few minutes of continuous contact.

In terms of fibrillation levels, [**63**] in his paper cites the minimum threshold (through the heart path) as approximately 67 mA's for adults and 30 mA's for children while Bikson [**22**] in his review cites currents >40 mA for contact of less than one minute in duration and for exposure times less than one second the value cited increases to >100 mA. In the fourth edition of the International Electrotechnical Commission (IEC) 60479-1, 40 mA is identified as the lower threshold for ventricular fibrillation for a shock of "long duration" with the current pathway through the body specified as left hand to feet. A heart current factor is given for pathways other than left hand to feet. Based on these factors the worst case scenario occurs for a pathway left hand to chest when approximately 27 mA could result in fibrillation.

From a designers perspective it would be useful to determine a definitive contact voltage level in 50/60 Hz range that would be considered acceptable. However due to the numerous variations in contact situations and many possible physiological and environmental conditions determining such a value is difficult. Bikson [**22**] does cite the single lowest voltage to cause electrocution in an adult as 17.8 V while according to [**71**] no fibrillation deaths have been recorded with voltages less than 50 V. For designers a recent IEC technical report [**99**] does provide a methodology for estimating threshold voltages, and gives guidance on the selection and application of voltage limits with regard to protection against electric shock. Generally in Europe with the exception of France a safe voltage limit of 35 to 50 V is accepted. 24 V is the figure used in France. This value in France is arrived at as the product of the minimum current causing ventricular fibrillation (50–80 mA) and the maximum and minimum body resistance for a path arm to arm or arm to leg [**146**].

Most electrical codes such as ET 101, BS 7671 and NEC have less stringent requirements for voltages less than 50 V. However it is worth highlighting that the NEC restricts Class 2 circuits to 30 V unless the current is limited to 5 mA. The Canadian Electrical Code Part 1 (CEC) has a similar restriction. Table

2-6 compiled by [**63**] provides a list of standards which suggest voltages below 15 V are relatively safe for wet contact areas and voltages below about 50 Vac are relatively safe for dry contact situations.

Reference Document	Published Level	Concern Category
UL-101 [4]	0.75 milliamps reaction current 2,000-ohm human body impedance.	Reaction Current
UL-60950-1 [8]	42.4 Vac and 60 Vdc is the stated limit under dry conditions and human hand path.	Shock Hazard
IEC 479-1 [9]	25 Vac clearly safe, 50 Vac marginally safe (duration dependent). 1000 ohm body impedance cited	Shock Hazard
OSHA Rule (29 CFR Part 1910) [10]	Circuits operating above 50 Vac or 50 Vdc.	Shock Hazard
NFPA 70E [11]	30 Vrms or 60 Vdc. 500-ohm wet human body resistance.	Shock Hazard
IEEE Yellow Book – Std. 902-1998 [5]	Currents as low as (10) milliamps and voltages above 50 V can cause fibrillation. 500-ohm minimum body resistance for wet conditions or cuts. 100-500 ohms for immersion (Table 7-2)	Heart Fibrillation
NACE [12]	15 volts.	Shock Hazard
NESC [13]	51 volts.	Shock Hazard
NEC® [14]	Circuits operating above 50 Vac or 50 Vdc or 15 V for wet areas.	Shock Hazard
IEEE Std 80 [2]	60 Vac for 4 sec. 1000 ohm human body impedance	Shock Hazard

Table 2-6 Review of Published Contact Voltage Levels of concern for humans **[**63**]**

In conclusion, electric shock is not a single phenomenon and it is not perfectly understood. It is evident that further experimental studies would benefit and enhance current knowledge in this field. Some areas that may warrant closer examination include current thresholds for children and conditions where subjects are completely immersed. In addition it would appear that the often exercised 50 V shock voltage threshold does not provide adequate protection under all conditions. This argument can be made based on accident investigations involving incidents where less than 50 V was reported but also on the findings of the IEC 60479 standard where touch voltage thresholds for ventricular fibrillation below 50 V is possible for various scenarios [**146**]. Therefore it would appear prudent that electrical codes such as ET 101 and BS 7671 have less stringent requirements for voltages less than 25 V instead of 50 V.

Chapter 3

Standards, Methods of Protection and Reason for Concern

Domestic electrical safety has progressed significantly since its initial introduction over a century ago. Advances in circuit protective devices and cables, coupled with the implementation of good wiring practices in conformance with national wiring rules, e.g., ET101: 2008 [**74**], BS7671: 2008 [**101**] or IEC 60364 on the part of designers and installers have all contributed to higher levels of safety. However, there are valid concerns over the widening gap between the present level and the required level of electrical safety in the domestic built environment.

In Europe there is an ageing housing stock (60% are over 30 years old) [**75**], there is also a lack of mandatory maintenance and inspection. Older dwellings with dated electrical installations are becoming progressively less suited to satisfying current electrical safety requirements. Their inherent inability to cope safely with growing energy demands and afford the functionality required is becoming more apparent as homeowners pursue a greater level of comfort and convenience. In the coming decades it is inevitable that the role electricity plays in buildings will continue to grow. The drivers of this include climate change mitigation measures such as electric vehicles which will require charging points in dwellings, home automation systems which will require sufficient wiring and communication capabilities while the introduction of renewable technologies to offset part of the energy consumption will require an electrical installation capable of such integration.

Injury and death as a result of electric shock and fires caused by failed electrics and unsafe installations are very often preventable. It has been shown statistically, that residential property is one of the leading locations for death due to electric current [**12**] [**138**]. Every year, it is estimated that 16,000 people are injured and 540 die across Europe from electrical accidents [**66**]. The impact of which, leaves a trail of socio-economic consequences in its wake and is felt by all of society. The need to improve domestic safety through enhanced regulation and engineering design is evident and will benefit the comfort and safety of all end users.

This chapter attempts to set out to the reader the electrical standards currently in place and outline the main methods of protection generally employed to provide protection against electric shock in the built environment. Following this a body of evidence is documented which aims to demonstrate the current concerns regarding electrical safety and provide justification for the development of a virtual reality model to feed into the ongoing effort to improve electrical safety levels.

3.1 Safety legislation, Regulations and Standards

Early attempts at General Safety Legislation in Ireland were dominated by a cavalier philosophy towards workplace safety [**106**]. The first attempt at subscribing to the principle of the provision of a healthy and safe work environment for all employees in the statute book of Ireland came in the form of The Factories Act 1955. This act, The Mines and Quarries Act 1965 and the Dangerous Substances Act 1972 as well as numerous Regulations made under them, regulated certain aspects of safety and health at work for years, but this legislation was defective because, it did not apply to all places of work and it did not reduce accident levels.

The British Health and Safety at Work Act 1974 (followed by the Northern Ireland Health and Safety at Work (Northern Ireland) Order 1978) was one of the earliest laws to address all aspects of work. Also, based on International research, it imposed positive general duties on all people; particularly at senior levels in organisations.

The Barrington Report 1983 (Commission of Inquiry on Safety, Health and Welfare at Work) also identified management as the key to improving performance in the area of safety and health at work. The requirement to implement European Directives on safety and health at work has also greatly influenced Irish Law in this area. In the early 80s these Directives tended to focus on narrow aspects of health and safety but momentum towards more general principles were well established by the mid to late 80s and in 1989 the

'Framework' Directive on safety and health which laid down general principles largely along the lines of the British Act of 1974 was developed.

The Safety, Health & Welfare at Work Act, 1989 was designed to lay down general principles for all places of work by imposing general duties on all people in all places of work, public and private sector, in connection with safety, health and welfare. The 1989 Act requires all organisations to compile
A Safety Statement setting out how safety, health and welfare is being managed and identify preventative strategies to protect those at work. This act improved on some deficiencies of previous legislation, for example it set up a new National Authority for Occupational Safety and Health, which became known as the HSA (Health and Safety Authority) - with the responsibility of enforcing the Act.

The HSA went on to prepare a Statutory Instrument titled *Safety, Health & Welfare at Work (General Application) Regulations 1993 – S.I. 44 of 1993*. *Part VIII* of this instrument is devoted entirely to *electrical safety* matters. Further to the 1989 Act, the *Safety, Health & Welfare at Work Act, 2005* came on stream. The 2005 Act updates, repeals and replaces its predecessor, the Safety, Health and Welfare at Work Act 1989. Since then a further statutory instrument came into being in November of 2007 and that is *Safety, Health & Welfare at Work (General Application) Regulations 2007 – S.I. 299 of 2007*. Part three of this instrument is devoted entirely to *electrical safety* matters. These are known as statutory regulations, which mean they have the force of law, and non-compliance can result in a fine, imprisonment or in some cases both. The last statutory regulations did include in early drafts legislation that prescribed periodic inspection of buildings at defined intervals, however commercial and industrial lobby groups persuaded legislators to omit this section due largely to the financial burden this would impose on business.

3.1.1 Role of Energy Regulator in Electrical Safety

In 1999, following the enactment of the Electricity Regulation Act, the CER (Commission for Energy Regulation) was assigned responsibility for the regulation of the Irish Electricity Market. Aside from overseeing the opening of the electricity market in Ireland and ensuring Ireland has a sufficient energy network to support a growing economy, the CER was given the statutory authority to "regulate the activities of electrical contractors with respect to safety" following the enactment of the Energy (Miscellaneous Provisions) Bill in 2006.

In 2007, the CER published a Vision Document (CER/07/203), this document provided a blueprint for the creation of the regulatory model for electrical safety. Following this, the CER published in 2008 a Criteria Document (CER/08/071), which gave details of the rules and obligations for participants operating within the electrical safety regulatory framework. In 2008 following the completion of a formal designation process the CER appointed two parties to act as an electrical Safety Supervisory Body with the objective of carrying out the day to day running of the scheme. The parties appointed were the Electrical Contractors Safety & Standards Association Ireland Ltd (ECSSAI Ltd) and the Registered Electrical Contractors of Ireland Ltd (RECI Ltd).

The role both Safety Supervisory Bodies are required to fulfil is the safety function on behalf of the CER (on a not-for-profit basis) which will be reviewed on a seven year basis. The CER however remains responsible for any major policy decisions regarding electrical safety. The self-regulatory model previously operated by both RECI and ECSSA became obsolete on the 5th of January 2009 when the statutory regulatory framework for electrical safety by the CER commenced.

One of the major pillars of the electrical safety framework is the consideration given to Regulated Electrical Works which consist of "controlled works" and "restricted works". This should enhance safety standards in buildings throughout the nation and raise the standard of the completed installation work. Now when a consumer or property manager engages a Registered Electrical Contractor to complete a Regulated Electrical Work, they will be entitled to receive a compliance Certificate, which confirms that appropriate safety tests have been carried out on the installation and that the electrical installation is safe.

3.1.2 Wiring Regulations

There is no single electrical safety code internationally enforced. The International Standard series governing electrical installations is IEC 60364. Part 4-41 of this series deals with protection against electric shock as applied to electrical installations. It is based on IEC 61140 which is a basic safety standard that applies to the protection of persons and livestock. The European equivalent to IEC 60364 is CENELEC HD 384. In most European countries there are national equivalents such as (AREI/RGIE - B, VDE100 - D, REBT - ES, NF C 15-100 - F, CEI 64-8 - I, NN 1010 - NL,). It must be noted that significant differences exist between national and international standards and their implementation. The IEC Standard consists of 7 parts. Part 4 deals with protection measures as already highlighted while Part 6 deals with inspection and testing. The IEC document recommends defining a time interval for periodic inspection in national statutory requirements and a 10-year interval for residential dwellings is mentioned as an example. Furthermore periodic inspection is recommended when there is a change in occupancy [**16**].

In Ireland the ETCI (Electro-Technical Council of Ireland) represents all aspects of electro-technology in Ireland and is the Irish member of the International Electro-technical Commission (IEC), the European Committee for Electrotechnical Standardisation (CENELEC) and the Electricity Section of the International Social Security Association (ISSA). In this capacity, ETCI has undertaken to write the National Wiring Rules for Electrical Installation, ET101:2008, these rules issued by ETCI encompass what is good wiring practice with what is emerging as common or harmonised set of rules for all European countries. These rules, which are not statutory, are designed to ensure minimum safety standards in the installation of electrical equipment.
ETCI is a voluntary body of twenty-four organisations representative of all aspects of electro-technology in the Republic of Ireland. Formally constituted in 1972, the council is the national body responsible for the harmonisation of standards in the electro-technical field in collaboration with the National Standards Authority of Ireland (NSAI). Compliance with ET101 by electrical contractors is not a statutory requirement at the moment.

In the UK, the 'Regulations for Electrical Installations' BS 7671, published by the Institute of Electrical engineers have for a long time been recognised as the national authority for safety requirements for installations within their scope. The IEE wiring regulations are closely aligned with those sections so far published of the corresponding Harmonization Document (HD 384) produced by the European Committee for Electro-technical Standardization (CENELEC), which in turn is based on Publication 364 'electrical Installations in Buildings' published by the International Electro-technical Committee (IEC)

Under Part P of the Building Regulations 2000, compliance with BS 7671 has become compulsory for new domestic buildings in England and Wales. In Scotland this Standard has been legally binding for a number of years under The Building Standards (Scotland 1990). In May 2003 the UK Government announced that it would introduce a new Part to the Building Regulations, Part P, which would bring domestic electrical installation work in England and Wales under the legal framework of the Building Regulations. It will, for the first time, place a legal requirement for safety upon electrical installation work in dwellings, although the sector is highly regarded for its high levels of conformity with its chief standard, BS 7671. It was announced that Part P would only be introduced in law when self-certification schemes were in place to ensure competency of the work undertaken. Such schemes are now in place. Part P of the Building Regulations became a legal requirement on January 1st 2005.

Part P places two requirements (i) Design, installation, inspection and testing of electrical installations-Reasonable provision shall be made in the design, installation, inspection and testing of electrical installations in order to protect persons from fire or injury and (ii) Provision of information-Sufficient information shall be provided so that persons wishing to operate, maintain or alter an electrical installation can do so with reasonable safety.

In the United States, the Department of Labor Occupational Safety and Health Administration (OSHA) standards are federally enforced. However, individual states and municipal authorities have adopted specific codes, such as the National Fire Protection Association (NFPA) and the National Electrical Code (NEC).

3.1.3 Methods of Protection

The fundamental rule of protection against electric shock is provided in the IEC document 61140 which covers both electrical installations and electrical equipment. The imprint of this standard via IEC 60364 can be seen across many national standards across Europe.

In general most standards require two lines of protection against electric shock. It is common sense to recognise that a piece of electrical equipment or an electrical distribution circuit contains normally energized conductive parts. The standard therefore generally requires fixed wiring to be provided with basic protection against direct contact of live parts under normal operating conditions. Additionally, it requires protection against contact with normally un-energised conductive parts that could become live under abnormal conditions (fault conditions). Although most national standards are not a product standard, the fundamental principles for electrical safety still applies to product development and design. To illustrate a typical example of what methods are currently employed, BS 7671:2008 Regulations for Electrical Installations will be used, this is the UK's national standard for electrical installation work and is considered to be the authoritative wiring rules not only in the UK but in many other countries (e.g. Sierra Leone, Sri Lanka, Trinidad and Tobago, and Uganda) throughout the world.

A Protection by extra-low voltage

One commonly used method of protection against electric shock for small electrical and mechanical products having relatively low power requirements is by supplying such products at extra-low voltage (*ELV*). A large number of low power electromechanical products today come with an external a.c.-to-d.c. transformer/rectifier adaptor. The d.c. voltage ranges from 3V to 24V, which is recognized as a voltage that is safe to be touched accidentally for even a prolonged period.

Although the range of extra-low voltage starts from 0V up to and including 120 V d.c. or 50 V ac rms, there are several particular protection requirements for different extra-low voltage systems. It is outside the scope of this chapter to give a detail description of the different forms of extra-low voltage circuits accepted by BS 7671:2008 to afford protection against the danger of direct and indirect contact. However in order to satisfy the requirements of protection against the risk and dangers of both direct and indirect contact shock hazards, the first rule of thumb that can be used is to specify the use of a supply that must be derived from a double wound transformer to BS3535 or an equivalent separately derived energy source (see Figure 3-1). As a second rule of thumb, if the utilisation voltage of the appliance or equipment does not exceed an ELV of 25V ac rms or 60 V ripple-free d.c. under normal dry operating conditions or 12.5V under wet conditions, and provided that there is no stepping up of the voltage internally within the product (e.g., like a TV set), the risk of accidental electrical shock will be deemed negligible.

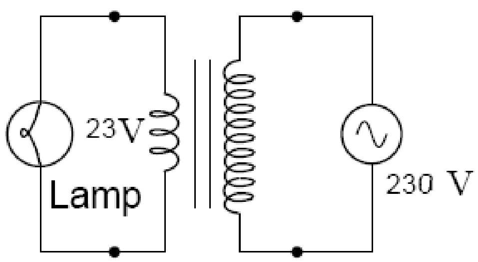


Figure 3-1 A BS3535 double wound transformer supplying a lamp

B Basic Protection (Electric shock arising from making direct contact of live parts under normal operating conditions)

Many electromechanical products have a 230V supply cable directly connected to the electrical terminals within the product. Here, in the first instance, one must consider the risk of electric shock under normal operating conditions. A durable warning notice with wordings saying "Danger, High (or 230 V) Voltage present, isolate elsewhere before removing cover" is commonly found in many such products. Since there is no automatic disconnection device that can save a victim who may accidentally make contact with two live (phase and neutral) conductors, BS7671:2001 recognizes only four methods of protection against direct contact, they are:

(i). Protection by *basic insulation*
(ii). Protection by *barriers and enclosures*
(iii). Protection by *obstacles*
(iv). Protection by *placing-out-of-reach*

Protection by *obstacles* and protection by *placing-out-of-reach* are methods that are used in special applications. They both require effective supervision and risk assessments. Such methods are only normally used by suitably qualified electrical engineers in electrical distribution projects.

The well accepted fundamental principle of protection against the danger of direct contact is to physically prevent a person from making contact with all live parts under normal operating conditions, engineers generally use one or both of the following protective methods

(i) *Protection by basic insulation*
Using this protective method, the engineer specifies and uses solid/laminated insulating materials having adequate thickness and adequate clearance and creepage distances over their surface to completely enclose the live parts and terminals. If the live part were to be exposed to touch after the insulation material was applied, the insulating material would be required to be cut or destroyed physically. One example of this protective measure is a pvc insulated conductor where the insulating material has to be cut back in order to expose the copper conductor for termination. All insulated cables use this method to afford protection against direct contact.

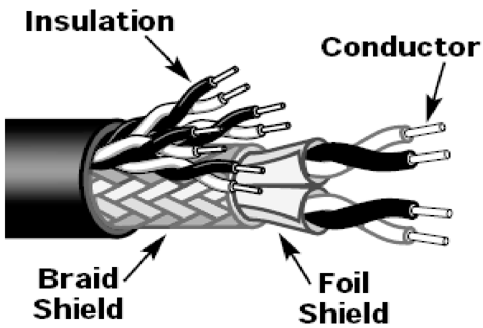


Figure 3-2 Basic insulation of cables

Figure 3-3 An enclosure of an extractor fan preventing direct contact of live terminals

(ii) Protection by barriers or enclosures

With this protective method, the engineer uses adequate clearance through air coupled with a solid barrier or an enclosure to completely enclose the live parts within. It will be necessary to use a tool (e.g., a screw driver) to remove the barrier or cover of the enclosure before it is possible to make contact with the live parts.

Since an enclosure has to be provided for most products, these two methods are often being used simultaneously by the product development engineer to safeguard against direct contact hazards of low voltage (e.g., 230 V or 120 V ac rms).

To further enhance the safety of the product, the product development engineer can add mechanical or electromagnetic interlock to disconnect the low voltage supply before the barrier and/or enclosure is opened or removed.

C Protection against faults (Indirect Contact)

An electric shock resulting from the contact of normally un-energized conductive parts being made live under abnormal operating condition (fault conditions) is defined as 'Indirect Contact'. In BS7671:2001, there are five recognized protective methods against the danger of indirect contact:

(i) Protection by *the use of Class II equipment or equivalent Insulation*
(ii) Protection by *automatic disconnection of supply* (*ADS*)
(iii) Protection by *electrical separation*
(iv) Protection by *non-conducting location*
(v) Protection by *earth-free local equipotential bonding*

Methods (iii), (iv) and (v) are for special electrical engineering applications, requiring continuous direct supervision and risk assessments, and are beyond the scope of this chapter which aims to highlight the generally applied means of protection against electric shock utilised in the built environment.

(i) *Protection by the use of Class II equipment or equivalent Insulation*
A large number of electromechanical products make good use of method (i) '*protection by the use of Class II equipment or equivalent insulation*' as the principal means of protection against indirect contact. It uses two layers of electrical insulation materials to prevent the live parts being exposed to touch should the basic insulation layer fail under abnormal operating conditions; the second layer of reinforced insulation will remain effective throughout the life expectance of the equipment.

Generally, Class II equipment is conceived to be an all-insulated type, however because of hostile environmental conditions, there are often Class II equipment having metal enclosures but two layers of electrical insulation remains between the enclosure and the live parts. The conductive casing is therefore a floating isolated metallic part and will not impart any voltage potential to any person who comes into contact with it. However, the incorrect provision of an earthing or bonding terminal can create an electric shock risk to the person.

To summarize, the general concept of Class II equipment is that it does not use earthing/bonding or automatic disconnection for shock protection. Household appliances constructed to BS EN60335 will not have an earth connection. However, there are some Class II products requiring an earth connection for functional purposes. In such cases the earth connection, which should be suitably insulated from the conductive metallic casing as well as the user, has nothing to do with safety of the equipment.

Since Class II equipment or equivalent insulation construction of products does not depend on any earthing, bonding and automatic disconnection, it can be concluded that it has the lowest probability of shock risk.

(ii) *Protection by automatic disconnection of supply (ADS)*
The principle of *ADS* relies on the fact that during an earth fault between a live part and a metallic enclosure, the low impedance of the earth fault loop will minimize the touch voltage, resulting in a high earth fault current and rapid automatic disconnection of the supply by a fuse, a circuit breaker or a residual current device. It is deemed to be able to protect any person who is accidentally making contact with a metallic casing made live under fault conditions.

This is a protection method commonly adopted by electrical engineers designing distribution and final circuits. Class I appliances form an integral part of this design measure and generally have two design characteristics to provide protection against electric shock, (1) basic insulation by either a layer of basic insulation or a maintained air gap, and (2) a conductive metallic casing which has provision for the connection of an earthing conductor

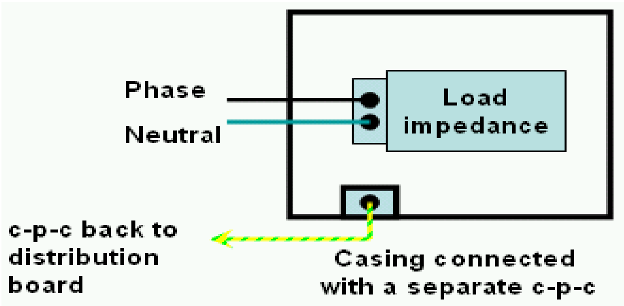


Figure 3-4 A Class I appliance with provision for earthing and bonding connections

Under normal operating conditions, the earthing and bonding connections maintain all Class I equipment at substantially the same electric potential (earth potential) even when they are located in different part of the building (see Figure 3-5). Chapter 5 carries out a detailed analysis of this protection measure.

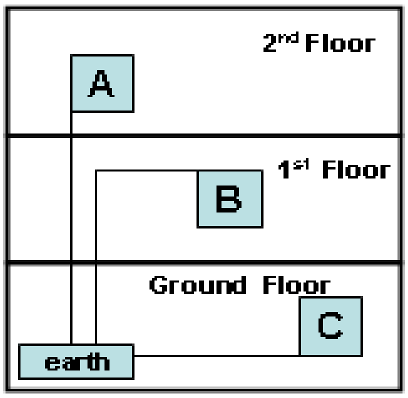


Figure 3-5 Three Class I constructed equipment (A, B and C) are at earth potential within the same equipotentially bonded building

3.2 Reason for Concern – Background

Electrical safety standards have made dramatic strides forward over the last century. However, there are valid concerns over the widening gap between the present level and the required level of electrical safety in the domestic built environment. Deaths and injuries resulting from unsafe electrical installations are preventable, and as the housing stock and population in Europe age, the need to introduce regulation and methods to enhance safety becomes increasingly important.

The concern over an ageing housing stock that is not maintained electrically can be supported with evidence. These buildings need to be adapted, and renovated to adhere to current standards or else will continue to become progressively less suited to the standards of functionality, security and safety required by today's society. For this to occur, domestic electrical safety needs to attract heightened attention from end users, regulatory and governmental bodies commensurate with the growing concerns in this area. Lack of electrical safety awareness in homes will lead to growing injury and fatality rates, fires and property loss, all of which are avoidable.

Injury and death is a key public health issue within the EU. Traffic safety and workplace safety have been enhanced through heightened awareness, regulatory approaches and safety innovations. A similar systematic approach to domestic electric safety is warranted. The formulation of a body of evidence, highlighting the major concerns related to domestic electrical safety throughout Europe by FEEDS [**75**] should give impetus to those in the industry to push for improved regulation and enhanced methods of safety engineering design.

3.2.1 Age of the housing stock

The prevalence of old electrical installations is one of the main reasons why domestic installations may be unsafe or unfit for purpose. 60% of Europe's housing stock was built before 1970, a date which marks a watershed in wiring practice in many countries, due to increased safety standards introduced at this period [**75**]. Approximately 10% were built in the last decade. Concluding from this, it is evident that the majority of the houses in Europe are old with ageing electrical installations designed and installed long before current electrical safety standards were developed. This trend is set to continue, due to the fact that 1% of the existing housing stock moves into the over 30 years old category each year while only 0.32% undergo renovation. This will result in a large but hidden group of 'electrically unsafe' houses. As an electrical installation deteriorates over time, hazards posed by ageing wiring systems, do it yourself modifications, overloading of sockets, aluminium wiring, use of extension leads, black burn marks on sockets and switches, etc. go unnoticed or are just neglected by homeowners. Figure 3-6 outlines the age profile of a sample of the EU housing stock.

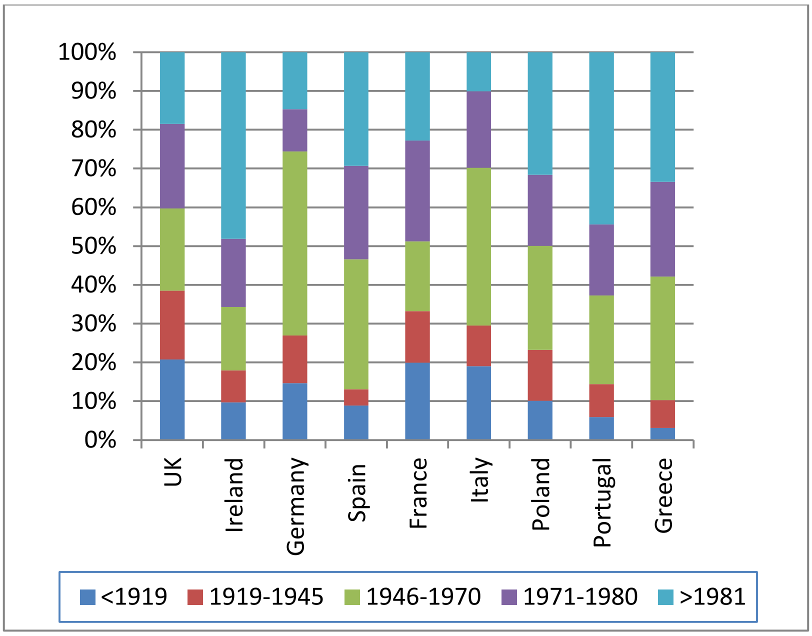


Figure 3-6 Age profile of a sample of the EU Housing Stock

Concern over domestic electrical safety due to an ageing housing stock is not just a European problem. There are rising concerns in the United States, where 30 million homes or approximately one third of the residences are 50 years old or older and residential fires involving electrical wiring systems annually result in 830 injuries and 320 deaths and $700 million in property damage [**143**] [**62**]. These studies demonstrated that the frequency of fires in residential electrical systems is disproportionately higher in older homes.

3.2.2 Lack of Maintenance and Inspection

The majority of Europe's ageing housing stock has not been designed for today's intensive use of electricity, and for the bulk of these dwellings, the requirement for mandatory maintenance or inspection has been minimal unless perhaps they are tenanted, communal or social houses. A UK study [**152**] [**164**] highlights this point concluding that, of the 46% of households which make some form of improvement to their home each year only 4.5% improve their electrical installation and only 15% of these carry out a complete rewire.

In recent times, many enhanced protective devices have penetrated the domestic electrical market such as RCD protection, overvoltage protection and arc detectors. However, unless there is mandatory maintenance and inspection at defined intervals, older dwellings may not fully benefit from such additional protection measures. A very good example where there is evidence to support such a claim is in the UK, where a study related to RCD protection found that 49% of all houses/dwellings are without RCD protection [**73**] and this raises to 52% when owner occupied houses are concerned.

Considering the long life span of houses (200 years in Europe) and electrical installations together with changing human patterns and energy demands, an increased level of periodic inspection should be introduced to protect society from the inevitable consequences of injury, death, damaged goods and fire. However, recent studies by Belsman et al [**16**], Desmet et al [**60**] and the European copper Institute [**67**] outline the current inadequacies for periodic inspection of electrical installations in Europe. To overcome this problem inspections carried out by certified experts at defined intervals or on a systematic basis is the only way to address this problem and would ensure that all dwellings are brought to a similar standard. In most countries inclusive of Ireland, mandatory inspection of the electrical installation in new builds is required. However as already outlined much of the housing stock across Europe is old with dated installations and many of the problems are associated with ageing installations. In the case where major renovation occurs, many countries do also require an inspection at this point, but if this measure is to enhance safety standards it would require that the renovation rate be much higher.

Regulation introduced in France in January 2009 highlights and reinforces this point from a European perspective. This new regulation required that inspection of the electrical installation occur whenever a property above 15 years was sold. Analysis of this scheme since its introduction has given rise to some interesting findings. From the approximate 400,000 homes that were inspected, 240,000 had one or more unsafe features [**123**]. Regulation such as this can drive change, enhance safety, while at the same time benefit society

Other positive examples of countries who have introduced enhanced regulation are Japan, South Korea and Singapore. Since the 1960's Japan has introduced mandatory inspection of electrical installations every four years. The utility executes the inspections and in the case where non-compliance occurs, inspectors return every year, until the issue is resolved. Nation-wide the number of inspectors is estimated at 2,000 and the inspection regime is financed through a %-mark up on the kWh-price for electricity. South Korea has introduced similar mandatory inspections since the 1970's. As a result the fire statistics in both countries show a drop in the recorded number of fires by close to 90% [**123**]. In Singapore, strict mandatory inspections are required for all new builds and major renovations. Also multi occupancy buildings and condominiums are inspected on a 6 monthly basis. In addition to the above, the Energy Market Authority undertakes random checks. This effort has achieved remarkable results in Singapore with zero electrical accidents recorded in residential dwellings in the last 15 years.

From the evidence above, to achieve similar positive results across Europe requires a systematic mandatory inspection scheme to be implemented and enforced. A solution very often cited in this argument is to use the template of the many car inspection schemes that are implemented successfully across Europe. [**123**] proposes the example outlined below, however there are many such examples documented that have similar merit and structure, but political and regulatory motivation to drive this forward is still lacking.

"For buildings of 20 years and older, a valid certificate is required for each new tenancy or sales agreement. Those certificates are granted through inspections and are valid for a limited period of time.

After inspection and certification at 20 years of age, for the renewal of the certificate the choice could be given between a light inspection every 5 years or an in-depth inspection every 10 years.

For high-risk groups, like student rooms, homes for the elderly, or social housing, a mandatory inspection every year could significantly lower the accident rate.

Inspection and certification should also be made mandatory when connecting a new major electrical application in the house, like for instance photovoltaic panels."

On a European stage, the only document that prescribes for periodic inspection in domestic electrical installations is CENELEC document ES 59009 [**35**], published in 2000. This document recommends inspection at intervals not exceeding 10 years. However, member states are not obliged to adopt it as a national standard. The implementation of this standard as a very minimum could significantly improve domestic electrical safety.

The Electrical Safety Council, Electrical Contractors Association (ECA) and Electrical Contractors Association of Scotland (SELECT) in the UK, and the Electro Technical Council of Ireland (ETCI), Register of Electrical Contractors of Ireland (RECI) and Electrical Contractors Safety & Standards Association (ECSSA) in the Republic of Ireland are authoritative bodies and reputable trade bodies prescribing recommended inspection intervals for both domestic and non-domestic buildings. However, the requirement of inspection is still not mandatory.

3.2.3 EU Safety levels

A recent study concluded that 60% of the housing stock in Western Europe and over 75% of it in extended Europe is electrically unsafe [**75**]. The findings from the ten individual countries surveys into installation safety highlighted some very noticeable breaches of safety for some of the key protective measures e.g. adequate earthing, overcurrent protection, correct sizing of cabling and wiring systems and protection against direct contact. Installations lacking such fundamental protective measures, vividly highlight clear electrical safety regulatory policy failure, an acute lack of electrical safety awareness among homeowners and of course a huge potential for danger.

A further electrical safety report [**67**], which investigated 16,000 dwellings, in 11 countries classified domestic homes in terms of their electrical safety based on the number of electrical safety issues present in each home. The outcome once again highlights considerable reason for concern. The percentage of houses considered safe in France and Italy was approximately 55% and 45% respectively, while less than 5% of the houses in Bulgaria, Poland, Romania, and Turkey were considered electrically safe.

In a study specific to Russia in 2001 only 0.5% of homes could be classified as safe with an average of 3-5 safety issues present in each dwelling [**109**]. 85% were considered very dangerous [**66**].

From this evidence above and the evidence gathered through the 2010 ONSE (Observatoire National de la Sécurité Electrique) study, which carried out 6,000 mandatory electrical surveys, revealing that 79% of the old electrical installations surveyed present earthing faults in one or more circuits of the electrical installation [**76**] in addition to the equally worrying evidence collected in France since the compulsory diagnosis of electrical installations at point of sale was introduced in 2009 (highlighted in section 3-3), safety of domestic electrical installations could be considered a major public health issue in Europe.

3.2.3.1 New potential risk

Recent times have seen the introduction of various renewable energy policy initiatives and climate change mitigation programmes across Europe which is undoubtedly welcome from an environmental view point. However as a consequence, an explosion of renewable technologies (PV, wind etc) being installed in residential dwellings has occurred. This does raise the question over the capability of some installations coping safely with this added electrical infrastructure and the certification system that is associated with this process. Evidence already exists in France to suggest that this is an issue that needs careful attention. In an investigation carried out by CONSUEL 50% of the residential PV installations in France did not comply with electrical safety regulations. Mandatory inspection before the connection of each major new system to a residential network should be a minimum for such installations especially in the case where the dwelling would not have been inspected for many years.

3.2.4 Domestic electrical incidents

There is only limited research extant in the area of electrical incidents in homes; however a recent UK study [**12**] (see chapter 4) based on hospital data investigated electrical injury in domestic properties. The outcome of this analysis further strengthens the idea that there is scope for improvement in domestic electrical safety, even within a country with a relatively strong electrical safety status. In the three year period investigated (2000-2002) domestic properties were one of the leading locations for death due to electric current.

3.2.5 Domestic electrical fires

Prevention of domestic fires has always been a main priority for researchers, safety bodies and indeed all of society. In the last decade research reports have continued to examine this issue along the impact ageing electrical installations that are not installed to current standards or misused over time have on domestic electrical fires. A summary of these reports from across different corners of the world is outlined below.

In a study of eight European countries (UK, Italy, Spain, Germany, France, Hungary, Poland and Netherlands) there was a 23% increase in electrical fires in domestic properties between 1988 and 1998 [**86**]. Schofield [**153**] in a UK fire statistics study showed that approximately 50% of all accidental fires occurred in dwellings and a disproportional 75% of all casualties result from residential fires. Examining the causes in this study for accidental fires showed 20% of them were electrically related and 5% could be specifically related to unsafe electrical installations. A Merseyside Fire and Rescue Service (UK) investigation showed that 79% of the accidental primary fires were caused by faults in the electric installation [**76**]. Undoubtedly, there is a significant relationship between unsafe electrical installations and domestic fires and as reported in [**16**] it is generally accepted that 10-20% of all domestic fires are electrically related. However this may perhaps be understated as Table 3-1 outlines statistics collated from data collected in the UK for the year 2007 [**73**]. For this year it is evident that approximately 50% of all accidental domestic fires are of electrical origin and 5% are specifically related to the installation. The electrical products that are the main cause of these electrical fires are electric cooking appliances 59% (excluding deep fat fryers), washing machine and tumble dryers 6.6%, lighting 4.4% and space heaters 3.5% followed by televisions 2%.

	All accidental fires	Accidental domestic fires of electrical origin					
		Faults	Misuse	Articles too close to heat	Total	Products	Installations
Deaths	267	23	12	14	49	41	8
Injuries	9,066	1,143	1,831	503	3,477	3,250	227
Fires	43,351	7,986	10,960	2,478	21,424	19,101	2,323

Table 3-1 Number of fires of electrical origin in the UK in 2007 [73]

In a European study based on primary data collected from national fire statistics, fire statistics published at municipal level in major European cities and data from the Geneva Association's world-wide fire statistics programme, FEEDS [**16**] constructed a demographic model. From this model, it can be estimated that about 3.2 fires per 1000 dwellings are reported each year in Europe. This report outlined that approximately 60% of reported building fires occur in the domestic sector and estimated that only 25% of fires are reported. From this it was proposed that the number of fires per year in the EU-15 is 510 000 and 620 000 in EU-25 and concluded that the average cost of an electrical fire is five times the average fire cost and cited €14 billion as the cost to society for domestic fires for the EU 15.

In the same report it was concluded that there are about 7 fire deaths/million citizens (Table 3-2) which relates to an approximate 1 in 200 fires in dwellings resulting in a fatality. This report also found that about 2 700 domestic fire deaths and 37 000 injuries occur each year in EU-15 and 3 250 domestic fire deaths and 45 000 injuries each year in EU-25.

In the USA (2002), following considerable interest regarding the influence of ageing and the quality of electrical installations on the fire safety of electrical systems, the Fire Protection Research Foundation commenced a collaborative research and development project [**62**] in an effort to address the issue. The report was based on a detailed survey on the condition of a representative sample of residential electrical components installed in different eras ranging in age from 30-110 years in various U.S. locations. As already highlighted, the National Fire Protection Association (NFPA) in the US estimate that there is an annual average of 24,200 home fires attributed to electrical distribution systems, or lighting equipment, causing 830 injuries, 320 deaths and $700 million in property damage. The Consumer Product Safety Commission (CPSC) in a 1987 study indicated that the frequency of fires in residential electrical systems was disproportionately high in homes more than 40 years old. [**62**] reports that the high incidence of fire in the electrical systems of older homes are usually attributed to one or more of the following factors:

- Inadequate and overburdened electrical systems.
- Thermally reinsulated walls and ceilings burying wiring.
- Defeated or compromised overcurrent protection.
- Misuse of extension cords and makeshift circuit extensions.
- Worn-out wiring devices not being replaced.
- Poorly done electrical repairs.
- Socioeconomic considerations resulting in unsafe installations

Country	Population (000s)	Dwellings (000s)	Deaths/ year	Injuries/ year	Deaths/10^6 persons/year	Deaths/10^6 dwellings/year
Czech Republic	10 300	4 700	66	*660*	6.4	14.0
France	61 700	28 000	800	10 000	13.1	28.5
Germany	82 000	37 500	380	*3 800*	4.6	10.1
Hungary	10 000	4 100	114	*1 140*	11.4	27.8
Italy	57 500	22 000	240	*2 400*	4.2	10.9
Netherlands	15 900	6 800	38	725	2.4	5.6
Poland	38 600	13 400	336	*3 360*	8.7	25.1
Spain	39 900	12 500	150	*1 500*	3.8	12.0
Switzerland	7 200	3 100	24	*240*	3.3	7.7
UK	59 400	24 300	400	12 500	6.7	16.5
Total	388 800	156 400	2 623	*36 323*		
Average					6.7	16.7

Table 3-2 Injuries and deaths in domestic fires for some European countries [16]

An interesting finding of this report concerned the testing of cables installed throughout the different eras. The results for older cables made from older rubber demonstrated their vulnerability to become brittle with age. However, the thermoplastic insulated cables installed typically from the 1950s onwards continue to perform to a high standard even after many years of service in the home. The factors that were identified as influencing most the likelihood of a residential fire were; the effects of natural ageing on the wiring system, misuse or abuse of the electrical system and finally non code compliant installations, upgrades or repairs.

In light of the European and US research, the Energy Safety Service in New Zealand carried out a similar research project [**136**] which aimed to determine the risks associated with older electrical wiring and whether any actions should be undertaken to address the replacement of older electric wiring. The results of this research which focused on analysis of electrical fire data between 1986 and 2003 found that overall risk of electrical fires over last few years to residential dwellings is 0.15% in New Zealand. 0.10% of fires is estimated to be related to heat from an electrical source and arc related fires is 0.048%. Notably, only 0.019% of fires were found to be related to ageing electrical wiring. Risk from older wiring systems used in 1940s and 1950s is also low compared to other types of electrical fire risks.

This report concluded that heat initiated fires from electrical equipment has increased by 260% in the last 18 years while arc related fires have remained unchanged. Electrical fire casualties were noted to be far greater than victims who suffered electric shock and finally in contrast to the FEEDS report, it was declared that due to the low risk in New Zealand associated with wiring in dwellings, the implementation of an ongoing inspection system would be unwarranted citing the high compliance cost to the consumer and the difficulty in monitoring the process as negatives.

3.2.6 Counterfeit Electrical Devices

The Organization for Economic Co-ordination and Development (OECD) estimates 2% of world trade – 176 billion USD is counterfeit. Lost electrical sales account for 2.4 billion Euro [**13**]. To counteract this challenge, the EU has allocated €12 million to improve the courts of several Asian countries and train more intellectual property rights judges. Counterfeit/fake protective devices cause problems for electrical manufacturers through loss of sales, and also their reputation is tarnished through poor quality replicas sold on at reduced prices.

Organisations such as British Electrotechnical and Allied Manufacturers Association (BEAMA) and many large electrical companies have already carried out a lot of good work to raise the profile of this problem. However, it is inevitable that most borders will be penetrated such is the problem. BEAMA estimate that £30 million worth of counterfeit electrical products reach the UK annually. One product that is particularly susceptible to counterfeiting is the low-voltage circuit breaker, the most common type of overcurrent protection. Such a counterfeit circuit breaker was located in the EU-Portugal in 2007. As can be seen in Figure 3-7 the counterfeit MCB has no internal workings, which would operate the device in the event of a fault occurring in the circuit that it is supposed to protect. So in this instance, fire may be a direct consequence or for faults in non-RCD protected circuits, the transfer touch voltage cannot be disconnected and fatalities could result.

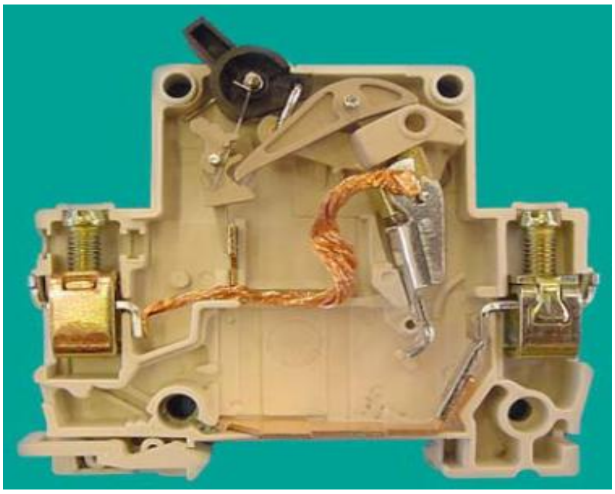


Figure 3-7 Counterfeit MCB with no internal workings

Similar counterfeit products (Figure 3-8), which did have internal workings, when tested by manufacturers failed to trip completely on overload. The existence of such counterfeit products impacts directly on the quality and level of domestic electrical safety.

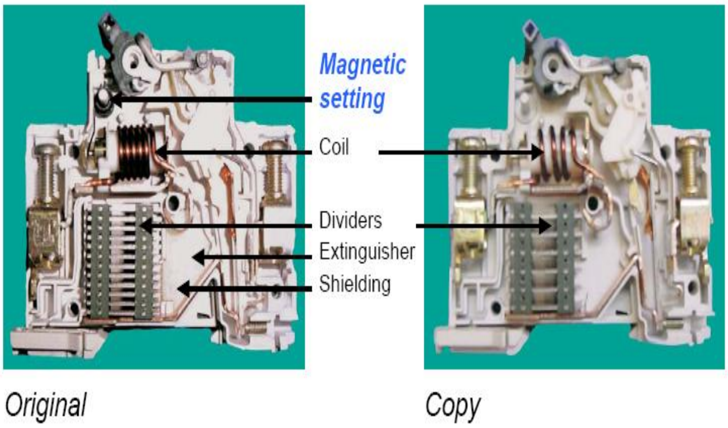


Figure 3-8 Counterfeit MCB

In a similar recent report by an Irish electrical contractors association ECSSA [**65**] there was a succession of complaints from contractors in relation to fires and near misses caused by one particular manufacturer's RCDs. Initial investigations have revealed that the fault must lie in the construction of the unit itself, or in the makeup of the insulating material used.

3.2.7 Reliability of Protective Devices

There are very few publications relating to the reliability of protective devices due to its commercially sensitive nature. However reliability data from an ERA Technology Report [**149**] in May 2006 concluded that electromechanical RCDs have an average failure rate of 7.1%. Although, if regularly tested this figure falls to 2.8%. However, the report has indicated that RCDs with an inadequate IP rating subjected to dust and moisture could have a 20% failure rate.

Since this initial report, the Electrical Safety council in the UK in conjunction with ERA Technology have continued their research into establishing the reliability of RCD's. In a report published in 2008 [**73**] further results on RCD's were reported for tests carried out on 607 electromechanical RCDs in properties owned by four Housing Associations and Local Housing Authorities in the UK. The tests were carried out on the load side and all appliances were turned off to prevent the effect any loads may have on the test results. From the results obtained, a total of 23 failures were recorded which gives a failure rate of 3.8%, this includes six RCD's that were shorted out to prevent nuisance tripping, when these are excluded the failure rate is 2.8%.

ERA concluded in its findings that the most likely causes of failure were, deliberate shorting out, ingress of moisture and contaminants, component misalignment and finally disruption of contact surfaces causing contact welding. It was clearly outlined that regular operation of the test button does have a positive effect on the overall reliability of an RCD when subjected to earth fault conditions.

3.2.8 Designing For Safety

Evidently, there are many concerns regarding domestic electrical safety today. If these issues go unchallenged the current low levels of safety in so many dwellings worldwide will decrease. Governmental and regulatory bodies require political courage regarding periodic maintenance and inspection to address these concerns at a national level. However, this approach alone will not be sufficient; a marked improvement will require a multifaceted approach to improve the current levels of safety. User awareness and willingness to engage in resolving this issue is vital. Nevertheless, focusing on safer designs should be a fundamental instrument going forward, leading to improved engineering and regulatory standards in designing for safety.

The level of safety of an electrical installation hinges on, the standards in place at the time of renovation or construction, how thoroughly they were carried out and finally, how effectively the installation has been maintained. Therefore, the initial standard of safety and quality of design at the time of installation is pivotal to what will follow. Admittedly, standards are evolving and safety innovations are coming online. Evidence of such, can be witnessed throughout the electrical industry, some examples being

(i) The stringent guidelines to which manufacturers of electrical goods must adhere to, ensuring their products are electrically sound and fit for purpose. However, opportunities still exist for improvements, a prime example being the number of electrical incidents resulting from direct contact with a lamp or light fitting. User awareness is also required; as misuse of equipment and lack of maintenance leads to electrical injury, fire or death.

(ii) Guidance on the provision of socket outlets and the required lighting levels are well documented and can improve functionality and comfort levels within a home. Adherence in designs to the guidance given can often ensure the initial installation meets the functionality the homeowner requires and helps future proof homes against the requirements of new technologies, preventing the need for extensions to the installation, which can often be haphazard and dangerous.

(iii) BS7671: 2008, 17th edition IEE Wiring Regulations, has set down new protective measures e.g. 30 mA RCD protection is now required for socket-outlets for use by ordinary persons for general use, mobile equipment outdoors and for concealed cables in walls and partitions where the installation is not intended to be under the supervision of a skilled or instructed person.

(iv) Still debatable and in its infancy stage is the possibility that further functionality and electric shock protection can be achieved by the introduction of the latest reclosing RCD technologies. The more sophisticated versions of these can automatically reinstate the supply subsequent to a transient fault after checking the insulation of the downstream circuit. It was claimed that the reliability of earth leakage protection is also enhanced by an electrical and mechanical test being carried out every seven days by automatically opening and closing the Residual Current Circuit Breaker (RCCB) during which time the continuity of supply is maintained downstream.

(v) Alternatively, by designing for safety through the implementation of a low touch voltage design can significantly reduce the possibility of receiving a dangerous electric shock in the home.

This list is not meant to be exhaustive but is there to recognise that by designing for safety, improvement is possible, and safety innovations and design measures such as these improve domestic electrical standards and help prevent electrical injury and death.

3.3 Conclusion

Upon analysis of the various national regulations regarding the safety of electrical installations, it would appear that many national authorities have developed regulation or good practice in relation to publicly accessible, commercial and industrial buildings. However housing appears to be an area that is least regulated and could most benefit in terms of electrical safety. It would seem from the body of evidence documented in this chapter that a major portion of domestic electrical installations across Europe are unfit for purpose. This is compounded by the lofty average age of dwellings and a poor renovation rate in tandem with lifestyles that require intense use of electricity. Modern practices such as the addition of renewable energy sources and home automation systems add significant burden to older installations. The culmination of these factors should require that regular periodic inspection and renovation of installations take place in order to ensure they are fit for purpose.

Inadequate safety measures can result in injury and death. Fire statistics suggest that fires which result from defective electrics result in more financial loss and personal injury than fires from alternative sources. Poor maintenance of electrical appliances can also cause injury through electric shock as clearly documented in chapter 4. The technical solutions to prevent such events are available and the required national electrical standards are in situ in most countries. However, in many homes these standard solutions have not been introduced and the existing safety measures may have deteriorated over time. Hence to enhance the rate of renovation requires some form of regulation. France is an example of a country that has introduced some regulatory reform, which in time will benefit society. A similar or slightly adjusted approach Europe wide would be beneficial. This could take the form of the requirement to supply a certificate of fitness when a home changes owner or tenant or as added component to ensure all dwellings are captured, regulations could be introduced to authorise a periodic inspection of all installations every ten years.

In summary, electrical safety can be maximised by a correctly designed and installed installation. By making the public more aware of electrical safety issues can create a more knowledgeable society which may lead to them having regular inspections or maintenance carried out. It is apparent that the standard of electrical installations is highly variable; a certification process based on periodic inspections would ensure best practice with the added benefit of giving the occupant a heightened sense of security, increased convenience using electricity and an increased property value.

Chapter 4

Analysis of Electrical Accidents

4.1 Introduction

Advances in electrical safety have contributed greatly to the well being of humans in the built environment; however the potential for danger from exposure to electric shock, fire, burns, explosion and electrocution is still significant. Much literature to date has presented the inherent danger of electric current in the workplace [**93**] [34]. However there is only limited research on electrical incidents in the home even though previous research into hospitalisations due to electrical injury, places the home as the number one location to sustain such injury [**138**]. For each of the years investigated in this chapter the number of deaths due to electric current in England and Wales is higher in the home than in the workplace [**165**].

This study investigates fatal and non-fatal electrical incidents from electric current causing shock or burn in domestic properties over a three-year period (2000-2002). The non-fatal incident data was obtained by interviewing patients who attended Accident and Emergency units, in hospitals across the UK. This data represents the UK input to the overall European Home and Leisure Accident Surveillance System (EHLASS)[3]. The fatal incident data is derived from the registration of deaths certified by a medical doctor or a Coroner.

[3] The purpose of EHLASS is injury prevention within the EU member states, by gaining an in-depth understanding of how and why domestic and leisure accidents occur to enable steps to be taken to prevent them in the future.

To prevent injury and death due to electric current requires study of case histories, previous experience and data [**59**] [**64**]. If key decision makers such as engineers, educators, manufacturers, regulators and occupants are starved of this information, negative trends in electrical injuries will not be impacted on. To this end, this study was conducted to highlight, the at-risk groups that could benefit from improvements in electrical safety, the main risk activities in domestic properties, the products involved, the outcome of the injured patients and also puts forward an "injury pyramid" for electrical incidents in the home. This study should also focus any future research on the most significant problems due to electricity in the home.

4.2 Data Sources

The electrical injury data presented is derived from the data used to publish the 24th report of the Home and Leisure Accident Surveillance System (HASS/LASS) funded by The Department of Trade and Industry (DTI) in the UK. For the years between 2000 and 2002, up to eighteen hospitals across the country submitted information to HASS/LASS by interviewing patients who attended Accident and Emergency units. Hospitals selected had to meet the following criteria, (i) attend to more than 10,000 accident and emergency cases a year (ii) operate a 24-hour service (iii) take ambulance cases. To produce a good mixture for national estimates, the hospitals chosen were from different geographical locations, urban and rural areas and serve different sized populations with different sized accident and emergency units.

Specially trained interviewers gathered the information. The interviewers were on duty in the participating Accident and Emergency units at peak times. They identified patients who have suffered a home or leisure accident and interviewed them using a standard questionnaire. The personal interview was supported with information from the hospital medical records.

The questionnaire used to gather data included: a short description of the immediate circumstances, details of where the accident happened, details of the victim, including age, and gender and details of any product involved. Collating this information gives a comprehensive picture of the incident and how it occurred. On request from The Royal Society for the Prevention of Accidents (RoSPA) who now hold this database, it was possible to derive the electrical incidents via the accident mechanism titled "shock or burn from electric current" from the overall database.

National estimates were produced using the sample data taken from the eighteen hospitals. The degree of uncertainty of these estimates is quantified using upper and lower limits which relates to a particular required level of confidence, customarily this is 95% [**101**]

The fatality data presented in this paper is derived from the Mortality Statistics produced by the Office for National Statistics in the UK [**165**]. This annual report presents statistics on deaths occurring in England and Wales that were attributed to accidents, poisoning and violence. From these statistics it was possible to attain the age profile, gender and location of all deaths due to electric current.

4.3 Electrical Injury Data Analysis

The electrical incident data was used to trend electrical injury for various categories and groups. This determined at-risk groups that could benefit from electrical safety interventions and highlighted the high-risk activities, which lead to receiving an electric shock in a residential home. The benefits of the narrative reports (see Table 4-1) that accompany each individual incident is also exploited to forge an insight into incident causes that may indicate where specific types of remedial action can be implemented (engineering controls, safety awareness campaigns, etc.) which may temper the number and severity of domestic electrical incidents.

Trying to fix cooker-Didn't turn power off – Fiddling around with fingers in the back of cooker and was thrown back across the kitchen.
Changing belt on washing machine, whilst it was still plugged in. Both arms stuck in for 10 seconds. Then jumped back after receiving shock.

Table 4-1 Two examples of the narrative reports that accompany each incident in the database

A. Accidents due to electric current in the home

From the data recorded from the eighteen hospitals between 2000 and 2002, 430,603 incidents were recorded which required the victims to attend Accident and Emergency (A&E). This translates to an estimated eight million incidents in the home in the UK for this period. Retrieved from this data, were the 468 incidents that occurred due to electric current in the home. As can be seen in Figure 4-1 below, this translates to an approximate 8,698 incidents due to electric current in the home in the UK during this period.

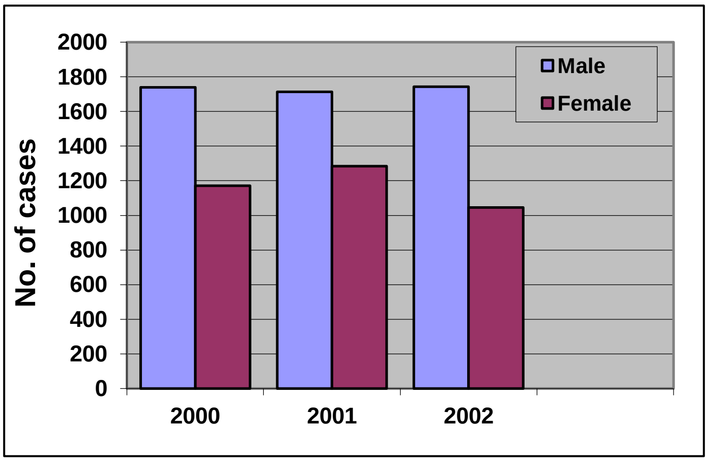


Figure 4-1 The estimated number of UK accidents due to electric current in the home 2000-2002.

This represents 0.11 % of all incidents in the home and can be equated to a rate of approximately 5 cases per 100,000 population for each year of the period studied. This represents a 1 in 20,000 probability of receiving a non fatal electrical injury in the home that required medical attention in A&E. However, it is important to be cognisant of the fact that electrical incidents have a high potential danger for victims. Past research carried out in the workplace indicates that the ratio of electrical fatalities to deaths is many times that for general safety hazards [**89**].

B. Age and sex

The rate of injury due to electric current in domestic properties for males was 1.5 times the rate for females. For both males and females, the incident rates were highest in the young adult and adult years with the exception of children in the 0-4 age category, highlighting the importance of electrical safety awareness for adults around young children and the potential for possible engineering control measures.

Previous research [**138**] into hospitalisations due to electrical injury in non-specific locations, (i.e. home, industrial and construction, street and highway etc.) indicated the rate of male hospitalisations was three times the rate for females for electrical injuries in non-specific locations. However, in contrast to this study, the rate of female hospitalisation due to electrical injury in the home was approximately twice the rate for males.

From Figure 4-2, it is evident that in this UK study, each age category is pre-dominantly male dominated with the exception of the 20-24 and 30-34 age categories. Female dominance in both these age categories is mainly due to high incident rates while carrying out household activities and DIY/maintenance. In general, 25-34 year olds are the age category most at risk from electrical injury in the home. This group accounts for 25% of all the incidents with an almost equal proportion of males (52%) and females (48%). 40% of the incidents for this age group related to carrying out maintenance/DIY/repairs in the home. De-energising equipment before work was carried out could have prevented all of these events. Other work related activities that incurred injuries for this age category were household activities (20%) and gardening (14%). Heightened awareness, isolation and preventative maintenance on electrical goods and appliance could have prevented many of these injuries.

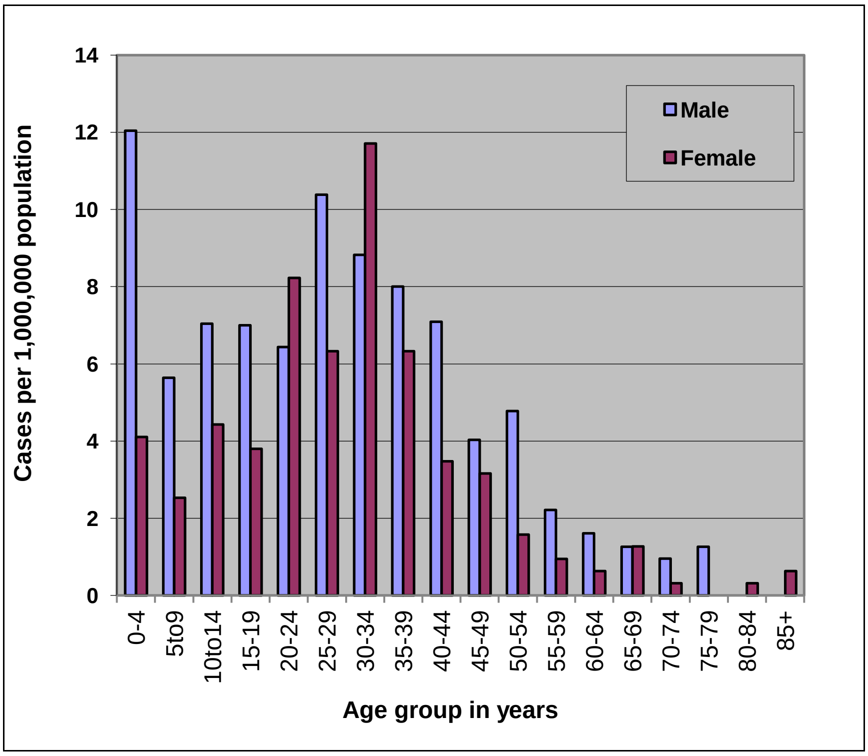


Figure 4-2 Estimated rate of attendance at A&E due to electric current in the home, by age and sex. UK, 2000-2002.

Figure 4-3 outlines the percentage of incidents in relation to the percentage of population for each age category and sex. From this it is possible to identify if there are a disproportionate amount of incidents occurring in each age category. Generally, there is a higher incident rate in the 0-40 age category in relation to the population. This is followed by a decline in the incident rate over this age category. Worth observing are the very noticeable contrasts in the 25-34 age categories, and the very high disparity of incidents for males in the 0-4 age category.

In total the 0-4 age category, accounts for 11% of all incidents. A frightening aspect for this group was that 60% of these incidents involved inserting a hand or object into a lamp or socket. Enhanced engineering and awareness could lead to a reduction in these incidents. The majority of the remaining cases involved contact with, or biting of cables.

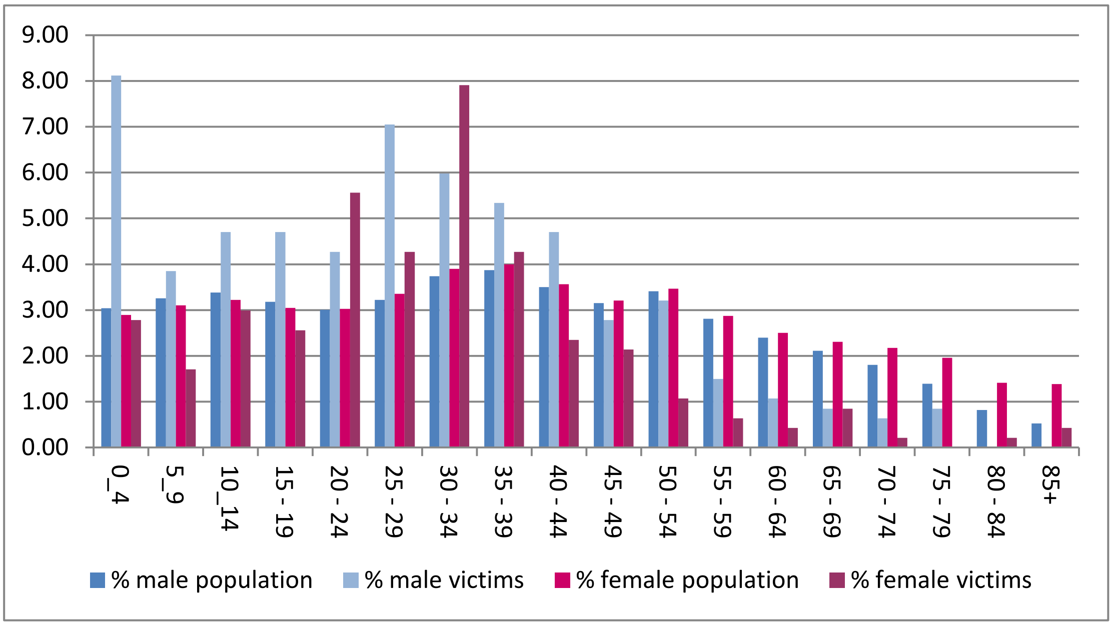


Figure 4-3 Percentage of UK population and victims in each age category.

C. Activities resulting in electrical injury

The activity that leads to most incidents due to electric current in domestic properties was DIY/Maintenance (33%). Male's account for 78% of injuries for this activity. Within this category the dominant causes are electrical repairs (to washing machines, plugs etc.) along with electrical maintenance (e.g. changing light bulbs).

The categories, 'Household activity' (19%), Gardening (7%), and 'Basic needs' (6%) are dominated by female incidents 70%, 59% and 65% respectively. 'Household activity' relates to general routine household activities (e.g. cooking, cleaning, dusting etc.), while 'Basic needs' refer to eating, sleeping, washing, walking, moving around etc. The activity 'Play/Hobby/Leisure (14%) is male dominated (77%) mainly due to the high number of incidents involving males in the 0-4 age bracket.

Analysis of the database under activities reveals the repetitive nature of the incidents resulting in injury due to electric current. Examining the standout activity that led to injury 'DIY/Maintenance', which accounted for a third of all incidents, 90% of these incidents could have been prevented by isolating the power to the equipment or room before the activity was carried out. One would believe that working live was not the intention of these victims who obviously have the confidence to attempt electrical repairs maintenance and

DIY about the home, but are inherently ignorant to the potential dangers of using electricity and the need to observe basic safety practices.

Combining all work related activities in the home accounts for 60% of all incidents. Corrective maintenance and de-energising equipment are simple methods of reducing this statistic. The people in this category can be clearly identified as people who could benefit from electrical safety awareness campaigns.

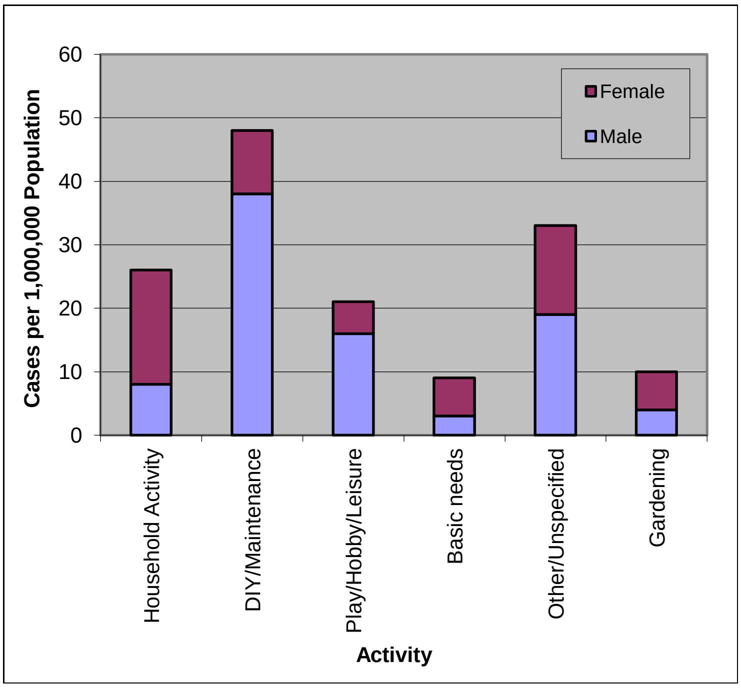


Figure 4-4 Type of household activity leading to injury due to electric current by sex, UK, 2000-2002.

D. Location of electrical injury

A place of occurrence was recorded for all incidents. Injuries sustained indoors accounted for 71% of all incidents, outdoor incidents were recorded at 10% while 19% of incidents were recorded against an unspecified location within the home. The highest incident rate for a specified location was the kitchen (17%), while the lowest incident rate for a specified indoor location was the bathroom (3%).

The most likely location for children aged between 0-14 to get injured are the bedroom and the Lounge/Study/Dining area, both account for 18% of all incidents within this age category. For young adults and adults the kitchen is the most susceptible location to electrical incidents accounting for 25% and 20% of cases within these age categories respectively. For older adults, no indoor location warrants particular attention, all locations are comparable for this age category.

As identified in Figure 4-5, the Kitchen/Utility was the number one specified location for electrical injury. Females were involved in 60% of these incidents. Once again however DIY/Maintenance/Repairs were the cause of 50% of the incidents in this location, and a third of the incidents were attributed to household activities. Almost 50% of the incidents can be attributed to individuals in the 25 - 39 age groups.

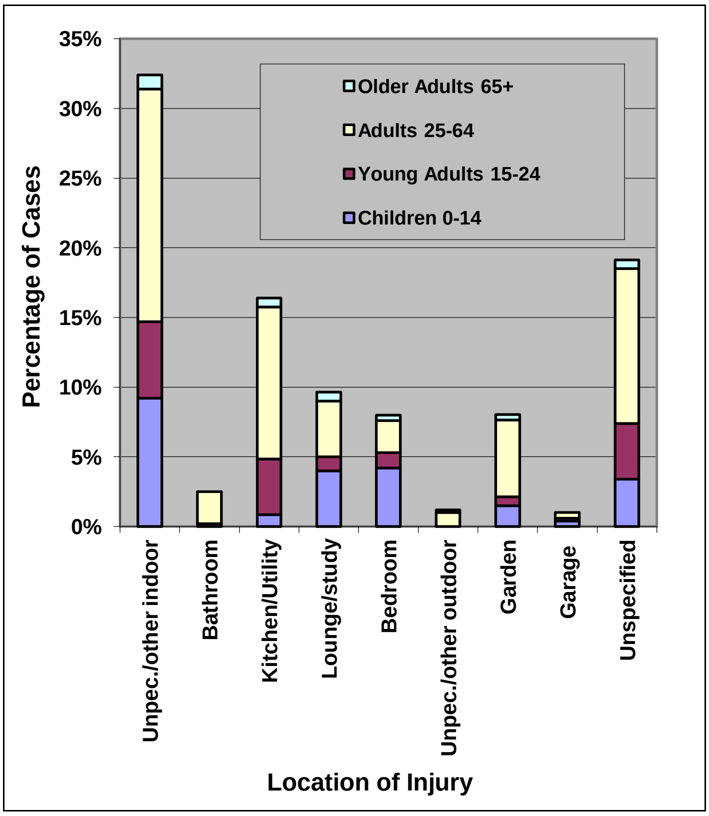


Figure 4-5 Place of injury by age category, UK, 2000-2002.

E. Equipment involved in electrical injury

The increased use of home electronics and electrical systems and appliance has led to a situation where the potential for electrical injury and death is increasing. Surveys have shown that 50% of new homeowners require additional socket outlets within twelve months of purchase of a new dwelling. A comparison of sales of all types of electric and electronic household goods between 1957 (£400 million) and 1984 (£5,000 million) indicates at least a fivefold increase in numbers of appliances sold.

Analysis of the database clearly outlined that electrical incidents and injuries occur when people interact with energized electrical equipment. However, injuries caused either directly or indirectly by domestic electric equipment are rarely documented [**24**]. Analysis of the narrative report allowed for the identification of the equipment/product involvement in the 468 electrical incidents, as presented in Table 4-2.

Equipment Involved	**Percentage of Cases**
Light/Lamp	17%
Washing machine/dryer	10%
Other/Unspecified	9.40%
Kitchen Appliances	9%
Garden Appliance	8%
Other Household Appliances (ex kitchen app)	8%
Plug of unspecified appliance	6.40%
Cable of unspecified appliance	6%
Socket	5%
TV/Video/Computer	4%
Hoover	4%
Distribution Board	3%
DIY Tools	3%
Light Switch	2%
Hairdryer	2%
Electric fire/heater	2%
Tap/copper pipe	1%
Electric Shower	1%

Table 4-2 Equipment involved in electrical injury in domestic properties, UK, 2000-2002

Incidents involving a light/lamp (17%) are by far the most prevalent in a domestic home, children aged between 0-14 accounted for 41% of these incidents. The majority of these incidents involved sticking fingers into the equipment. One third of the incidents related to 'light/lamp' involved carrying out maintenance on the equipment while live. Washing machines and Tumble Dryers are the next biggest offender (10%), adults aged between, 25-64, account for 82% of these incidents which basically can be attributed to carrying out maintenance/repairs live.

Undoubtedly it is important to ascertain the appliances involved in electrical incidents as they can be beneficial in thwarting electrical injury and death in the home, however this does not always give us the full picture, causal analysis of the narrative reports identified that practically a fifth of all incidents involved receiving an electric shock from a plug from various appliances which in some respect provides us with more useful information than simply pinpointing the equipment involved. This identifies perhaps that the fault may not lie with a specific appliance in many instances but rather poor maintenance or lack of maintenance of the plug connection.

One of the primary objectives when designing electrical equipment is to afford safe interaction between people and electricity. Electrical equipment must also be maintained so that the integrity of the equipment is not compromised and the equipment remains fit for this purpose [**125**]. Depending on manufacturer's requirements for installation, and standards in BS7671 is not always enough. Homeowners must bear some responsibility and ensure the equipment is properly maintained. However, awareness that the appliances should be isolated from the supply prior to carrying out maintenance on the equipment is essential.

F. Victim hospitalization outcome

Figure 4-6 shows the victim's A&E outcome by age category and gives an insight into the severity of the injuries sustained in domestic electrical incidents. The primary outcome for all age categories is 'Treated, no more treatment required' (32%) followed by 'referred to outpatient clinic' (19%). Approximately 64% of victims were treated as outpatients, 15 % were admitted to hospital as inpatients while 1% required plastic surgery or specialist treatment.

Using the narrative reports and integrating it with the victim's outcome to determine if the victims injury could be correlated to any specific location, sex, activity etc did not lead to any obvious outcomes, this led to the conclusion that there is no direct relationship between the location, activity, age or equipment and the severity of electrical injury in the home.

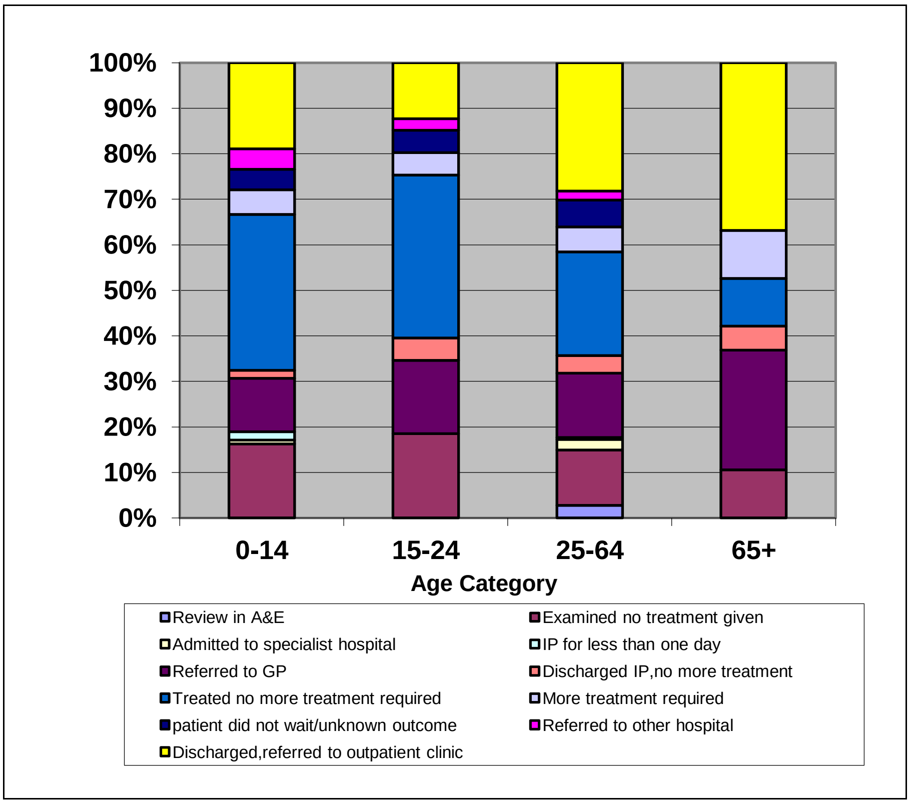


Figure 4-6 A&E outcome of victims due to electric current in the home, by age category in the UK, 2000-2002

4.4 Fatal Data Analysis

Contact with electricity is the fifth leading cause of workplace fatalities in the UK [**93**]. However, death due to electric current in the home in England and Wales is higher for each year of the study (see Figure 4-7). In the past, much attention has been given to workplace safety with good success in many cases. Good communication, clear safety guidelines, good work practices and targeted control measures have been found to play a vital role in reducing fatalities. However, safety in the workplace is subject to The Management of Health and Safety at Work Regulations 1999. Implementation of this is often business led and commercially driven and in many instances has financial and legal consequences. Many of these deterrents/incentives are absent in the home.

Analysis of the data for fatal incidents [**165**] for the years investigated gave clear evidence that the home was the number one location for death due to electric current. Approximately 46 % of all fatal incidents occurred in this location. This data is derived from the registration of deaths certified by a doctor or a coroner. The reliability of information about cause of death depends on the reliability of ICD (International Classification of Disease) codes. Trending the fatality statistics against the injury statistics (see Figure 4-8) clearly outlines that the same age categories are the most vulnerable to both electrical injury and death. Interestingly however, for the period 2001-2005 the fatality rate in the home for males (90%) is nine times that for females (10%). This is in stark contrast to the male injury rate which is only 1.5 times that of females as shown in Figure 4-2. This disparity warrants further investigation.

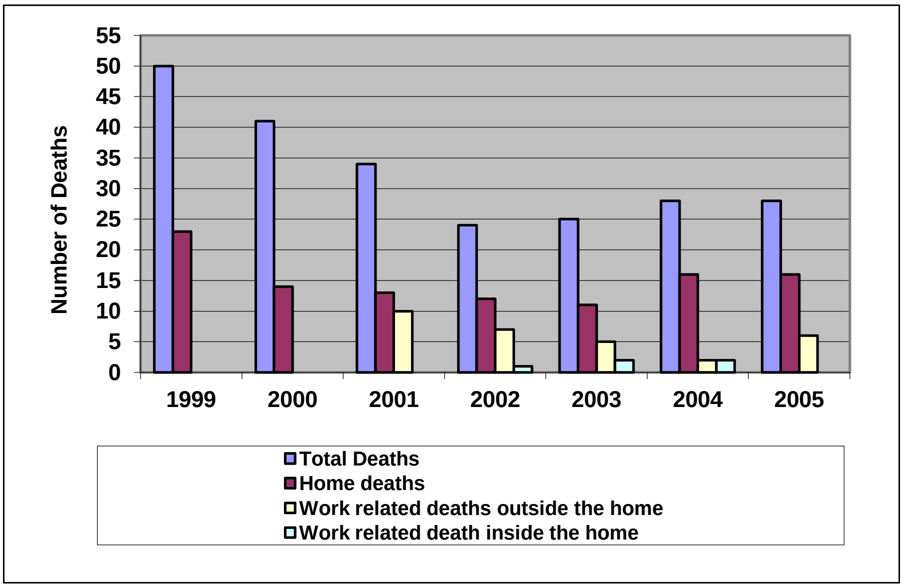


Figure 4-7 Deaths due to electric current, England and Wales, 1999-2005.

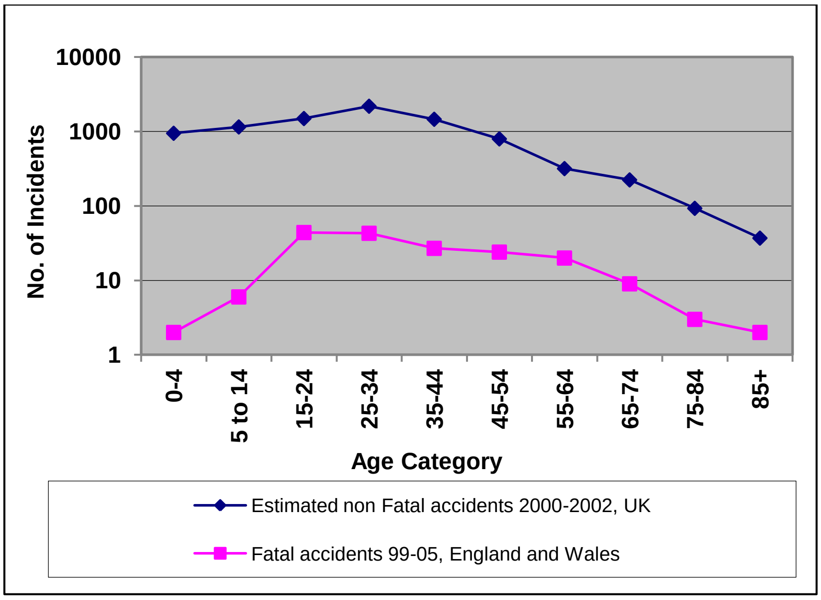


Figure 4-8 Trend of electrical injuries and deaths due to electric current

Using the A&E and fatality data an "injury pyramid" (see Figure 4-9) for domestic injury due to electric current for England and Wales was developed. The data indicates that statistically each fatality corresponds to at least 170 cases presenting at A&E. Safety experts generally agree that every electrical incident has the potential to be fatal. This research indicated that electrical incidents in the home have a higher fatality rate than general safety hazards but are less likely to lead to a fatality than an electrical incident in the workplace, where it is proposed that for every 10 recordable incidents there is one fatality [**64**]. One could assume that this is down to variety of reasons, most notably reduced voltage levels.

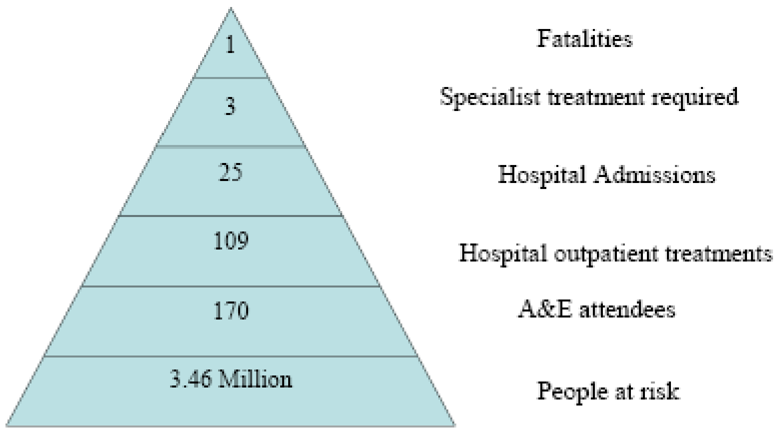


Figure 4-9 Proposed "injury pyramid", for incidents due to electric current in domestic properties, England and Wales.

4.5 Discussion

The potential for dangerous electrical incidents in domestic properties is increasing. The number of homes in the UK continues to grow annually expecting to reach almost 30 million by 2020 [**88**]. The demand for electrical power has risen as householders seek greater convenience, comfort, and enhanced entertainment. In addition to this, 59% of the housing stock in the EU and 60% in the UK was built before 1970 [**131**], an era when electrical control and protective measures were not designed to today's standards. Bearing all this in mind along with the fact there is no requirement for periodic inspection of domestic properties unless perhaps they are tenanted or communal properties should highlight that many domestic properties across the UK and Europe have ageing electrical installations that are not installed to the current safety standards and not designed for today's intensive use of electricity. If the current situation continues unaltered, a spiraling increase in domestic electrical incidents via fire, injury or death will be inevitable.

Tighter engineering controls have been introduced in the 17th edition IEE Wiring Regulations (BS7671: 2008) by making Residual Current Device (RCD) a requirement for unprotected cables installed in walls and for all socket and lighting circuits. With good confidence, one could suggest that this will reduce the fatality rate, but the time delay for this requirement to filter through will obviously delay any rewards that can be reaped from these enhanced regulations.

Furthermore, good communication, can highlight the main risk activities, provide education on good maintenance practices, enhance the prevention of injury to children etc. Occupants, who can identify key safety issues, which allow them to monitor the condition of their installation and carry out minor repair work safely, can significantly improve safety levels. Also, increased levels of awareness among homeowners of the potential dangers may improve the renovation rate of electrical installations and hence the electrical safety of their dwelling.

To further progress domestic electrical safety, an improvement process needs to be implemented. The onus is on all of society however particularly on governments, regulators, manufacturers, engineers and electricians. For homeowners to have peace of mind with regard to electrical safety, they must have a correctly installed well maintained installation, they must understand the very minimum safety requirements, they must be aware of the relevant safety hazards and have a method of measuring their safety status.

Generally government and health authority statistics provide good indicators that can flag key hazards in the work and home environments, but these can have a limited impact. In this research, it was possible to marry statistics such as these with real world situations as given in the narrative reports. This allowed for a more effective analysis. It stands to reason that understanding how incidents occur can provide the impetus to reduce them in the future.

Homeowners are around electricity so much it is possible that they may become over familiar with it and underestimate its potential danger. Complacency is inevitable unless awareness campaigns and safety training are provided. An obvious example of this point is easily identified in this work by the overwhelming number of incidents that occurred as a result of maintenance work being carried out on energised equipment. With sufficient knowledge and training, the dangers associated with this practice would be fully appreciated.

As identified by [**64**] case histories are a valuable tool in reducing employee incidents and improving electrical safety programs in the workplace. Relating this to the home, the narrative reports that accompany each incident in this database combined with the statistics generated along with improved engineering could prove to be decisive tools in combating electrical incidents in domestic properties. The following are suggested benefits.

(a) *Scenario based awareness campaigns* concentrating on the narrative reports could prove to be a very effective training tool that could allow homeowners to identify themselves with the victim rather than just highlighting the do's and don'ts that surround electricity in the home. These reports are concise, easily understood and relate to everyday tasks performed in almost every home. Key points could be transferred in an affable manner. An education program such as this, which highlights the main causal factors, may save lives.

(b) *Domestic electrical regulation and policies* may be influenced by those having responsibility for drafting the regulations having a good understanding of what is occurring. The development of enhanced regulations can only benefit from an analysis of recorded incidents.

(c) *Elimination of reoccurring incidents* can be achieved. Common repeat incidents can be easily communicated to individuals and impacted on, with clear commentary on the lessons learned. Also, frequently occurring electrical incidents involving equipment can lead to evolving manufacturing and engineering designs that could eradicate further injuries and deaths caused by these products.

(d) *Design for safety* can be achieved by the implementation of RCD's and low touch voltage design. A set of, touch voltage design analysis equations, developed by Barrett et al [**10**] can be used by designers and installers to achieve a low touch voltage design.

(e) *Periodic testing and inspection*, CENELEC document ES 59009, published in 2000, is the only document prescribing periodic inspection in domestic electrical installations. This specification recommends inspection at intervals not exceeding 10 years. However, the standard is not mandatory, and being an ES-document, member states are not obliged to adopt it as national standard. In the UK, a home information pack [**87**] (also known as a HIP) is now compulsory for most homes on the market in England and Wales. A HIP consists of a set of legally required documents that provides the buyer with vital information on a property and must be provided by the seller. Currently, an electrical safety report is not one of the compulsory documents required in this pack. However, implementation of the CENELEC standard and the UK's HIP, inclusive of a compulsory electrical safety report as a very minimum could significantly improve domestic electrical safety.

(f) *Electrical installation information pack*, similar to the operating manual for intruder alarms, the occupants of the home should be provided with a pack consisting of information on how to operate, maintain, test and isolate electrical systems and appliances to enhance safety.

4.6 Conclusion

It is fair to say that when compared with other kind of accidents in a domestic environment, electrical accidents in the home are relatively infrequent events. Over the 3-year period examined in this article an estimated 8698 electrical accidents occurred. This translates to a yearly incidence rate of approximately 1 per 20 000 of the population in the UK.

Electricity is generally regarded as a faithful servant by homeowners, yet from the data gathered in this article, the home appears to be the number one location for electrical deaths. Although it is far from being one of the top hazards in the home, there is still capacity for advances in electrical safety. One prime example being the new RCD requirements that was proposed by BS7671 JPEL64 committee to guard against faults inflicted on twin and earth cables installed without any mechanical protection against nails/screws inside plasterboard walls.

The fact that every electrical accident has the potential to be fatal cannot be understated. To improve on current injury and death rates in the home, everyone must understand how people are exposed to electric current and the protective measures that are required to keep them safe. Domestic electrical safety needs a multi-dimensional approach. The key findings are:

- The home was singled out as one of the prime locations for electrical accidents that resulted in deaths in the UK for the years investigated.
- Approximately 46% of all fatalities due to electric current occur in the home, in England and Wales.
- In England and Wales, approximately 15 people die per year due to electric current in the home (1999–2005).
- Approximately 2900 people attended A&E per year as a result of electric current in the home causing shock or burn in the UK from 2000 to 2002.

- 25–34 year olds (25%) are the main at risk group to electrical injury in the home. 0–4 year olds (11%) were also highlighted to be a vulnerable group. This topic warrants further investigation.
- In the home, the electrical injury rate for males is 1.5 times than that for females. However, the fatality rate due to electricity-related accidents is nine times higher for males than the corresponding rate for females. This topic also warrants further investigation.
- The leading location for electrical injury in the home is the kitchen.
- The majority of electrical injuries (60%) were found to occur during household work activities, for example, 'maintenance/ DIY/repair', 'household activities' and gardening.
- Light/Lamps are the leading products involved in domestic electrical injury.
- Regulated periodic maintenance/inspection of the fixed electrical installation, aligning it with the current standards of the day could further reduce electrical accidents.
- It is recommended that the accident interviews should be made mandatory as part of A&E's normal record.
- It was concluded that the new 17th edition IEE Wiring Regulations (BS7671:2008) coupled with best practice of de-energising equipment before maintenance/repair and corrective maintenance on electrical appliances could significantly reduce injury and death rates.

Chapter 5

Analysis of Touch Voltages in low Voltage Electrical Installations

5.1 Introduction

Protection against electric shock in our homes and work places is one of the most important priorities for electrical services engineers who are now designing electrical installations to conform to the requirements of the 17th edition IEE Wiring Regulations BS7671:2008 [**101**] and ET101:2008 [**74**]. As prescribed in these regulations, the earthing arrangements, the characteristic of the protective devices and the impedance of the conductors concerned shall be co-ordinated under earth fault conditions such that the *voltages* between simultaneously accessible conductive parts shall be of limited magnitude and duration to prevent risk to human life. These *voltages* which can develop are the so called ***touch voltages*** and will be the subject of this chapter. However, there are few publications and little information available on the theory describing how touch voltages of a dangerous magnitude can develop and can be possibly transferred from a faulty circuit onto the exposed conductive-parts of Class 1 equipment of another healthy circuit. This chapter summarises the theory of transfer touch voltage and analyses many of the significant factors related to the development of a safe touch voltage design.

Some of the notable features of this chapter include; a touch voltage case study, the outcome of which suggests that there is sufficient evidence to show that it may not be sufficiently safe to use the nominal external earth fault loop impedance quoted by the electricity utility companies for adopting a low touch voltage design; an original touch voltage sensitivity equation which can be used as a powerful tool for designers and installers of electrical installations to investigate and identify the sensitivity of resulting touch voltages of any electrical circuits; following on from this, two software tools, developed by the author to aid electrical designers are outlined. The 'touch voltage simulator' application presented is a powerful tool for designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters. It can also be used to identify the sensitivity of resulting touch voltages to any variations in the four main design parameters U_{oc} (open circuit voltage of the mains supply), Z_e (earth-fault-loop impedance external to the faulty circuit), R_1 (phase-conductor resistance) and R_2 (circuit-protective-conductor resistance) and finally the 'interactive touch voltage charts' can plot interactive graphs, which can be used as visual aids for engineers to ascertain how the touch voltage could fluctuate with variations in the major design parameters at the design stage.

5.2 Touch Voltage Concept

For occupants of buildings in the built environment to be protected against electric shock there are some basic requirements. Live parts (such as energised conductors) must not be accessible and conductive parts (such as metal pipes or enclosures of class I appliances), which are accessible, must not be hazardous live, under both normal and single fault conditions. Various wiring regulations such as BS7671:2008 outline the methods of protection against these risks, which are, basic protection (formerly known as protection against direct contact) and fault protection (formerly known as protection against indirect contact). An individual description of each method of protection is well documented in various publications and further explanation is unwarranted at this point.

However, protection against electric shock by automatic disconnection of supply (ADS), which gives rise to touch voltages (for the purposes of this chapter we shall define 'touch voltage' as a difference in voltage potential being experienced by a person who makes contact with more than one conductive part simultaneously, which is not normally energised) is a universally agreed protective measure used by electrical designers for general applications and implemented in approximately 95% of all installations in the UK and Republic of Ireland.

To outline the touch voltage concept and illustrate how such a voltage can develop, a schematic diagram for an installation utilising a TN-C-S system of earthing will be utilised as shown in Figure 5-1. The system shows an external source of energy solidly bonded at the neutral. Within the installation itself all exposed conductive parts are connected to the main earth terminal via a circuit protective conductor and all extraneous conductive parts are connected to the main earth terminal via the main equipontential bonding conductors. The main earthing terminal is connected via an earthing conductor and the PEN (protective earth and neutral) conductor to the source earth

U_0 = nominal voltage to earth, V
U_{OC} = the U_{OC} value will depend on the nominal supply voltage U_O (which is fixed by the electric utility supplier), V
Z_T = internal impedance of transformer, Ω
Z_1 = impedance of the phase conductor, Ω
Z_2 = impedance of the circuit protective conductor, Ω
Z_3 = impedance of the supply cable phase conductor, Ω
Z_4 = impedance of the supply cable protective conductor, Ω

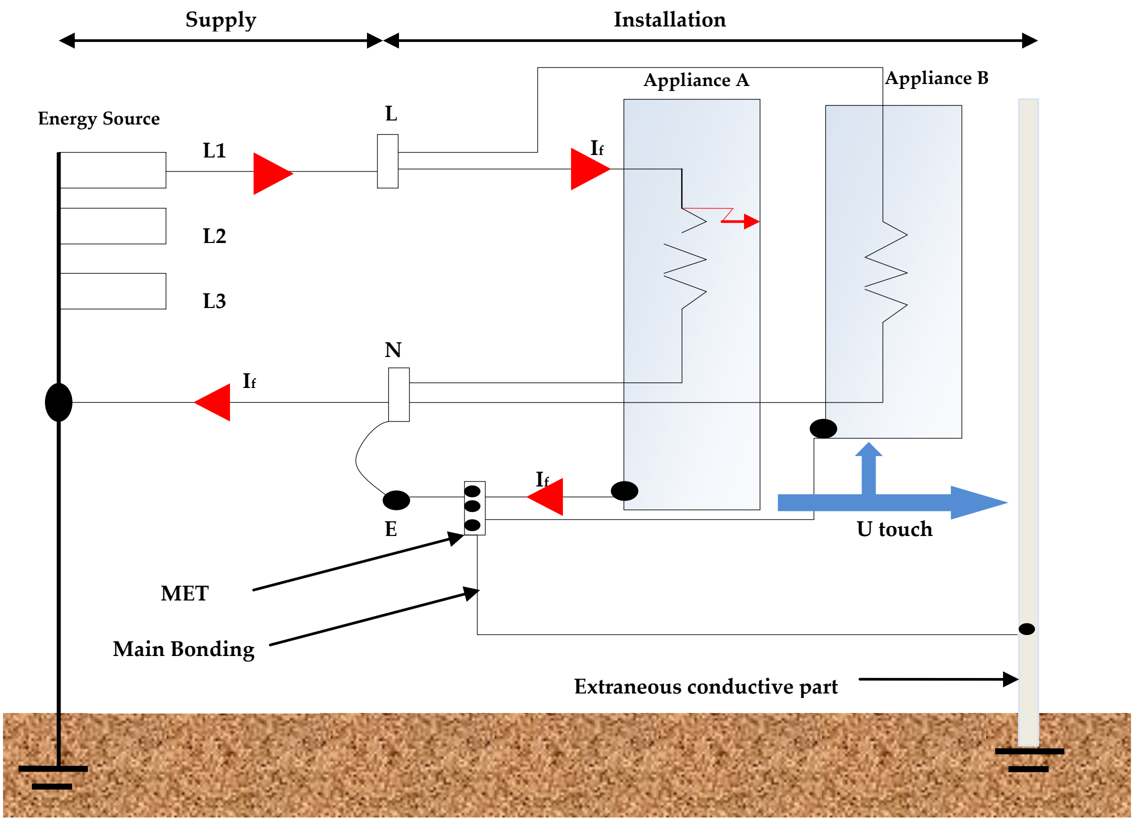


Figure 5-1 Schematic diagram for a single fault in a TN-C-S system

If we consider the situation where a breakdown of insulation occurs between a live conductor and the exposed conductive part of appliance A (class I appliance) and assuming the fault has negligible impedance and that a complete open circuit has occurred, the conductive frame of the appliance will rise to a potential above true earth which is determined by the impedance parameters of the earth fault loop concerned.

Under these conditions the fault current will be given by:

$$I_f = \frac{U_0}{Z_T + Z_1 + Z_2 + Z_3 + Z_4} = \frac{U_0}{Z_s}, (A) \qquad (5.1)$$

where Z_s is the impedance of the complete earth fault loop.

The external fault loop impedance, Z_e, is the phasor sum ($Z_T + Z_3 + Z_4 = Z_e$) of the constituent parts of the earth fault loop up to the origin of the installation. This would include the impedance of the transformer secondary winding, the impedance of the line conductor of the supply cable and the earth fault back to the earthed point of the supply transformer.

Hence,

$$I_f = \frac{U_0}{Z_e + Z_1 + Z_2} = \frac{U_0}{Z_s}, (A) \qquad (5.2)$$

For cables which have conductors of cross sectional area not exceeding 35 mm^2, their inductance can be ignored [**100**] such that where cables are used in radial circuits the fault current can be calculated as follows:

$$I_f = \frac{U_0}{Z_e + R_1 + R_2}, (A) \qquad (5.3)$$

Therefore, if the situation is considered where an earth fault occurs as shown in Figure 5-1, and the person at risk simultaneously touches the exposed conductive part of the appliance and an extraneous conductive part but is inside the equipotential zone and hence not considered to be in direct contact with the general mass of earth, the touch voltage U_t they will be subjected to is as follows:

$$U_t = I_f R_2, (V) \qquad (5.4)$$

U_t will also exist between an appliance A and healthy appliance B (even if this appliance is not energised). There will be no voltage between appliance B and the extraneous conductive part.

If the person at risk is within the so called equipotential zone and due to the probability that he/she would more than likely have some footwear and considering the nature of flooring, it can be assumed that person will be well insulated from true earth. As a result the shock current would be almost completely hand to hand.

An examination of the complete earth fault loop under fault conditions as shown in Figure 5-2 should allow one to appreciate that the supply voltage will be distributed around the complete loop in accordance with ohms law. In other words the voltage dropped across each section of the loop will be dependent upon the impedance of each section of the loop and hence the touch voltage can be calculated using a voltage divider circuit as shown in Equation 5.5 (and explained in more detail in section 5.5).

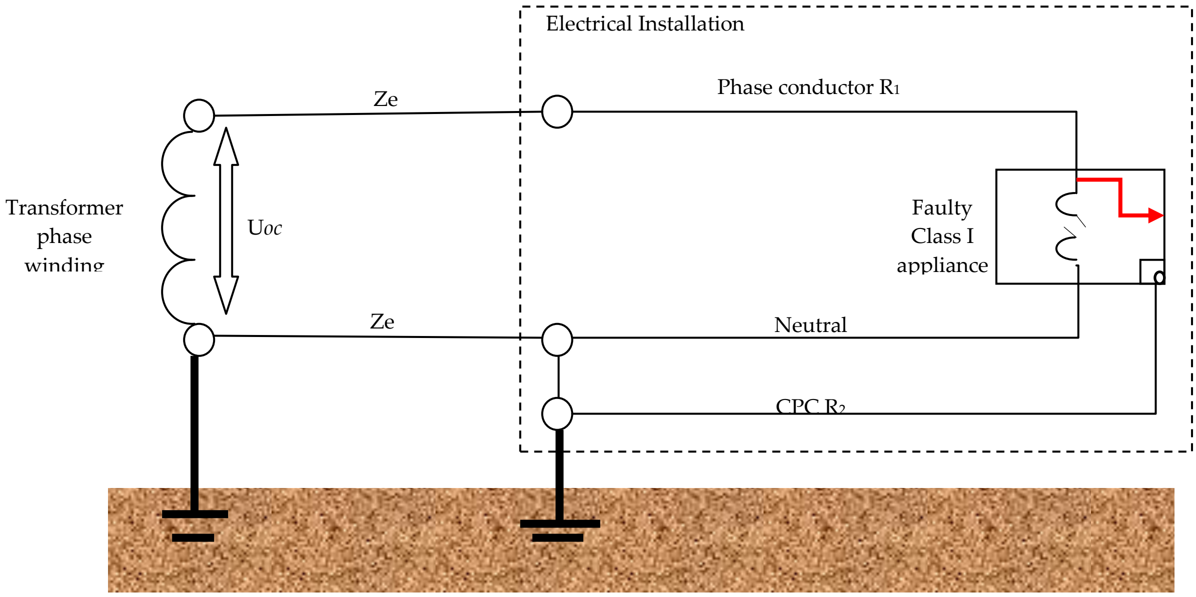


Figure 5-2 Distribution of voltage under earth fault conditions

From this it can be concluded that if the impedance between the exposed conductive parts of an appliance and true earth is high, then the voltage between the exposed conductive parts and true earth will be a significant proportion of the supply voltage. It also follows, that even though the overall fault loop impedance will determine the fault current, the fault current will not determine the distribution of the voltages.

$$U_t = U_{oc}\frac{R_2}{Z_e + R_1 + R_2}, (V) \tag{5.5}$$

The touch voltage equations developed to this point are suitable to determine the touch voltage in a radial circuit. However ring circuits are still very common in the UK and Ireland and the ability to determine the touch voltage in such circuits is of equal importance. Of course the marked difference from a designer’s viewpoint when a ring circuit is considered is the parallel path offered to the fault current by the phase conductor feeding the fault and also the parallel path offered by the cpc (circuit protective conductor) leaving the fault returning to the MET.

Hence, assuming x is used as the fractional value from the fault to the consumer unit, then (1-x) must be the fractional length of the other parallel path back to the consumer unit.

Knowing for parallel circuits that $R_{total} = \frac{R_X R_Y}{R_X + R_Y}$, where R_x and R_y are two resistances in parallel and applying the fractional lengths above to the cpc. A value for R_2 is obtained, where R_{2total} is the total resistance of the cpc (before connecting the two ends to complete a ring).

Therefore,

$$R_2 = \frac{x(1-x)R_{2total}^2}{xR_{2total}+(1-x)R_{2total}} = \frac{x(1-x)R_{2total}^2}{xR_{2total}+R_{2total}-xR_{2total}} = \frac{x(1-x)R_{2total}^2}{R_{2total}} = x(1-x)R_{2total}$$

By the same method, $R_1 = x(1\text{-}x)R_{1total}$

Substituting these values into Equation 5-5, an expression for determining the touch voltage in a ring circuit is obtained:

$$U_t = U_{oc}\frac{x(1-x)R_{2Total}}{Z_e + x(1-x)R_{1Total} + x(1-x)R_{2Total}}, (V) \tag{5.6}$$

Furthermore, when the denominator in Equation 5.6 is at a minimum the touch voltage will be at a maximum. It can be readily shown that this occurs when x = 0.5 i.e. at exactly the midway point in the cable. Knowing this, an equation for the maximum touch voltage in a ring circuit can be obtained:

$$U_{tmax} = U_{oc}\frac{0.25R_{2Total}}{Z_e + 0.25R_{1Total} + 0.25R_{2Total}}, (V) \tag{5.7}$$

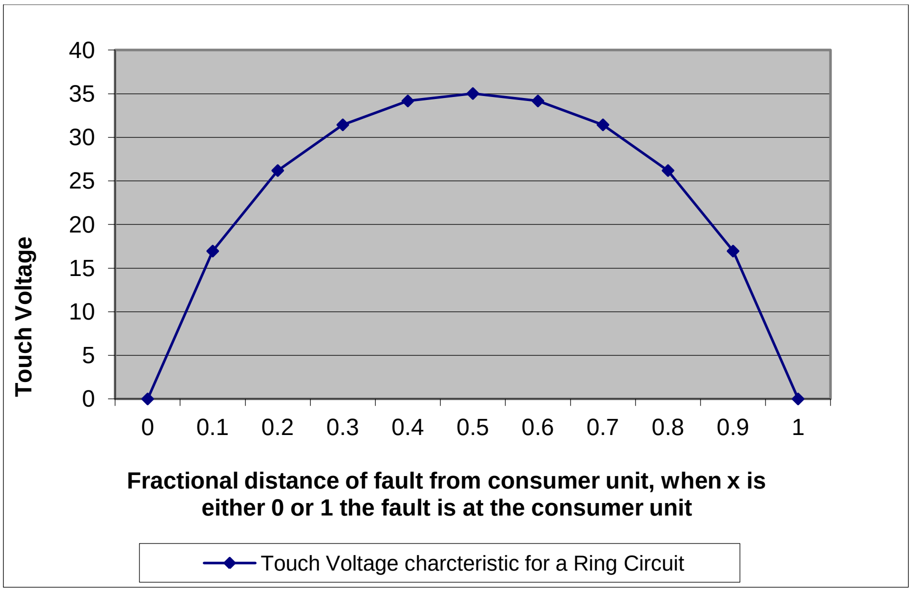


Figure 5-3 Touch voltage characteristic for a ring circuit

5.2.1 Touch Voltage considerations

Very often, much emphasis is placed on the actual return path of the earth fault current to the supply source. For different installations, this return path can vary ranging from a path via a dedicated earthing conductor to a path via dedicated earth electrodes or indeed a hybrid of both. What is of significance when we consider this return path, is the *impedance,* whether this is via the protective conductor or the combined impedance of the earth electrode at the installation and at the supply transformer as this is what will govern the voltage around the earth fault loop.

As an example, consider a domestic installation using a TN-C-S system of earthing which has a dedicated earth electrode and low impedance PEN conductor. One could reasonably assume that the fault current has two alternative paths back to the energy source, however unless the earth electrode has an extremely low resistance it will have very little impact on the distribution of voltages around the circuit. In contrast, in an installation with a very detailed earth grid which has a low impedance to earth, the distribution of voltages will be affected due to significant reduction in earth fault impedance.

In the preceding text, reference to an equipotential zone and true earth has been made and for the purposes of clarity it is important that these are clearly outlined so that a useful understanding of touch voltages can be developed.

If an effective equipotential zone is established, there should be no lethal potential differences a person can reach within that zone. A misconception commonly associated with main bonding (discussed in detail in section 5.3) is that it creates an equipotential zone such that under earth fault conditions exposed and extraneous conductive parts attain the same potential with respect to earth so that a person would not be subjected to an electric shock. From Figure 5-1 above, and our discussion on touch voltages to date, it is obvious that this is not strictly true. Indeed voltages as high of at least half the nominal voltage maybe attained under certain conditions. It is worth noting that if in addition to main bonding, supplementary bonding is installed, touch voltages under earth fault conditions may be extremely low (see section 5.3.4).

If we are to consider true earth we must initially examine the connection that is required to interface an electrical conductor (earth rod) to the general mass of earth. One of the fundamental requirements of an earth electrode is to provide a path with a high current capacity with relatively low impedance so that voltages which develop under fault conditions are not hazardous. To achieve this low impedance connection requires a highly conductive, corrosion resistance conductor buried at such a depth that it will neither become frozen or dry out. It should also be large enough to contact an appropriate volume of earth and in such a position that it will not be influenced by other earthing systems. Further to this, by reducing the current density in the soil by having contact with a large volume of earth, results in a reduction in the resistance to earth [**167**]. What has been just described is commonly referred to as a clean earth, of course problems only ensue when a connection is made between such an earth electrode and equipment.

If the situation where an earth fault current flows through an earth electrode is considered, a voltage determined by the circuit parameters will develop at the connection point of the electrode. Therefore, the electrode is not at the same potential as the general mass of earth. Under such conditions a voltage gradient results as ones moves away from the electrode. The gradient which develops is variable and will be determined by several factors, notably the electrode construction and the resistivity of the soil. At a certain distance away from the electrode, the voltage gradient will become negligible and this can be considered true earth. One resulting hazard this voltage gradient produces is known as step potential or step voltage and can be defined as the difference in earth surface potential experienced by a person when their feet are outstretched at a distance of approximately one metre apart, this is potentially very dangerous producing a foot to foot shock risk.

From the above discussion it can also be seen that exposed conductive parts within the installation may rise to a potential above true earth and dependent upon their location within the fault loop there may be a difference in potential between them. This possible difference in voltage potential is the touch voltage. It also worth noting, in light of the above discussion regarding step voltages that for a given installation, the max value of touch voltage can be up to two or three times greater than the maximum value of step potential [**28**]. From this it is possible to conclude that if an installation is deemed safe against touch voltage, it will normally be safe against step voltages.

Where touch voltages have been considered to date, it has been automatically assumed that any fault which gives rise to touch voltages occurs on the LV side of the supply system. However this is not always true, faults on the HV side of the supply system can also lead to dangerous touch voltages developing in a low voltage electrical installation. Nowadays, it has become common practice in densely populated areas to bond the HV and LV earthing rods. However, there are some specific design requirements that must be adhered to for this to be tolerated. ET101 [**74**] outlines these and provides defined levels of fault voltages U_f that are tolerable (Fig. 44.1 ET101) U_f can be defined as the voltage which appears in the low voltage system between exposed conductive parts and earth for the duration of the fault. In a properly designed installation, the touch voltage will be less than this value. In the case where a HV fault occurs, the LV earth connection will rise to a potential above true earth referred to commonly as a rise of earth potential or a ground potential rise. The net effect will result in the exposed conductive parts of the installation attaining a potential above true ground.

5.3 Earthing and Bonding

To ensure a negligibly small risk of electric shock in the built environment, designers and installers adopt good wiring practices and abide by the relevant national wiring rules, e.g. NEC 2008, BS7671: 2008, ET101:2008 or IEC 60364 to enable them to produce a safe electrical installation. As already highlighted, it has been agreed universally that for general applications, an earthed and potentially equalised (i.e. main-bonded) system will afford protection against electrical shock hazards. The circuit-protective-conductor (cpc) of a final circuit provides a dedicated low resistance and high efficiency earth fault current return path to the supply source. An effective low impedance earth-fault current return path ensures an almost guaranteed operation of the overcurrent and/or shock protection device thus disconnecting the electric shock energy source under earth-fault conditions, limiting the duration of the touch voltage. In addition the main bonding will limit the magnitude of the touch voltage one can receive across two simultaneously accessible bonded conductive parts. Therefore, the use of proper earthing (i.e. grounding) and bonding techniques remains the best way to protect people and equipment against electric shock hazards. However, when an installation has a large number of interconnected circuits and exposed-conductive-parts, a fault in another circuit can result in a touch voltage of a dangerous magnitude and duration being transferred onto a circuit feeding healthy equipment with exposed conductive-parts.

Evident from the above is the importance 'earthing' and 'bonding' and also the ability to differentiate between them. These terms are commonly misunderstood by the electrical industry. Indeed, all over the world earthing and bonding have different interpretations. Some relate the terms to a solidly formed link with the general mass of earth while many others refer to a point of common connection in the electrical installation. Added to this, in North America the term 'grounding' is commonly used, this is equivalent to 'earthing' for those of us who live in Europe.

When we consider earthing it is important to distinguish between connecting one point of the supply system (generally the star point) to the general mass of earth and the provision of a path for an earth fault current to return to the earthed point of the system. The latter process being achieved by connecting metallic enclosures and frames (exposed conductive parts) in the installation to the general mass of earth by means of conductive materials or via the provision of a fault currying conductor back to the earthed point of the system. ET101 [**74**] defines earthing as "the connection of the exposed conductive parts of an installation to the main earthing terminal or bar". Of course, using the word earthing with regard to exposed conductive parts can be misleading, many believing that by so doing these elements will be held at earth potential. However, this is not strictly true [**117**].

Bonding is a related process and can be taken to mean the process of interconnecting two conductive parts which may be exposed or extraneous conductive parts (e.g metallic water pipes) which may not form part of the electrical installation. ET101 [**74**] defines equipotential bonding as "electrical connections intended to maintain exposed conductive parts and extraneous conductive parts at the same or approximately the same potential, but not intended to carry current in normal service". It should be noted that bonding does not ensure simultaneously accessible conductive parts remain at the exact same potential under all conditions

In general, earthing and bonding have three main objectives: [**36**]

- *Safety*: protection of human and animal life by limiting step and touch voltages to safe values. This is achieved by limiting the magnitude and duration of voltages which may appear on metallic surfaces under fault conditions
- *Protection of building and electrical plant/equipment*: This is primarily achieved by ensuring fault currents are large enough to achieve effective reaction times in protective devices.
- *Correct operation of equipment*: this is achieved by a noise free electrical reference plane.

When the first electrical distribution system was set up in the late eighteen hundreds by Edison in the USA, he only used one insulated phase conductor and the earth as the return conductor. As a result the flow of electric current in the earth gave rise to electric shocks to horses, and to his employees as they dug beside the underground system [**159**]. Evidently the flow of current in the earthing and bonding paths in any building can give rise to dangerous step and touch voltages which could potentially put the occupants at risk. However, under normal conditions, earthing conductors (e.g circuit protective conductors) should not carry any current with the exception perhaps of some leakage current. The only time they carry current is during abnormal conditions, when there is a faulty appliance etc which will become a potential shock or fire risk.

5.3.1 Earthing Systems

ET101 [**74**], BS7671 [**101**] and BS7430 [**28**] have all adopted the internationally agreed classification of earthing system types: TN-C-S, TN-S, TN-C, TT and IT. Irish practice is in harmonisation with the UK and other European countries and a detailed description can be found in part 3 of ET101 [**74**]. In this classification system the first letter T or I is used to classify the earthing arrangement of the energy source. The second letter will be either T or N and is used to denote the earthing arrangements of the electrical installation, while the third and fourth letters are used to indicate the connection arrangement of the neutral and protective conductors. It is not uncommon to find different earthing systems utilised within the one country or indeed within one installation where perhaps an outbuilding could have with an alternative earthing system to the main building.

5.3.2 The Concept of Earthing

Earthing is not essential to the operation of a supply system. However, there are some very good technical and economic reasons for doing so. One of the main hazards to humans in an electrical installation is that a current will flow through the region surrounding the heart and cause ventricular fibrillation.

Therefore one of the most predominant reasons for providing a LV earthing system is to reduce the touch voltage of exposed conductive parts under earth fault conditions. Most European countries utilise the TN or TT system. Norway is an exception and is an example of a country that operates an un-earthed supply system mainly due to the great difficulty in achieving a low electrode resistance due to very cold and frozen earth conditions coupled with the fact that many of the domestic dwellings in this country were built using wood, and hence earthing for the reduction of potential shock risk was historically of less importance [**117**]. If we consider an unearthed electrical system and a hypothetical situation where no live conductor ever came in contact with earth, the risk of an electric shock from a live conductor to earth would not exist and would only exist if one was to come in contact between two live conductors simultaneously. Unfortunately though, we know with pretty much certainty that at some point in an electrical systems life span a live conductor will come in contact with earth, whether this is from mechanical damage, breakdown in insulation or an un-insulated overhead line falling to ground, it is inevitable. In this event, where a live conductor comes in contact with the earth in an unearthed system, there must be means to ensure that the supply is disconnected if a second fault were to occur. Otherwise the magnitude of the potential shock voltage could realistically be equivalent to the line voltage of the supply system.

Unearthed systems are classified as IT systems in ET101 [**74**] and BS7671 [**101**] and such systems require indication such as an alarm to alert trained staff that an earth fault has occurred which allows them rectify the problem. The major benefit of an unearthed system such as this is that under earth fault conditions, disconnection from the supply is not required and the installation can continue to run uninterrupted. However, there must be provision of protection in the case of a second earth fault. IT systems are generally not permitted to be used by utility suppliers to distribute electricity to the general public. It is used within an electrical installation where security of supply is important and where there is a disciplined well trained staff.

In the early part of the nineteen hundreds, equipment installed with a two wire cable/power supply were readily accepted to be safe from an electric shock hazard due to the fact that the metal casing was not connected to either wire of the supply cable [**159**]. This is commonly referred to as a “floating case”. In an earthed system which is by far the most common, a very serious shock risk would be introduced if the phase conductor came into contact with the so called “floating case”. The introduction of a connection between the “floating case” and the neutral terminal of the appliance partially reduced this shock risk. However, it is important to recognise that making such a connection results in a TN-C system and hence under fault conditions the case to neutral connection provides a low impedance path for the fault current via the neutral conductor. As it transpired, earthing of the exposed conductive parts of appliances was first introduced in 1924 with the publication of the eight edition of the IEE wiring regulations [**159**].

From a touch voltage perspective even under normal conditions, the use of a TN-C system as described above will introduce a touch voltage with a possible magnitude of up to fifty percent of the phase to earth voltage between the case of an appliance and extraneous conductive parts. Also, in the event of a broken neutral the touch voltage could rise as high as the supply voltage. This level of safety seems hard to comprehend in a modern world and ultimately TN-C systems were phased out. Nowadays only under specifically agreed conditions with the utility supplier may such a system be employed.

Today most European countries employ either a TN or TT system, this is achieved when one point of the supply system is earthed (generally the star point of the distribution transformer). Under earth fault conditions in such systems, an earth fault current will flow and the circuit loop will comprise of, a phase winding of the distribution transformer, the phase conductor to the point of fault and is completed by a protective conductor in a TN system back to the earthed point of the supply system. In contrast in a TT system the return path from the point of fault will be generally through the installation earth electrode and the systems earth electrode resulting in a significantly lower fault current. The fault current that flows in such systems allows the operation of protective devices to interrupt and clear the fault from the defective section of the system. The circuit protective device that has operated identifies the circuit which is faulty and allows that problem to be rectified while also protecting the occupants from a potential shock risk and possible fire.
A common misconception related to earthing is to suggest that if an appliance is earthed it is not possible to receive an electric shock. Of course this is clearly untrue as can be seen from the touch voltage that develops in Figure 5-4 which will persist until the fault is interrupted. The goal when earthing an item of equipment is to provide a low impedance path back to the supply source in order that the fault current will have sufficient magnitude to cause the protective device to trip.

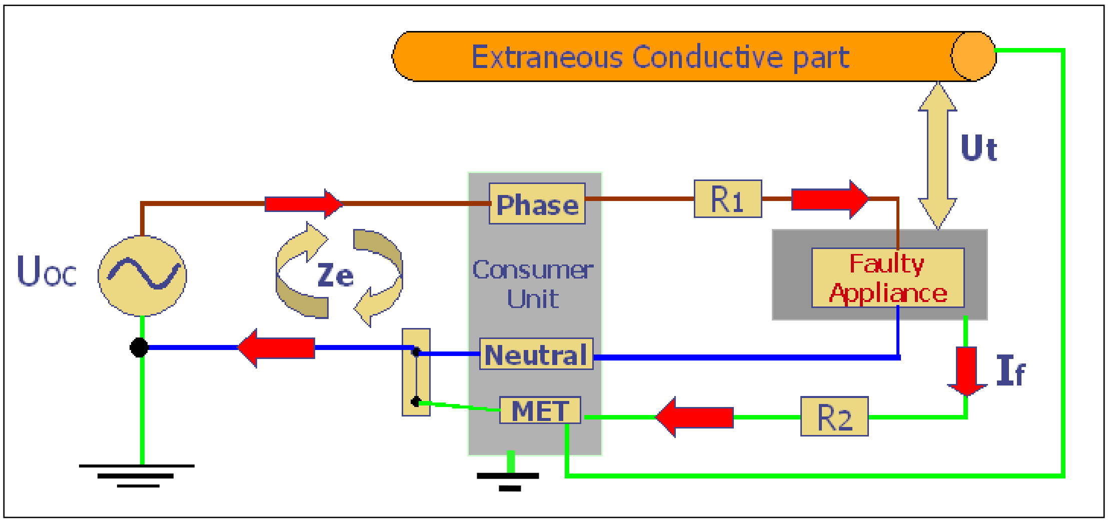


Figure 5-4 Flow of fault current during an earth fault in a TN-C-S system

It is also commonly misconceived that if the touch voltage exceeds 50 V, the installation does not comply with ET101 [**74**] or BS7671 [**101**]. This is not true either, under earth fault conditions touch voltages of up to 50 V and well in excess of this value are commonplace, however compliance with the regulations should ensure that the magnitude and duration of the touch voltages will be such as not to cause danger. It is also important to emphasise that if an installation has been correctly designed and installed using a safe touch voltage design method, a person who simultaneously makes contact with two conductive parts may receive an electric shock in the event of an earth fault. However the electric shock received should not be fatal.

One could argue that the probability of a person being in contact with an item of equipment which suddenly develops and earth fault and simultaneously being in contact with an extraneous conductive part is very low and should not be the basis for this protective measure. However, arguments such as this have not received general support. The opposing argument being that if all extraneous conductive parts are bonded to a main earth terminal and all exposed conductive parts are connected to that same terminal then the person at risk in the case of an earth fault will only be exposed to a hand to hand touch voltage assuming they are well insulated from the general mass of earth [**108**].

If the opposite to the above is examined and the situation where an item of equipment which was intended to be earthed but through poor diligence an earth connection was not made to a class I appliance or through a refurbishment a circuit protective conductor was open circuited, the consequences can be life threatening. In this event and should an insulation failure occur such that a live conductor comes in contact with the frame of a class I appliance, the enclosure or frame will rise to the full phase voltage to earth. The protective device protecting this circuit will not operate due to the simple fact that there is no path for the fault current to flow. Now, should a person make contact with this frame and simultaneously touch another exposed or extraneous conductive part within the installation, they will be subject to a shock current hand to hand which could be potentially fatal. The person at risk could also be subjected to a hand to feet shock current. The shock current in each instance would be dependent upon the impedance of the body at this instance, and also the impedance of the fault path, external to the body. In the absence of supplementary bonding, the only protective device that could provide protection against a potentially fatal shock current would be a residual current device (RCD) that has a suitably rated residual current and disconnection time.

Another scenario worth consideration is the possibility of the earth connection in a power supply cable becoming detached from the earth pin and coming in contact with the phase conductor. In such an event the operation of a portable appliance would be unaffected. However the exposed conductive parts of such a portable appliance will be raised to the full phase voltage to earth. If a person were to simultaneously come in contact with the portable appliance and an exposed or extraneous conductive part, they would be subjected to a touch voltage hand to hand equal to the full phase voltage to earth which could be potentially fatal. Once again, the only means of protection in such an event would be by a suitably rated RCD.

Evident from the above analysis is that in order to provide protection against indirect contact by using overcurrent protective devices, it is of paramount importance that all protective conductors are properly installed and are of sound construction both electrically and mechanically. It is worth bearing in mind that this should remain the case for the entire life of the installation if it is to be deemed safe. Of course in all parts of the built environment, over time alterations, maintenance and renovations take place which do influence the integrity of the electrical installation and undoubtedly, if an electrical installation is to remain fit for purpose, it should be tested and inspected on a periodic basis.

5.3.3 Main equipotential bonding

Both ET 101 [**74**] and BS 7671 [**101**] require extraneous conductive parts such as the structural metal work of a building, metal gas pipes, water pipes, metal sinks etc to be bonded as close as practicable to their points of entry to the building. In the absence of such bonding a person who simultaneously comes in contact with the metallic frame of a defective class I appliance and an extraneous conductive part will be exposed to a voltage potential equivalent to the fault voltage. With main equipotential bonding installed, the touch voltages between exposed conductive parts and extraneous conductive parts will be significantly reduced or removed. Also, any fault currents flowing in the earth external to the installation will not introduce any touch voltages via earthy metallic pipes within the installation as all exposed and extraneous parts should attain the same potential.

The benefit of main equipotential bonding is best illustrated where only *earthing* is employed in both a TN and TT installation under fault conditions. Typical values of resistance are utilised to analyse both these systems. The circuit used as illustrated in Figure 5-5 comprises a metallic framed portable appliance with a 1.5mm^2 two metre long flex, plugged into a standard socket outlet 25 metres from the distribution board. The cable used in the radial socket circuit is a standard twin with cpc (circuit protective conductor), 2.5mm^2/1.5mm^2 combination. The external fault loop impedance will be taken as 0.2 ohms.

Examining the TN system, the total fault loop can be calculated to be 0.7334 ohms, using a U_{oc} of 240 V, the fault current is approximately 327 amps. By applying ohms law, the voltage dropped across each component part of the circuit can be determined. The voltage drop across the supply phase conductor and the system protective conductor is 32.7 V. 60 V is dropped across the installations radial socket phase conductor. 7.9 V is dropped across the phase and protective conductor of the appliance's flex, 99 V is dropped across the cpc of the cable feeding the radial socket circuit. From the diagram it can be seen that voltage potential from true earth to the exposed conductive part of the faulty appliance is 7.9 + 99 + 32.7 = 139.6 V

If the same faulty circuit is now considered using a TT system of earthing as outlined in Figure 5-6, it is also possible to determine the voltage drops around the circuit. In this instance, it will be assumed that the combined resistance of the consumer's earth electrode and the electricity supplier's earth electrode is 15 Ω. Repeating a similar calculation to the one above gives a fault loop impedance of 15.63 Ω. Hence the fault current under such conditions would be approximately 15.35 A. By examining the circuit, it can be found that the potential to true earth of the faulty appliance is 235 V.

Upon examination of these two earthing systems where only earthing is employed, it becomes apparent that earthing through an earth electrode can result in the fault voltage attaining a value close to the phase voltage and in addition by connecting the exposed conductive parts of an installation to the systems earth via metallic conductors does not necessarily mean a safe fault voltage will be attained.

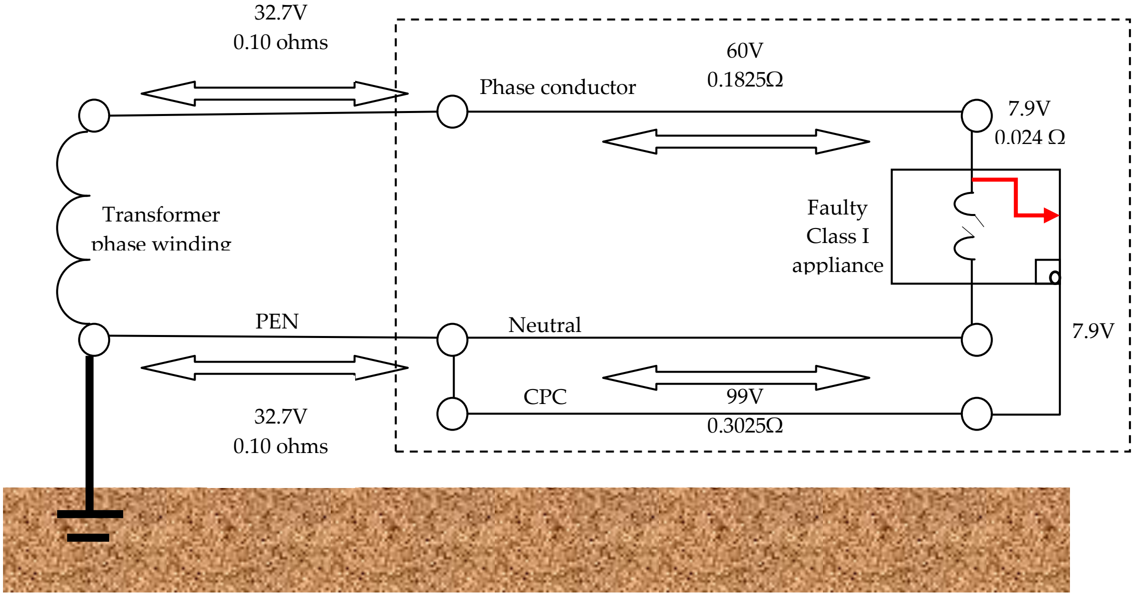


Figure 5-5 Illustration of touch voltage in a TN system in the absence of main bonding

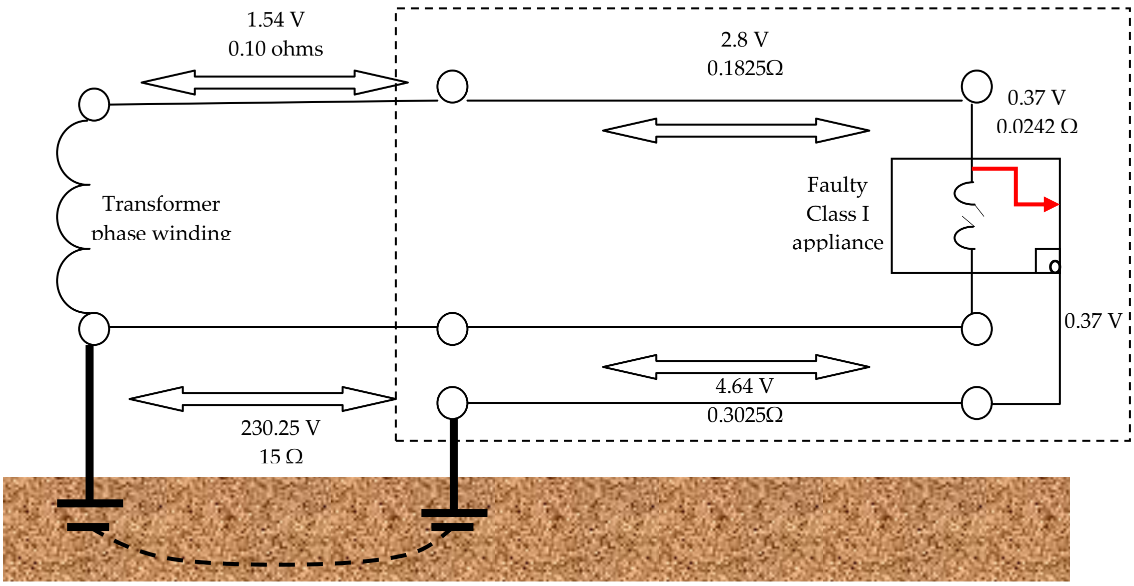


Figure 5-6 Illustration of touch voltage in a TT system in the absence of main bonding

A further potential problem that warrants consideration is the possibility of a broken protective and neutral conductor external to the electrical installation.

Under such conditions as demonstrated in Figure 5-7 below a voltage will be distributed around the circuit as before, however in this case due to the infinite resistance caused by the open circuited neutral, the neutral conductor may attain a potential in the region of phase voltage to earth. Also, if as shown in Figure 5-7 the earth terminal is connected to the neutral as would be the case in a TN-C-S system, the earth terminal and all the exposed conductive parts connected to that terminal would rise to phase voltage above earth.

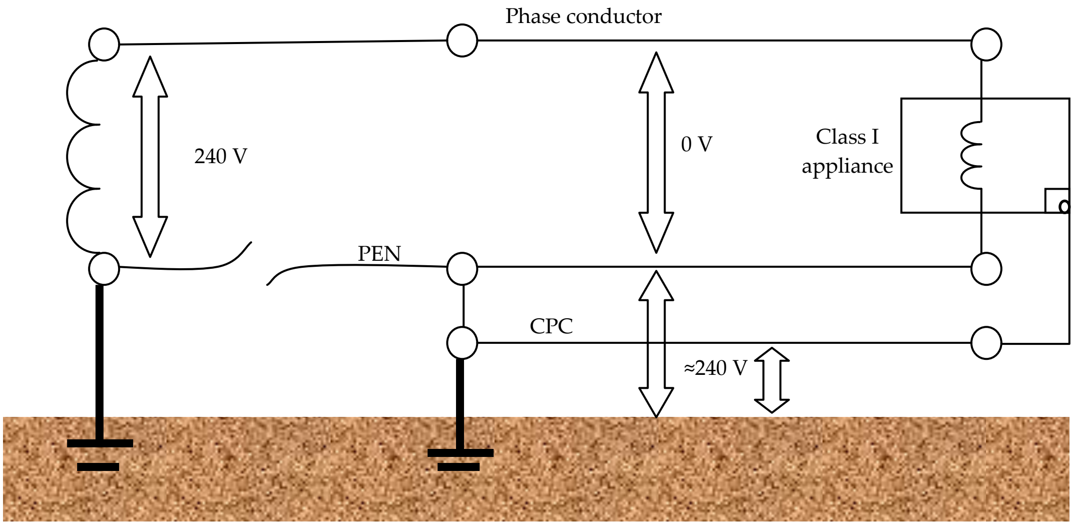


Figure 5-7 Illustration of touch voltage in a TN system the event of a broken neutral

From the discussion above it becomes clear that in the absence of main equipotential bonding, metallic objects such as water and gas pipes within an installation which may be in good contact with earth will present a danger. Indeed a person who simultaneously comes in contact with a faulty exposed conductive part and for example an earthy metallic gas main may be subjected to the full fault voltage. From our calculations above, these voltages are undoubtedly dangerous. It is worth noting that these values are by no means worst case scenarios and values well in excess of what were demonstrated are attainable.

Fortunately, the introduction of main equipotential bonding can significantly reduce the touch voltages attainable. If we take our TN system outlined in Figure 5-5, with the implementation of main equipotential bonding the touch voltage will be reduced from 140 V to 107 V (note: this is still dangerous). In our TT system outlined in Figure 5-6 the touch voltage will be reduced from approximately 235 V to 5 V and in the case of the open circuited PEN conductor outlined in Figure 5-7 the touch voltage will be reduced to practically zero. Hence the increased safety achieved by virtue of main equipotential bonding conductors is easily recognised.

Another notable benefit main equipotential bonding offers is in the event of an earth fault occurring on the supply cable feeding the installation and also in the event of an earth fault occurring in another installation served by the same cable. When this happens, the main earthing terminal of the installation will attain some value of potential above true earth, however in a correctly installed installation all exposed and extraneous conductive parts will also reach the same potential hence alleviating the danger. It should be noted though, if for any reason an extraneous conductive part is not bonded, a 'hole' will be created in the equipotential zone. Therefore in the event of an external fault, a touch voltage will exist between that un-bonded extraneous conductive part and all the other exposed and extraneous conductive parts within the installation which will be held at the same potential as the main earth terminal.

5.3.4 The role of the supplementary bonding conductors

It was shown in Figure 5-5 above, that even when main equipotential bonding is employed a touch voltage will exist between the exposed conductive part of a faulty appliance and other conductive parts within an installation. In a well designed installation under normal conditions this touch voltage should be interrupted in such a time as not to cause harm. However in locations such as bathrooms, kitchens, swimming pools and certain other special locations where the resistance of the human body is reduced, increased safety measures are required. The reduction in body resistance in such locations can be attributed to the presence of water, sweaty conditions etc. Under conditions such as these, even low voltages can cause quite unpleasant electric shocks that can be potentially fatal.

By providing supplementary bonding between all the exposed and extraneous conductive parts in such locations the touch voltage will be significantly reduced. This point is clearly demonstrated in a domestic case study outlined in section 5-7 where the touch voltages were measured in a bathroom in the absence and then the presence of supplementary bonding. The main requirement when installing supplementary bonding is to ensure the resulting touch voltage must not exceed a safe value. (A value of 12 V is often used for locations of extreme low body resistance.) Supplementary bonding will not notably effect the fault voltage, but it will reduce the touch voltage within the location it is installed. Guidance on the minimum size of bonding conductors required and the correct installation methods are provided in various guidance publications produced by the relevant professional engineering institutions and electrical trade associations.

Ultimately, once the prospective touch voltages have been calculated for various fault conditions in a given earthing system it is necessary to determine if the values obtained exceed the recognised safety thresholds. From a designers perspective this requires knowledge of the max disconnection for a predicted touch voltage and this information can be derived from IEC 60479 'Effects of current on human beings and livestock' [**97**]. Various touch voltage threshold for various environmental conditions are derived from this report and as such are inextricably linked to a thorough understanding of touch voltages and hence will be the subject of the next section.

5.4 The touch voltage concept and its relationship to the standards

Standards and safety guidelines have been developed by numerous agencies to protect humans and livestock against electric shocks in installations and electrical products. Examples of such in North America include the National Electrical Safety Code developed by the IEEE [**105**] which contains the rules and provisions for the safety of persons during the installation, operation, or maintenance of electric supply and communication lines and associated equipment. IEEE also produced an ANSI standard for the safe grounding procedures in substations [**103**] and the National Fire Protection Agency published the National Electrical Code [**132**] which provides guidance on the installation of electrical wiring in domestic and commercial buildings. In Europe the IEC (International Electrotechnical Commission) are to the fore in developing electrical safety standards and IEC 60364 'Electrical Installation for Buildings' is the IEC's international standard for electrical installations in buildings. This standard attempts to harmonise national wiring standards. Many wiring regulations across Europe including ET 101 and BS7671 follow the structure of IEC 60364 closely. However many national wiring regulations contain additional language to cater for historical practices that may be practiced in individual countries.

Through the development of IEC 60364 first published in 1970 which examined some of the fundamental concerns related to electric shock and the considerable research (as detailed in chapter 2) carried out on various animals and to a lesser extent on humans, IEC in 1974 published its first initial report titled 'Effects of current passing through the human body'. This report detailed five zones (drawn more or less on an arbitrary consensus) related to the severity of electric shock using a graph which plotted current against time.

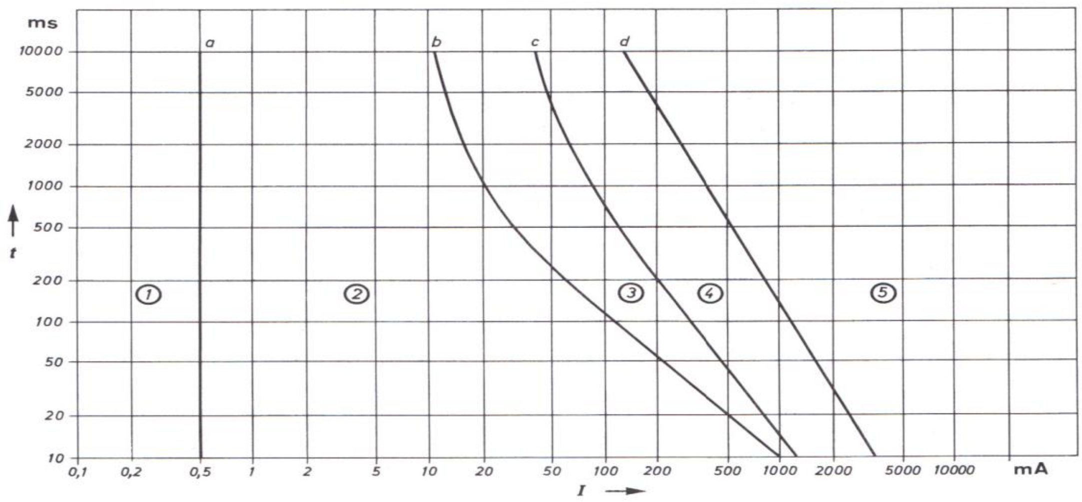


Figure 5-8 Time current zones for alternating current 50/60 Hz IEC Report 479 (1974)

Zone 1 - usually no effects
Zone 2 – usually no pathophysiologicallly dangerous effect
Zone 3 – usually no danger of ventricular fibrillation
Zone 4 – ventricular fibrillation likely
Zone 5 – danger of ventricular fibrillation (probability higher than 50%)

Although the current/time zones produced in this report had considerable merit in terms of the information it provided at the time, the practicality of adopting such information in terms of protection against electric shock proved problematic [**97**].The necessary criterion is the accepted limit of touch voltage. Therefore to enhance the suitability of the information for circuit design purposes, the information contained in the graph was transformed into a more appropriate touch voltage duration curve, which plotted prospective touch voltage against maximum disconnection time. The graph was developed on the basis of certain environmental conditions and body resistance. (It is important to emphasise at this point however, that the application of ohms law is not straightforward when developing a touch voltage threshold, as body impedance is a function of many variables including path of the current, area of contact, voltage across one's body, level of moisture in the contact area and so forth.)

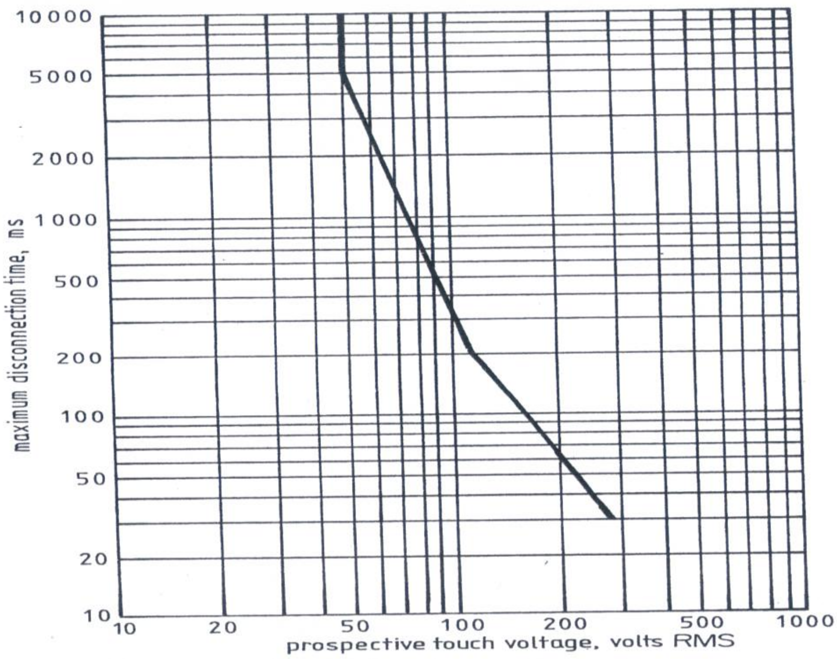


Figure 5-9 Early touch voltage duration curve [108]

The touch voltage curve developed was intended to be utilised for circuits supplying portable equipment while circuits supplying fixed equipment had no specified touch voltage limit and a maximum disconnection time of 5 seconds. Even still, implementation of the touch concept still proved troublesome, therefore when CENELEC (European Committee for Electrotechnical Standardisation) adopted the IEC requirements, an agreement evolved whereby each member country could make their own interpretations in terms of applying the concept [**108**]. As a result in the UK and Ireland the relevant national wiring authorities introduced a maximum disconnection time of 0.4 seconds for circuits supplying portable equipment under normal conditions and a maximum disconnection time of 5 seconds for circuits feeding fixed equipment under normal conditions. One notable difference however between ET 101 and BS 7671 was the allowance in the IEE wiring regulation for an increased disconnection time of 5 seconds for circuits supplying portable equipment once the resistances of the circuit protective conductors were limited to certain values as outlined in that document.

The findings of the first edition of IEC 60479 1974 was also based on the evaluation of replies received to a questionnaire related to electrical accidents from several countries [**97**]. The findings of which suggested there was no conclusive evidence that accidents occurred at voltages not exceeding 50 V rms, under normal conditions [**108**]. As a result and as can be appreciated by examining the touch voltage duration curve, for a touch voltage of 50 V rms the disconnection time goes from 5s to infinity. IEC has defined the "conventional touch voltage limit", denoted U_L, as the maximum touch voltage that can be maintained indefinitely under the specified environment conditions. The value used for normal conditions is 50 V AC rms or 120 V ripple free d.c. Lower values may be used for special locations. This value is consistent with an average impedance value of 1700 Ω and a maximum current of 30 mA. Hence from a designer's viewpoint, at a touch voltage of 50 V rms, disconnection for the purposes of protection against indirect contact is not required under normal conditions.

The initial time/current zones as shown in Figure 5-8 did not pass however without criticism. Straight line 'a' represents the threshold of perception while curve b the threshold of let go was incorrectly derived from the physiological law of excitation (I x t = constant). The straight line 'd' relates to Dalziel's assumption for a probability of fibrillation of 50% with curve 'c' more or less arbitrarily chosen between 'b' and 'd'. In the meantime, recognition of the steep decline of the threshold of fibrillation around the duration of one heart beat was beginning to come to the fore all of which led to further revisions of this document

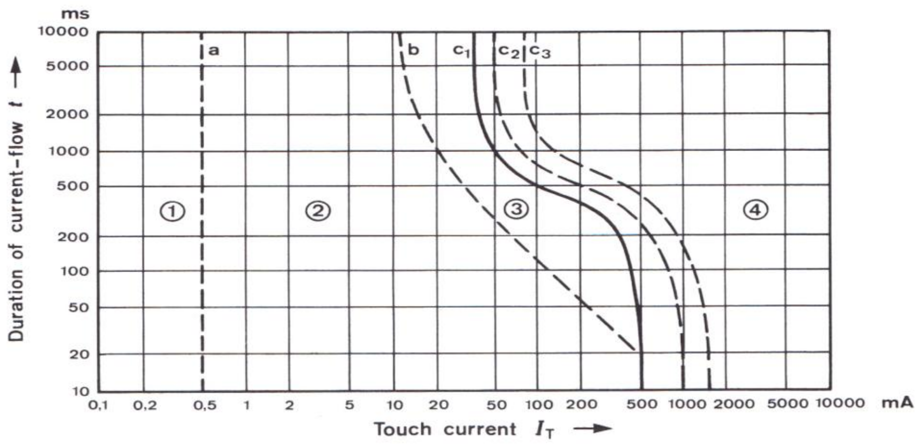
Subsequent to the first initial report published in 1974, IEC published a second edition in 1984. Based on new knowledge the second edition was developed on much more detailed and plentiful data. In this edition the threshold of perception was taken as 0.5 mA for 1% of the population while 10 mA was taken as the threshold of let go for 1% of the population based on Dalziel's experiments on men. This value may be lower for females and children depending on environmental and physical conditions. The safety curves c_1-c_3 were derived by adapting the results of Kouwenhoven's experiments on dogs and applying them directly to humans. This was a marked difference compared to the first edition as these curves highlighted the change in threshold levels in the vicinity of one heart period. Figure 5.10 below shows the revised time current zones produced in the second edition.

In 1994, a third edition of IEC-Report 479 was published. In this edition only line b was changed in order to make zones AC-2 and AC-3 more consistent [**6**].

The fourth and latest edition of IEC 60479-1 was published in 2005. Once again this advanced our understanding mainly based on new information on body impedance based on touch voltage for various contact areas. Values of impedance for the 5th, 50th and 95th percentile rank of population were determined based on reliable data gathered from experiments on cadavers and humans. Biegelmeier was one of the main contributing authors and indeed some of the most detailed results came from experiments he performed on himself (detailed in chapter 2). This latest edition also benefits from recent research work on cardiac physiology and fibrillation thresholds [**97**]. Upon reflection major revisions have ensued since the initial report and the fourth edition now comprises of five parts. 1) General aspects, 2) Special aspects, 3) Effects of currents passing through the body of livestock, 4) Effects of lightning strokes on human beings and livestock and 5) Touch voltage threshold values for physiological effects.

IEC 60479-1 2005 refers specifically to the effects of electric current and it directly applies to the threshold of ventricular fibrillation which is deemed the main cause of death due to electric current. In contrast to its predecessors this latest technical report is more in depth and provides body current thresholds and information about body impedance for various physiological effects. From this it is possible to derive estimated a.c. and d.c. touch voltage thresholds for defined body pathways, contact moisture conditions, and skin contact areas [**97**]. The latest edition also contains research conducted on other physical accident parameters including waveform and frequency of the current and the impedance of the human body.

Additionally, the third edition IEC 60479 contained little information on the dependence of the impedance of the human body on the surface area of contact, and the information it did include only related to dry conditions. The latest edition includes the findings of measurements carried out on persons using various surface areas (the surface areas ranged from small 100mm^2 to medium 1,000mm^2 to large 10,000mm^2) in dry, water-wet and saltwater-wet conditions who were subjected to a touch voltage of 25 V rms 50 Hz hand to hand. Due to the inherent danger associated with such experiments, one person was subjected to touch voltages ranging from 25 V up to an including 200 V a.c. for the various conditions already mentioned. With the aid of deviation factors it proved possible to derive values of the total body impedance for a population of people using various percentile ranks [**97**]. It is worth noting that the report does express that the thresholds outlined are valid for men, women and children independent of their state of health.



Time/current zones for alternating current 50/60 Hz according to IEC-Report 479:1984, Chapter 2

Zone 1	usually no effects	
Zone 2	usually no harmful pathophysiological effects	
Zone 3	transition zone without definite limits, normally no organic damage to be expected, no danger of ventricular fibrillation, muscular reactions, difficulties in breathing increasing with current intensity and duration of current flow	
Zone 4	curve c_1	ventricular fibrillation with increasing probability
	curve c_2	probability 5 %
	curve c_3	probability 50 %

Figure 5-10 Time current zones for alternating current 50/60 Hz IEC Report 479 2nd edition (1984)

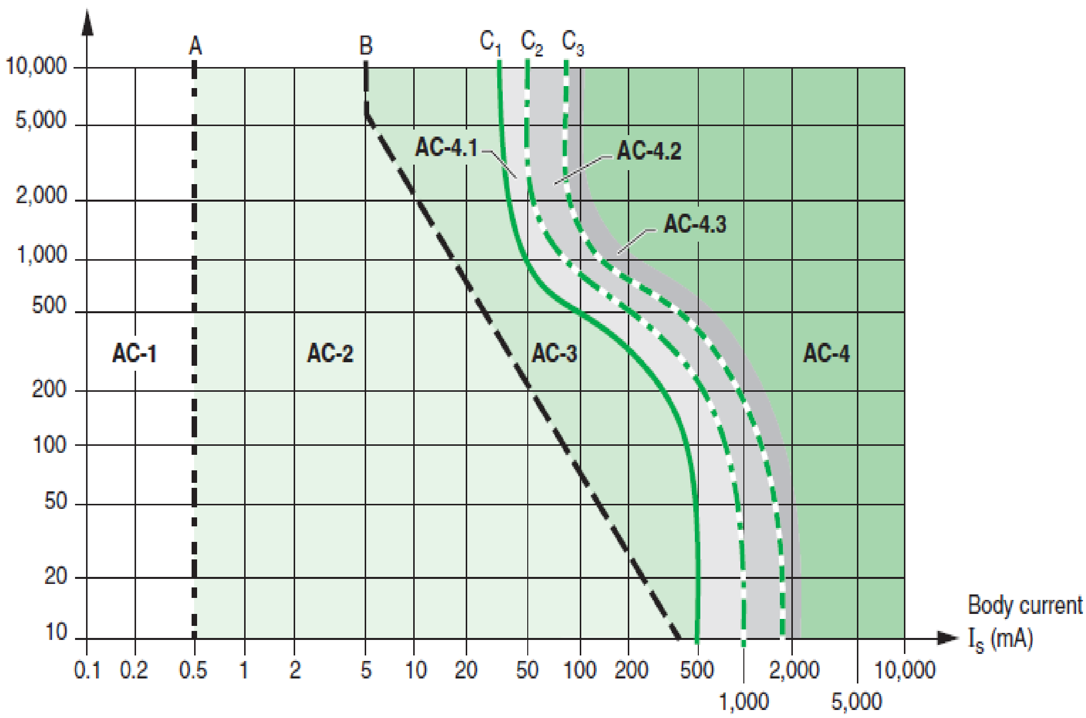


Figure 5-11 Conventional time/current zones of effects of a.c. currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet

Ultimately the five zones of shock severity outlined in the first IEC 60479 edition has been reduced to four as outlined in Figure 5-11. The physiological effects related to each of these zones are shown in Table 5-1 below. The current pathway for which these zones relate to is left hand to feet. Using the 'heart current factor' which is outlined in the document, it is possible to determine the relative danger of various other current pathways. As an addition to the third edition, the fourth edition of IEC 60479 includes an additional current path 'foot to foot'. This is important in the assessment of electrical risks caused by step voltages.

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 heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4 [1)]	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	AC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	AC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation above 50 %
[1)] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to feet. For other current paths, the heart current factor has to be considered.		

Table 5-1Time/current zones for a.c. 15 Hz to 100 Hz for hand to feet pathway [iec 2005]

The introduction of technical report 60479 part 5 [**99**] in 2007 provides a methodology for estimating voltage thresholds with the aim of giving guidance to technical committees on the selection and application of voltage limits for protection against electric shock. The objective of the report being, to derive touch voltage thresholds corresponding to zones of physiological effects as shown in Figure 5-11 and for the equivalent d.c. time/current zones given in Figure 22 in IEC 60479-1. From a designers perspective the introduction of such techniques allows one to provide a greater variety of circuits that will attain the relevant level of user protection under a wider set of circumstances [**99**].

To predict with reasonable accuracy the severity of physiological effects caused by electricity, the magnitude of the current and the path it takes through the human body needs to be attained. As it has already being alluded to, from a practical design point of view, it is very beneficial to be able to anticipate if unwanted physiological effects are possible furnished with only details about the voltage levels accessible on conductive parts under fault conditions. Part 5 of IEC 60479 imparts such information on the reader and as such the designer can now effectively decide if the maximum touch voltage under certain conditions is sufficiently low as not to cause enough touch current to cause danger. By attaining this information the designer may decide to reduce or eliminate the safeguards previously employed as the levels of voltages expected are unlikely to cause danger. The physiological effects scrutinised in part 5 are startle reaction, effects involving muscular contractions and ventricular fibrillation and the threshold levels are based on curves a, b and c_1 (c_1 being the level beyond which the probability of ventricular fibrillation becomes a concern) outlined in part 1 which is still considered the primary standard. An example of a time/voltage zones curve is shown in Figure 5-12 below.

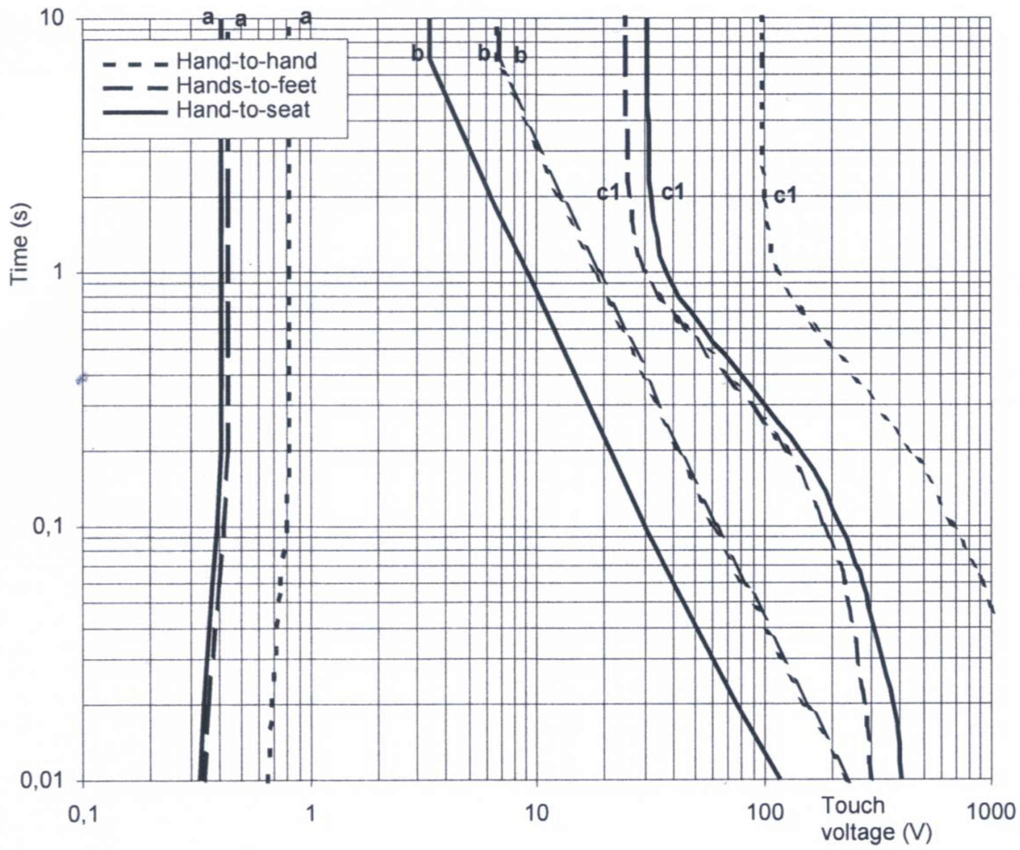


Figure 5-12 Conventional time/voltage zones of effects of a.c. currents (50/60 Hz) on a person for water-wet condition and large contact area [99]

In the latest edition of both ET 101 (4th Edition) and BS 7671 (17th Edition) there are no direct references to the time voltage zones outlined in part 5 or the time/current zones in IEC 479 part 1. However there is one significant change in contrast to earlier editions of these wiring regulations in relation to protection against electric shock. Circuits not exceeding 35 A and 32 A respectively must disconnect in 0.4s. This regulation refers to circuits feeding both portable and fixed appliances. BS7671 also removed requirements fully mandating bathroom bonding, providing certain other conditions are adhered to. The introduction of a 0.4s disconnection time for all circuits eliminates the possibility of transfer touch voltages appearing (examined in more detail in section 5-6) for five seconds on exposed conductive parts supplied via a circuit with a 0.4 s disconnection in installations with mixed disconnection times.

Caution must be emphasised in the UK however in the case where a bathroom is refurbished in an existing installation with a distribution board with a mixed disconnection time. Under such conditions, if the installer protects the circuits serving the new bathroom with RCD's and the new part of the installation is carried out to the 17^{th} edition standard (which excludes the need to bond provided certain conditions are met) and the existing copper pipes are reused, there is a possibility under some conditions that a fault on a circuit with a disconnection time of 5s outside the bathroom location but with earthed parts in contact with the copper parts inside the bathroom could lead to a transfer of potential in excess of 50 V a.c. into the bathroom for the duration of the fault. Going forward, in completely new installations the introduction of a mandatory 0.4s disconnection should eliminate this potential danger.

From Figure 5-12 for a person in 'water-wet' condition and large contact area the touch voltage permissible corresponding to a disconnection time of 0.4s is 70 V. From previous touch voltage examples already examined in this chapter the possibility of a touch voltage exceeding 70 V under fault conditions is highly probable in many installations. However an important difference worth highlighting when selecting a protective device for an installation is the comparison of MCB's to fuses for protection against electric shock. Both ET 101 and BS 7671 give limiting values of earth fault loop impedance to ensure instantaneous tripping of an MCB under fault conditions. The instantaneous tripping time for such devices is 0.1s. Examination of the time/voltage curve shown in Figure 5-12 shows for a disconnection time of 0.1s, a touch voltage of almost 200 V is permissible. For less onerous conditions such as dry conditions and small contact area, 400 V is permissible. (taken from Figure 13 in IEC 60479-5). Consequently, even in very onerous conditions MCB's give a high probability of protection against electric shock, assuming the earth fault loop impedance does not exceed the values given in the relevant wiring rules.

5.5 Theory of Touch Voltage Design

Touch voltage has already been defined as the difference in voltage potential being experienced by a person who makes contact simultaneously with more than one conductive part, which is not normally energised. By this definition, we have excluded the 'direct contact' electric shock hazard which is defined as the hazard of electric shock arising from making an unimpeded contact with normally live parts and we explicitly restrict our discussions to touch voltage arising from contact with exposed-conductive-parts and extraneous/exposed-conductive-parts.

The touch voltage U_t of the faulty equipment circuit shown in Figure 5-13 below can be calculated using the voltage divider circuit detailed in Equation 5.5.

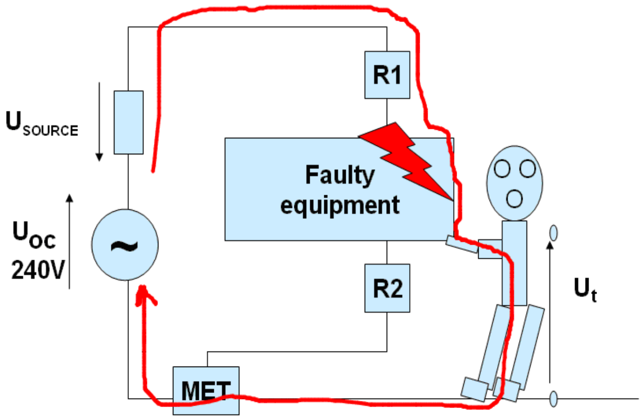


Figure 5-13 Touch voltage Concept of a single faulty equipment circuit

From this formula (Equation 5.5) for touch voltage, it is evident that in practice the magnitude of touch voltage U_t is dependent upon four values U_{OC}, Z_e, R_1 and R_2.

1. The U_{OC} value will depend on the nominal supply voltage U_O (which is fixed by the electric utility supplier),
2. The external earth fault loop impedance Z_e will depend on the system earthing type,
3. R_1 will depend on the final chosen size of the phase conductor (which mainly depends on the size of the overcurrent protective device - overload protection in particular), and
4. R_2 will depend of the final installed size of the cpc (which depends on the standard twin-with-cpc cable if not single-core conductor cables).

It can be seen from Figure 5-13 that R_2 governs U_t and the size of the cpc of a circuit can be designed or selected to provide a touch voltage that is restricted by the designer or installer intentionally. By assigning a boundary value to each of U_t, U_{OC}, Z_e, R_1 and R_2, the size of cpc can be designed using the following expression:

$$\frac{U_t}{U_{oc}} \geq \frac{R_2}{Z_e + R_1 + R_2} \tag{5.8}$$

In the UK and Republic of Ireland, for locations where low body resistance is not expected (i.e., normal dry locations) the following boundary values are used by designers and installers:

- Safe touch voltage value: $U_t \leq 50V$
- Utility supply voltage (no-load):
- $U_{OC} = 240V$ (16th edn IEE Wiring Regulations) or

  $U_O = 230V$ (17th edn IEE Wiring Regulations) where U_O is the nominal declared voltage of the mains supply

For simplicity, this chapter assigns $U_{OC} = 240V$ and a safe touch $U_t = 48V$, a limiting value of R_2 is found to be

$$R_2 = \frac{1}{4}(Z_e + R_1), (\Omega) \tag{5.9}$$

From IEC 60479 part 1 [**97**] (Effects of current on human beings and livestock), when the touch voltage is 50V a.c. or less under normal dry conditions, the body impedance of a person is high enough to prevent a touch current of high enough magnitude to cause any injury. Based on this assumption, Table 41C of the 16th Edition of IEE Wiring Regulations [**102**] permits the extending of the disconnection time from 0.4s to 5s maximum. The use of a safe touch voltage is limited by the types and rating of a protection device and the associated maximum impedance of the cpc.

It will be a simple design procedure for the designer or installer to apply Equation 5.9 and the appropriate value of Tables 41C and 41D to the required circuit to adopt a safe touch voltage design with an extended 5s disconnection time.

In the UK and Republic of Ireland, R_1 and R_2 are normally dictated by economics and standard practice. The standard combinations of conductor size in twin-with-cpc cables are: 16mm^2/6mm^2, 10mm^2/4mm^2, 6mm^2/2.5mm^2, 4mm^2/1.5mm^2, 2.5mm^2/1.5mm^2 and 1.5mm^2 /1.0mm^2. These are general purpose wiring cables used for final circuits in domestic type properties. These would be under the control of the designer and installer.

However, during the design stage, the earth-fault-loop impedance that is external to the electrical installation (Z_e) is normally an estimated figure. The exact value cannot be ascertained until the supply is actually installed and energised by the utility company. In most cases at the enquiry stage of a project the utility company will only provide the designer and installer with a worst case nominal Z_e of 0.35 Ω for a TN-C-S supply or 0.8 Ω for TN-S supply. However, the actual installed Z_e could be completely different and it is outside the control of the designer and installer. Using the typical nominal value quoted by the utility supplier and assigning a boundary value of $U_t = 50\ V$, Equation 5.8 will give the result of

$$U_t = 50 = U_{oc} \frac{R_2}{0.35 + R_1 + R_2}$$

It can be seen that for a final circuit which was originally designed based on a $Z_e = 0.35\ \Omega$ to provide a touch voltage of 50V under an earth fault condition, the actual resulting touch voltage will be higher than 50 V should the actual Z_e be lower than 0.35 Ω. Hence, the consequence of not knowing the exact value of Z_e means that the actual touch voltage resulting from a faulty circuit could not be accurately calculated using a nominal Z_e indicatively quoted by the electricity supplier. The indicative Z_e is only useful in providing the designer or installer a frame of reference to check if the overall fault-loop impedance (Z_s) of the circuit is designed correctly to ensure operation of the overcurrent or shock protection device promptly. Unfortunately it will err on the unsafe side for the touch voltage value.

To illustrate the deficiency of an indicative worst case maximum Z_e, the results of touch voltage variations with a decrease in the actual value of Z_e and increasing circuit lengths were produced using an Excel spreadsheet for a typical TN-C-S supply with $U_{OC} = 240\ V$ and $Z_e \leq 0.35\Omega$. The outcomes are plotted in Figure 5-14 for final circuits wired in 1.5mm^2/1.0mm^2 twin-with-cpc cables.

It can be seen from Figure 5-14 that the touch voltage U_t will rise from a safe-to-touch value (45V) to an unsafe value (>50V) with decreasing Z_e and increasing circuit length. It should be noted that U_t, will be at its maximum or worst case when Z_e is at its minimum value (The minimum value expected for each situation was calculated using the prospective short circuit current (I_{pf}) value of the incoming supply.) irrespective of the actual circuit length. Most of the results plotted indicate a value of U_t well above 50V.

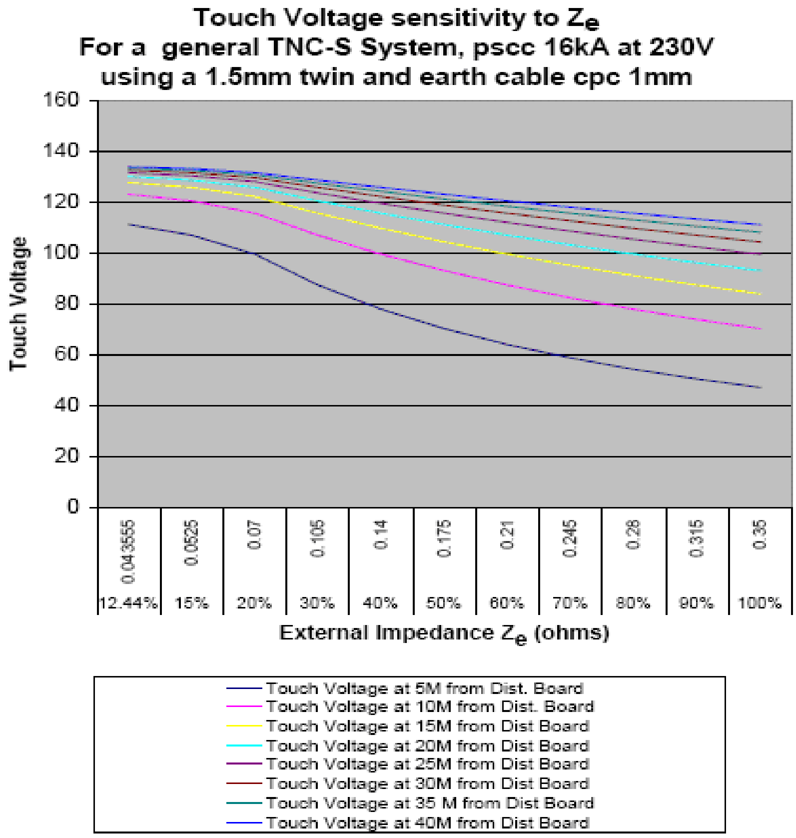


Figure 5-14 Touch voltage plot of 1.5mm²/1.0mm² twin-with-cpc cable circuits

5.6 Transfer Touch Voltage

The latest IEE wiring regulations BS7671:2008 [**101**] was introduced in January 2008, replacing the 16th edition and Table 41C is removed. However, additional protection by means of a 30mA 40ms residual current protection device (RCD) will have to be provided for final circuits supplying general purpose socket outlets that are intended for use by ordinary persons. It should be noted that the use of RCDs can help to reduce the risk of a high touch voltage and touch current of the associated circuit in the event of an earth fault, but it is unable to provide protection against any touch voltage transferred from a fault arising from another circuit not protected by an RCD within the same installation.

It is also essential to appreciate a building where a number of circuits with mixed disconnection times exist, as illustrated in Figure 5-15 [**100**], it can be shown that the resulting touch voltage from an earth fault of another defective circuit will be transferred to the exposed-conductive-part of a healthy circuit. Clearly, unless every circuit within the same installation is protected by an individual RCD or the whole distribution panel by one main RCD, a touch voltage of an unsafe value could appear on exposed-conductive-parts for a short duration until it has been cleared by the associated overcurrent protection device.

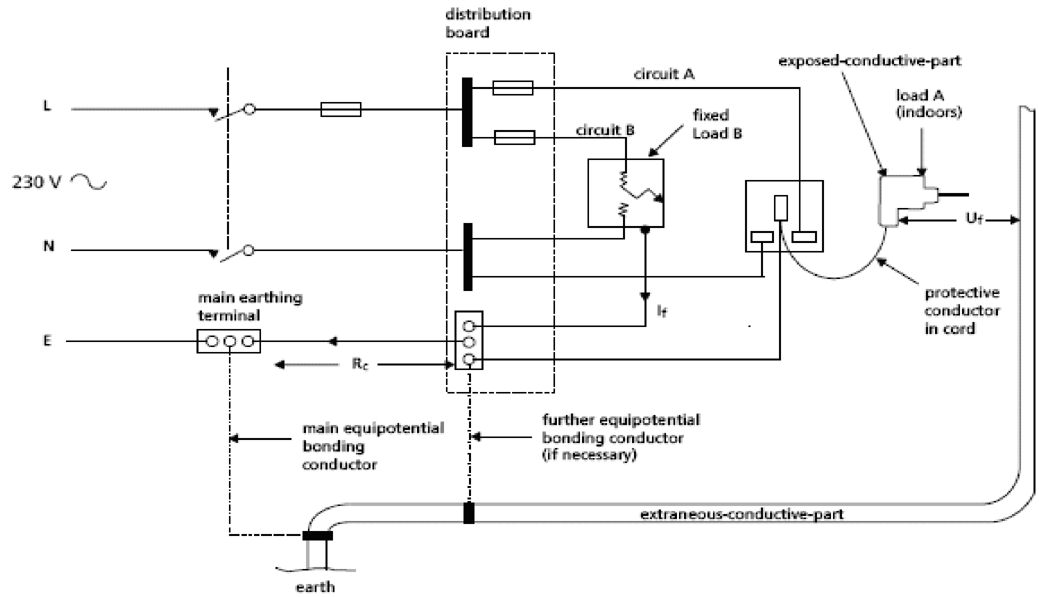


Figure 5-15 Transferred touch voltage appearing on healthy equipment (source: IEE GN 5)

Hence, when carrying out a touch voltage assessment, it is important for designers and installers to be aware that touch voltages will not just develop at the source of the fault. In an installation with a variety of interconnected circuits, a fault in one location could give rise to a transfer touch voltage in a separate location or circuit and this could prove to be dangerous and even by implementing the new RCD requirements set down in BS7671: 2008, users are still susceptible to transfer touch voltages.

To illustrate this point, in Figure 5-16 three Class I appliances are installed in an ADS (Automatic Disconnection of Supply) protected domestic property sharing a common circuit-protective-conductor (metal conduit). Appliance A is RCD protected and appliance B and C are non-RCD protected. Under earth fault conditions at appliance B, if the fault goes uninterrupted for a significant period of time due to a sluggish/faulty MCB, the resulting touch voltage can be calculated as follows.

$$U_{t(atB)} = I_f \times (R_{A2} + R_{B1} + R_{B2})$$

assuming,

$$R_{A2} + R_{B1} + R_{B2} = R_{cpcB}$$

$$U_{t(atB)} = I_f \times R_{cpcB}$$

Where: I_f = earth fault current, and R_{cpcB} = resistance of the circuit-protective-conductor measured from the main earth terminal of the electrical installation to appliance B.

In this situation, even though appliance A is RCD protected, it will not detect the transfer touch voltage and anyone coming simultaneously in contact with the metal frame of appliance A and another extraneous object will be subject to a potentially dangerous touch voltage which will remain present until the earth fault current is interrupted. The touch voltage at appliance A is given by

$$U_{t(atA)} = I_f \times R_{A2}$$

while the touch voltage at healthy appliance C is given by

$$U_{t(atC)} = I_f \times (R_{A2} + R_{B2})$$

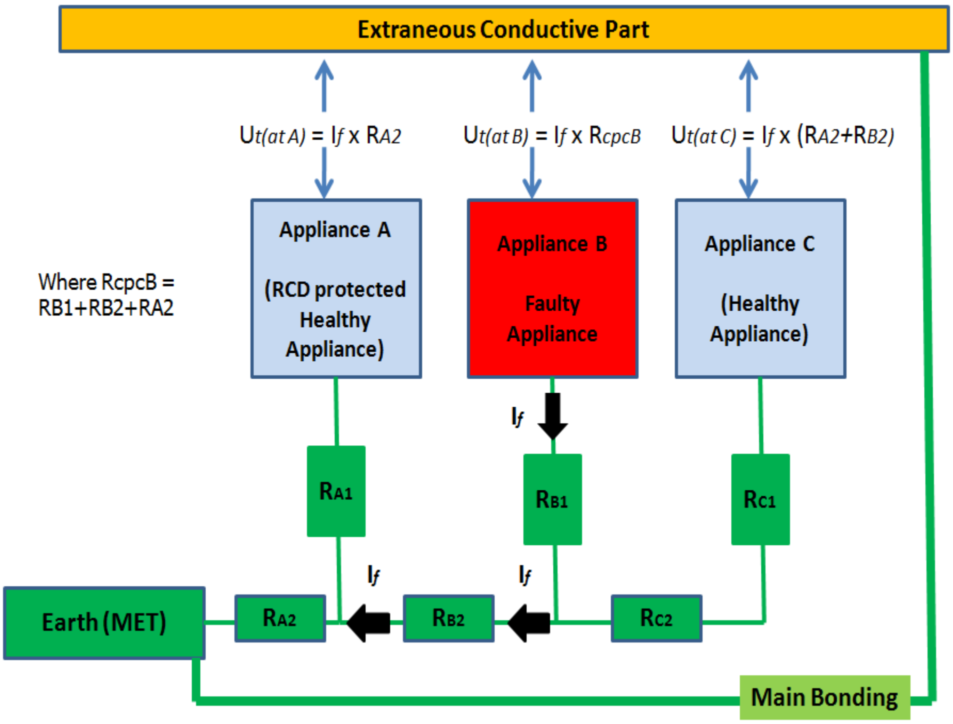


Figure 5-16 Touch voltage transferred from location B to locations A and C in the same building

5.7 A Domestic Dwelling - Touch Voltage Case Study

This section outlines a method of simulating an electrical fault in the built environment. 50 Hz a.c. currents up to 20 A were circulated through the cpc of several electrical circuits in a domestic property to simulate earth fault conditions. The resulting transfer touch voltages in the dwellings were measured and recorded.

The electrical installation tested is a domestic property in Dublin built around 1980. The supply is single phase 230V 50 Hz a.c. TN-C-S. A new consumer unit has recently been installed to meet ET101 (equivalent to BS7671: 2008). The meter board has recently been re-housed outside the dwelling for ease of access. At the meter board the measured Z_e was 0.37 Ω at a U_O of 233 V and frequency of 50.1 Hz.

The practical measurements were carried out as illustrated in Figure 5-17. A variac acted as the source of supply. One of the output terminals of the 225 VA Variac, which can be varied from 0-14 V was connected to the associated cpc at the chosen fault locations and the other terminal was connected to the main earth terminal at the main distribution board. The characteristics of the simulated fault were recorded using a voltmeter and ammeter. The temperature of the associated cpc was recorded using a digital thermometer before and during each simulated fault.

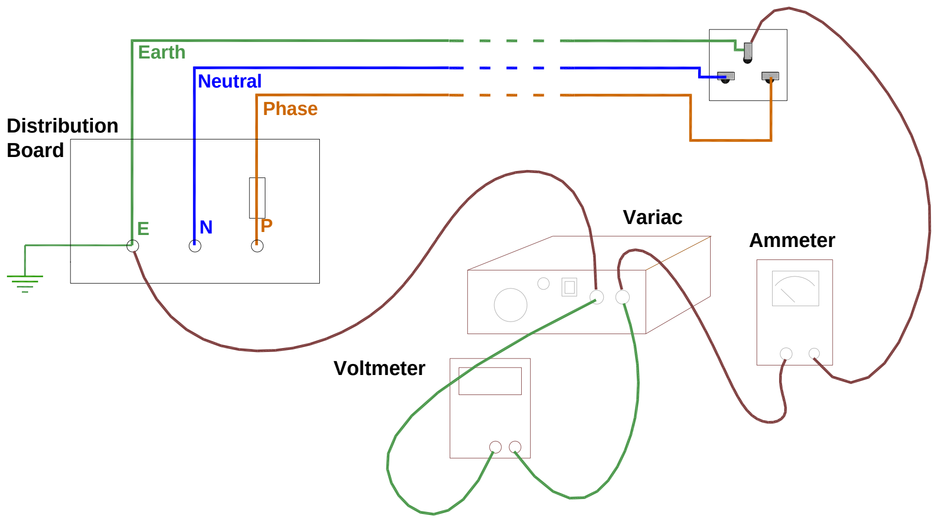


Figure 5-17 Circuit diagram of the test setup

Figure 5-18 illustrates the circuits present in the test dwelling. During the simulation of the fault, transferred touch voltages that appeared in various locations were recorded. The test was setup to study in particular what magnitude of transfer touch voltage can exist in a location (i.e., bathrooms) where low body resistance would be commonly encountered.

There are a number of countries where supplementary bonding in bathrooms may not be required but the main equipotential bonding should be correctly installed. It is for this reason that the new 17th edition of IEE Wiring Regulations requires that all electrical circuits supplying appliances or equipment in the bathroom be protected by RCDs so that any touch voltage originating from within the bathroom will be automatically disconnected within 40ms.

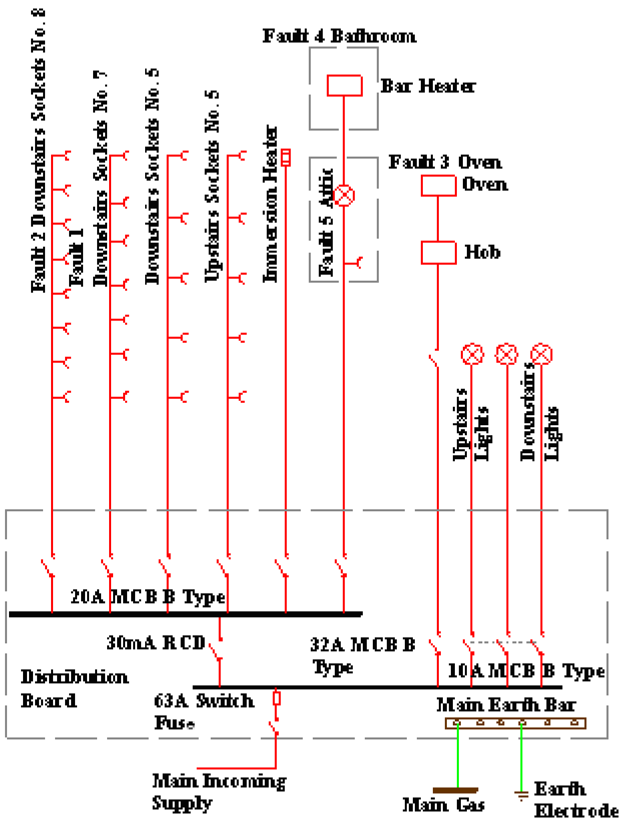


Figure 5-18 Single-line diagram of the test dwelling

This particular test has deliberately disconnected the supplementary bonding in the bathroom to study the magnitude of transfer touch voltage in the particular location. For such a case, the results are shown in Figure 5-19 with an earth fault in the light fitting in the attic.

Simulation Results - At the faulty light prior to simulation, the impedance of the cpc was recorded at 0.18 Ω. Under test conditions, the voltage and current were recorded at 6.4 V and 15 A respectively. Using the recorded values (6.4 V/15 A = 0.4266 Ω) and subtracting the impedance of the variac/ammeter combination and the earth wire from the variac to the MET, the impedance of the cpc can be calculated to be 0.196 Ω. The increase of resistance is due to copper having a positive temperature coefficient.

Under test conditions, the touch voltage recorded between the light and earth in the attic was 2.95 V, while in the bathroom the touch voltage was 2.95 V between the heater and the cold water copper pipe and shower.

Hence, under true fault conditions, if a fault occurred at the light in the attic and a touch voltage developed, a voltage of the same magnitude would develop on the heater in the bathroom where there was no supplementary bonding present.

Using the recorded values an approximated value for the touch voltage can be calculated.

Fault loop impedance at distribution board = 0.42 Ω

Resistance of R_1 is approximately 0.12 Ω

Resistance of R_2 is approximately 0.1966 Ω (both R_1 and R_2 will vary depending on the temperature of the copper under fault conditions)

Using Equation 5.5:

$$U_t = 64.056 \text{ V} = 240\left(\frac{0.1966}{0.42 + 0.12 + 0.1966}\right)$$

It was found that a touch voltage is transferred into the bathroom where the exposed-conductive-part of a heater, although it was not switched on, has attained a value of *64 V,* which is considered a dangerous voltage for people with low body resistance.

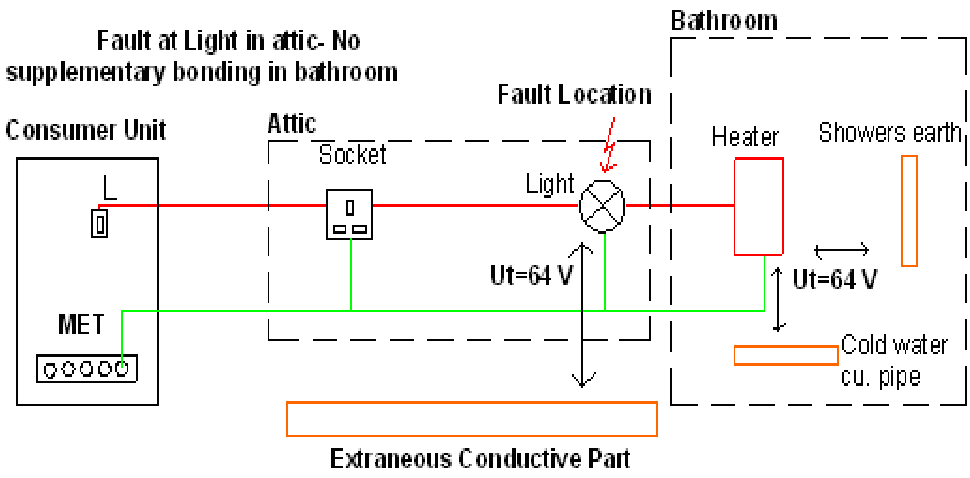


Figure 5-19 Presence of dangerous touch voltage in bathrooms with no supplementary bonding

In addition to using "Earthed Equipotential Bonding and Automatic Disconnection of Supply (EEBADS)" as the primary method of protection against electric shock faults, IEE Guidance note 5 [100] suggests that additional supplementary equipotential bonding conductors can be installed at strategic locations so that any touch voltage U_t originating from outside the particular location is lowered to a safe-touch-value. This was implemented as a control comparison and the results are shown in Figure 5-20.

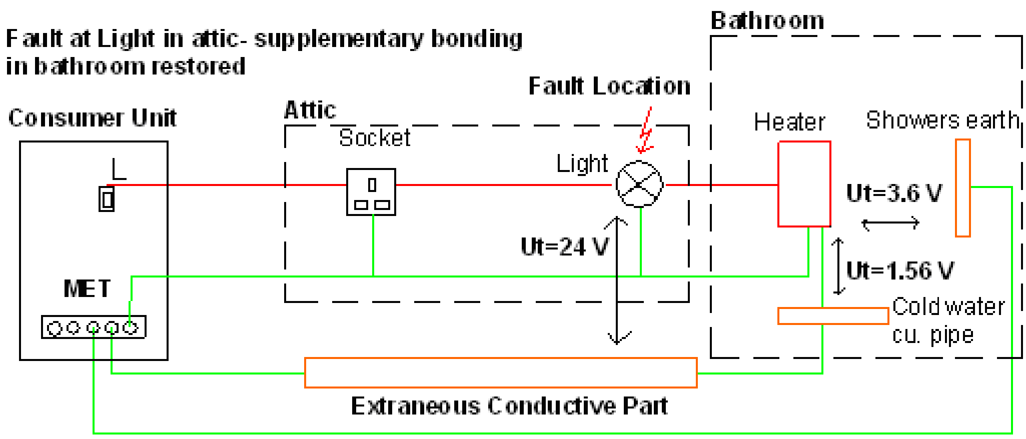


Figure 5-20 Elimination of presence of transfer touch voltage in bathrooms by mandatory supplementary bonding

Simulation Results, supplementary bonding restored - With a fault simulated on the light in the attic, touch voltages were recorded at the fault location and in the bathroom. The voltage and current were recorded at 4.35 V and 15 A respectively. The reduction in the voltage required to drive 15 A through the circuit dropping to 4.35 V due to the parallel paths back to the MET as shown in Figure 5-20.

10 A of the 15 A is recorded flowing towards the bathroom and the remaining 5.0 A is recorded flowing from the fault towards the Distribution board. In the bathroom the 10 A splits in two directions, 7 A flows through the electric showers earth circuit and 3 A flows through the copper pipes

The touch voltages recorded under simulation were as follows, 0.96 V at the faulty light in the attic, 0.144 V between the heater and electric shower in the bathroom and 0.066 V between the heater and cold-water copper pipes.

From the recorded values it was possible to calculate the resistance R_2, 4.35/15A = 0.29 Ω = resistance of circuit under fault conditions. 0.29 Ω - 0.23 Ω (impedance of earth wire and variac) = 0.06 Ω = R_2. Also, the resistances of the supplementary bonding in the bathroom could be calculated, 0.144 V / 7 A = 0.02 Ω and 0.066 V/ 3 A = 0.02 Ω

Using the recorded values an approximated value for the various touch voltages can be calculated: Using Equation 5.5:

Touch Voltage at Faulty light = U_t = 24 V = $240\left(\frac{0.06}{0.42 + 0.12 + 0.06}\right)$

To determine the touch voltages developed in the bathroom, the prospective fault current (I_{pf}) at the fault location was calculated

$$I_{pf} = \frac{233V}{0.6\Omega} = 388 \text{ A}$$

Two thirds (259 A) of the total fault current flows towards the bathroom under fault conditions. The current that would flow to earth via the cold water copper pipes is given by (3/10) x 259 A = 78 A. Hence the touch voltage between heater and cold water copper pipe would be approximately 78 x 0.02 Ω = 1.56 V

Therefore the touch voltage between heater and the shower would be approximately be 259 A (7/10) x 0.02 Ω = 3.6 V

The findings demonstrate that with supplementary bonding, the transfer touch voltage was reduced to less than 4 V within the bathroom. Therefore it appears that there is sufficient evidence to show that with supplementary bonding in place, even in the event of a defective RCD[4] or a sluggish overcurrent protection device such that the faulty circuit might remain in an energised state for quite some time, a person in the bathroom would only be exposed to a touch voltage of 4V or less.

Alternatively, a designer or installer can opt for making sure that all the circuits within the same dwelling will have a very low safe touch voltage value in the event of a fault. e.g., to have a transfer touch voltage not exceeding 12 V maximum, which would provide protection against electric shock for a person with very low body resistance in a special location. This requires the designer and installer to have a good understanding of the sensitivity of the resulting touch voltage in relation to percentage changes of U_{OC}, Z_e, R_1 and R_2 between design and as-installed phases.

5.8 Touch Voltage Sensitivity Analysis

In this section, the technique of Partial Differentiation for small percentage changes was used to determine the sensitivity of touch voltage in relation to the four design parameters:

Equation 5-10 is obtained by applying partial differentiation to Equation 5.5

$$\Delta U_t = \frac{\partial f}{\partial U_{OC}} \Delta U_{OC} + \frac{\partial f}{\partial Z_e} \Delta Z_e + \frac{\partial f}{\partial R_1} \Delta R_1 + \frac{\partial f}{\partial R_2} \Delta R_2 \qquad (5.10)$$

where $f = U_t = U_{OC} \times \left(\frac{R_2}{Z_e + R_1 + R_2} \right)$ and

ΔU_t is the small change in touch voltage, giving the result of (For simplicity, we have let Z_e , R_1 and R_2 be summed directly. The actual ΔU_t can vary significantly when complex quantities are used.)

[4] From the ERA Technology Report "In-service reliability of RCDs" published in Italy in May 2006 - electromechanical RCDs have an average failure rate of 7.1%. If RCDs are tested regularly this figure falls to 2.8%. RCD reliability is improved if the test button is operated regularly. However, the report has indicated that RCDs with an inadequate IP rating subjected to dust and moisture could have a 20% failure rate.

$$\Delta U_t = \frac{R_2}{Z_e + R_1 + R_2}\Delta U_{OC}$$
$$+\frac{-U_{OC}\times R_2}{\left(Z_e + R_1 + R_2\right)^2}\Delta Z_e$$
$$+\frac{-U_{OC}\times R_2}{\left(Z_e + R_1 + R_2\right)^2}\Delta R_1$$
$$+\left[\frac{-U_{OC}\times R_2}{\left(Z_e + R_1 + R_2\right)^2}+\frac{U_{OC}}{\left(Z_e + R_1 + R_2\right)}\right]\Delta R_2$$

$$\Delta U_t = \frac{R_2 \cdot \Delta U_{OC} + U_{OC} \cdot \Delta R_2}{Z_S} - w \cdot \Delta Z_S \qquad (5.11)$$

Where $Z_S = Z_e + R_1 + R_2$, $w = \frac{U_{OC}\times R_2}{{Z_S}^2}$, and $\Delta Z_S = \Delta Z_e + \Delta R_1 + \Delta R_2$

$$U_t^{'} = U_t + \Delta U_t \qquad (5.12)$$

where U_t' is the final touch voltage after changes of U_{OC}, Z_e, R_1 and R_2 been accounted for.

Equations 5.11 and 5.12 allow the designer and installer to investigate the resulting magnitude of the change in touch voltage U_t for any combination of percentage changes of the four design parameters U_{OC}, Z_e, R_1 and R_2.

As an example: for a final circuit with a $U_O=230\ V$, $U_{OC}=240\ V$ TN-C-S system, R_1=0.1 Ω and R_2=0.15 Ω, during the design stage $Z_e=0.35\ \Omega$ and $I_{pf}=16\ kA$ were obtained from the electricity supplier by enquiry[5]. Using Equation 5.5, the estimated touch voltage U_t can be evaluated equal to *60 V*. However, the actual touch voltage will change due to the percentage variation of the four parameters for reasons beyond the control of the designer as below:

- $\boldsymbol{U_{OC}}$ changes by +6%[6] due to the variation of the utility supply, $\Delta U_{OC} = 240\times(+6\%) = +14.4V$
- $\boldsymbol{Z_e}$ changes by -35% due to the location of the utility supply transformer, $\Delta Z_e = 0.35\times(-35\%) = -0.1225\Omega$

[5] BS7671: 2008, Regulation 434.1 suggests determination of prospective short circuit current (I_{pf}) at the relevant point of the installation may be done by calculation, measurement or enquiry.

[6] The UK ESQC Regulations state that the declared nominal voltage on LV networks is 230 V ± 10%, the open circuit voltage at the DNO supply transformer is normally set at 240V, hence 240V +6% is used in the analysis.

- $\boldsymbol{R_1}$ changes by -15% due to shorter cable runs in the construction stage, $\Delta R_1 = 0.1 \times (-15\%) = -0.015\Omega$ and
- $\boldsymbol{R_2}$ changes by -15% due to shorter cable runs in the construction stage, $\Delta R_2 = 0.15 \times (-15\%) = -0.0225\Omega$

Using Equation 5.11, the change of touch voltage

ΔU_t = (3.6 = (-9)) – (-16) V = 10.6 V

Hence, U_t'= (60+10.6) V = *70.6* V approximately. The actual U_t is *73.72* V if the exact value of R_1 = 0.085 Ω, R_2=0.1275 Ω, Z_e= 0.2275 Ω and U_{OC} = 254.4 V were applied to Equation 5.5. The discrepancy of *(73.72-70.6)* V= *3.12* V is mainly due to the large percentage change of Z_e but the overall result is still within an acceptable margin.

It can be seen from the above, the touch voltage sensitivity Equation 5.11 derived is thus a powerful tool for designers and installers of electrical installations to investigate and identify the sensitivity of resulting touch voltages of any electrical circuits.

5.9 Interactive Touch Voltage Tools

Carrying out touch voltage calculations can be a time consuming and arduous task when designing an electrical installation. In an effort to meet the needs of those concerned, a 'Touch Voltage Simulator' was developed and also an 'Interactive Touch Voltage Chart' for various earthing systems (e.g. TN-C-S, TN-S and TT). Figure 5-21 shows a typical chart for a General TN-C-S system, prospective short circuit current I_{pf} is taken as 16 kA.

Using the interactive chart, it is possible to vary U_{OC}, R_1, R_2 and the distance a potentially faulty appliance is from the distribution board, via the scroll bars. By doing this, the touch voltage can be observed for any combination of cables used in the design for varying values of Z_e. As a result, the designer can immediately identify the worst-case touch voltage that could develop in a circuit design. In Figure 5-21 a standard $6\text{mm}^2/2.5\text{mm}^2$ twin and cpc cable is selected feeding an appliance at 10 m from the main distribution board. The touch voltage goes from a safe 50 V for a dry location at maximum Z_e to a potentially dangerous 120 V at minimum Z_e.

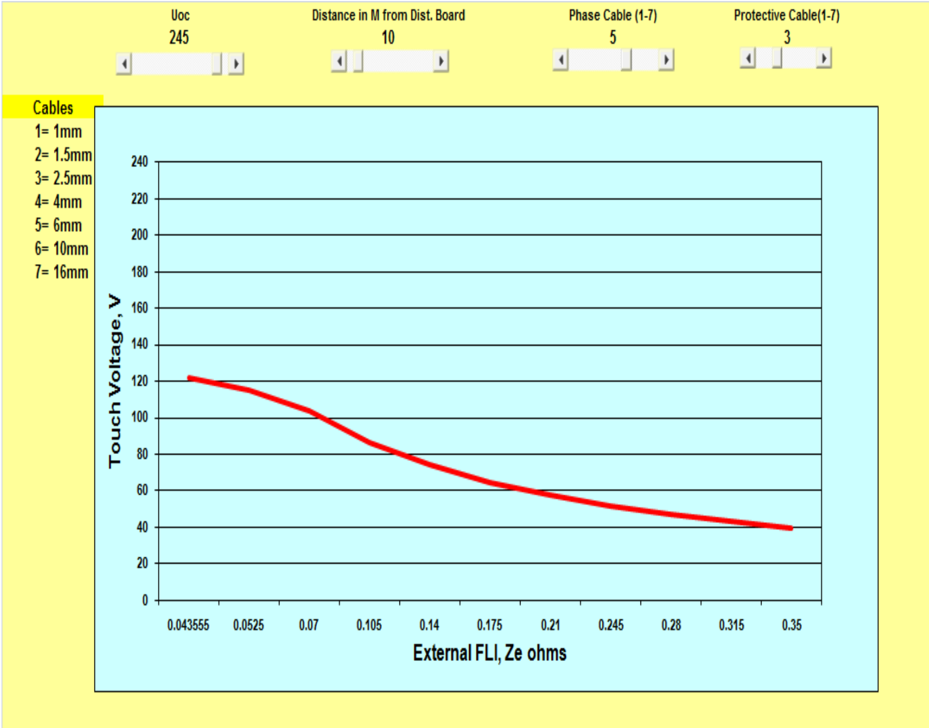


Figure 5-21 'Interactive Touch Voltage Chart' for a General TN-C-S, I_{pf} 16kA.

5.9.1 Touch Voltage Simulator

The 'simulator' is a powerful tool for designers and installers of electrical installations to calculate the touch voltage that could develop under different design parameters for various earthing systems and can also aid in carrying out a low touch voltage design.

The 'simulator' is also seen as an educational tool for third level students in Dublin Institute of Technology wishing to enhance their understanding of touch voltage calculations. Students who familiarise themselves with the simulator can quickly immerse themselves in touch voltage design. Adopting the use of the 'touch voltage simulator' as an educational tool is a more student centered approach and shifts away from conventional learning techniques to one where students can self learn by investigating the touch voltage outcomes for their own inputted data in their own time.

To cater for a variety of user groups, two versions of the 'Touch Voltage Simulator' were developed, a controlled version and an uncontrolled version. The controlled version allows only qualified input data to be selected from the dropdown lists. The uncontrolled version caters for the more discerning user and input data can be directly inputted or alternatively can be selected from the dropdown lists.

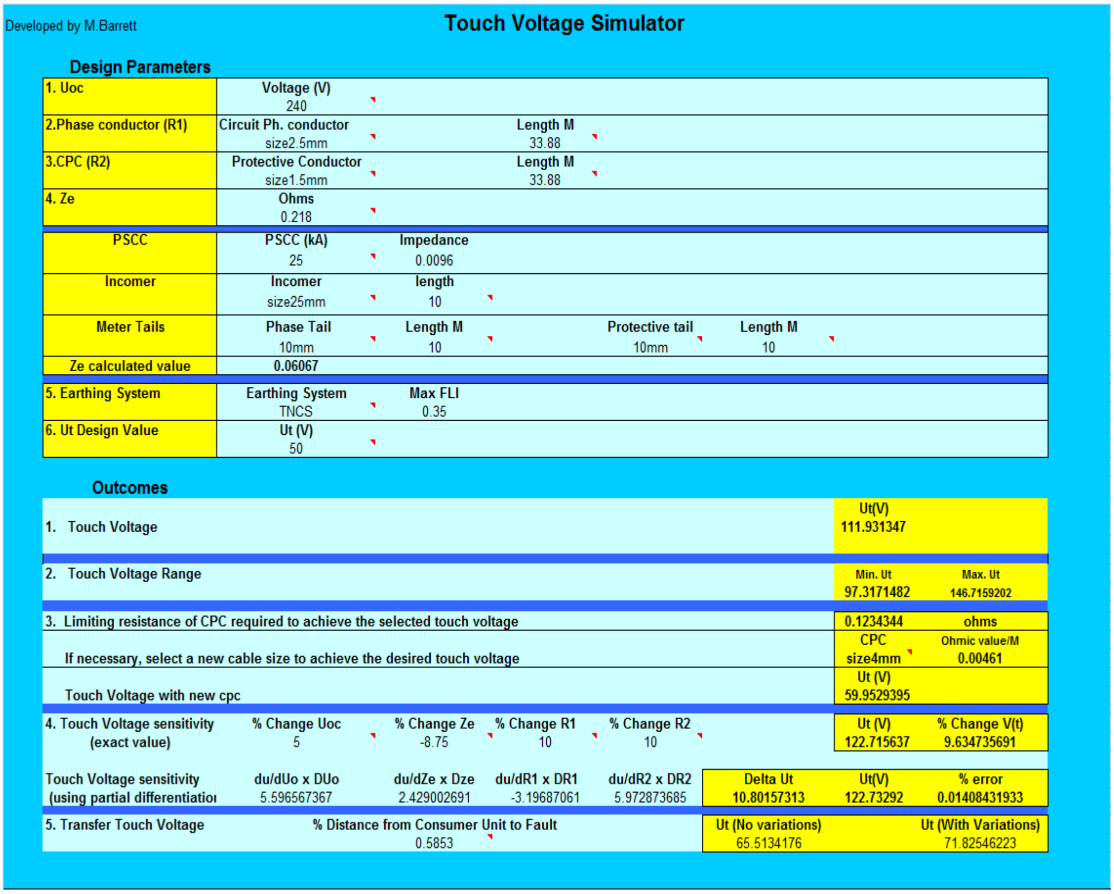


Figure 5-22 'Touch Voltage Simulator' developed in Excel for touch voltage calculation

5.9.1.1 Setting the Design Parameters

To utilise the simulator correctly the user must first input the desired design parameters and subsequently review the calculated outcomes (1-5). As seen in Figure 5-22, there are six individual design parameters to be inputted. (The triangles at various points on the simulator denotes the location of the dropdown menus)

1 U_{OC}, the user selects a value for the worst possible driving voltage (i.e., open circuit voltage) of the mains supply from the dropdown lists or alternatively inputs his/her own value.

2 R_1, the user selects the size of a circuit phase conductor from a dropdown list, which consists of the standard general purpose domestic cables used in the UK and Ireland. The user must also select the length of this cable from a separate dropdown menu.

3 *R_2,* the user selects the size of a circuit protective conductor from a dropdown list, which consists of the standard general purpose domestic cables used in the UK and Ireland. The user must also select the length of this cable from a separate dropdown menu.

4 *Z_e,* the user has two choices for selecting the external fault loop impedance. Firstly the user can simply select an independent value for *Ze* from the dropdown menu or alternatively the user can insert the "calculated value", which is calculated by virtue of the user selecting data for the prospective short circuit current (I_{pf}), incomer, and meter tails.

5 *Earthing System.* The user can select from three earthing systems from the dropdown menu e.g. TN-C-S, TN-S and TT, in doing so; the maximum external fault loop impedance (maximum external fault loop impedance as quoted by the utility supplier in the UK at the enquiry stage) is automatically selected.

6 *Desired touch voltage,* the user selects the desired touch voltage for the circuit design.

5.9.1.2 Touch Voltage Simulator Outcomes

Having entered the design parameters, the user can now observe and utilise the five outcomes for the inputted data. To demonstrate the merits of the 'simulator, each outcome is discussed individually

1 *Calculated Touch Voltage*, the simulator outputs the calculated touch voltage for the inputted design parameters. Therefore, for any circuit design, a designer can readily check the touch voltage, which could develop under fault conditions. If the user changes any of the four major design parameters U_{OC}, Z_e, R_1 and R_2, the touch voltage automatically updates.

2 *Minimum and Maximum touch voltage range.* Very often at the early stages of an electrical installation design project, the true Z_e value will not be known until the supply is energised by the utility company. A touch voltage design implemented using the initial worst case nominal Z_e given by the utility company may vary significantly to the onsite value. This outcome highlights to the user, the possible range in which the touch voltage will sit for the selected U_{OC}, R_1 and R_2, design parameters. Minimum Z_e is calculated using the prospective short circuit current (I_{pf} value of the incoming supply)

3 *Low Touch Voltage Design*. In the event of the touch voltage being high and potentially dangerous, outcome 3 aids a designer wishing to implement a low

touch voltage design by allowing the user to select a new circuit protective conductor and observe the revised touch voltage. Outcome 3 has three separate parts, part (a) identifies the limiting value of resistance for the circuit protective conductor required to achieve the "desired touch voltage". Part (b) allows the user to select a new circuit protective conductor from a dropdown menu and part (c) informs the user of the new touch voltage if the cable selected in part (b) was implemented in a design.

4 *Touch Voltage Sensitivity.* Very often the design parameters used to calculate the touch voltages for an electrical installation may vary significantly to the actual values at the installation stage. For example U_{oc} may vary due to a change in the utility supply, Z_e may differ due to a location change in the supply transformer and R_1 and R_2 may increase due to a longer cable run. Outcome 4 allows the designer to identify the sensitivity of resulting touch voltages to any variations in the four main design parameters. By selecting the dropdown menus next to the four parameters the user can implement a plus or minus percentage change to U_{oc}, Z_e, R_1 and R_2. As a result, the simulator produces the new touch voltage and the percentage change these variations have on the original touch voltage.

5 Transfer Touch Voltage. As already identified in this paper, touch voltages will not just develop at the source of the fault. It is possible for a transfer touch voltage to develop on healthy equipment. For example, if an earth fault developed on a radial socket circuit, a person using a portable appliance connected to any of the other socket outlets on this circuit could potentially be subjected to a transfer touch voltage. Outcome 5 allows the user to identify the transfer touch voltage at a percentage distance between the fault and the main consumer unit. In this way a designer can carry out a transfer touch voltage assessment for any radial circuit to identify the possibility of any dangerous transfer touch voltages developing under fault conditions.

5.9.2 Verification of Touch Voltage Simulator

To verify the accuracy of the simulator a series of onsite measurements were carried out on an electrical installation. The practical measurements were carried out using a Variac, which acted as the source of supply. One of the output terminals of the 225 VA Variac, which can be varied from 0-14 V was connected to the main earth terminal at the distribution board and the other terminal was connected to the circuit under fault at the mcb in the main distribution board. By connecting the apparatus this way the external Z_e can be varied by varying the resistance of the cables between the variac and the connection points on the distribution board. The phase conductor was shorted to earth at the fault location and the neutral disconnected at the distribution board to prevent a separate path for the current to flow. The characteristics of the simulated fault were recorded using a voltmeter and ammeter. A diagram of the experimental set up is shown in Figure 5-23.

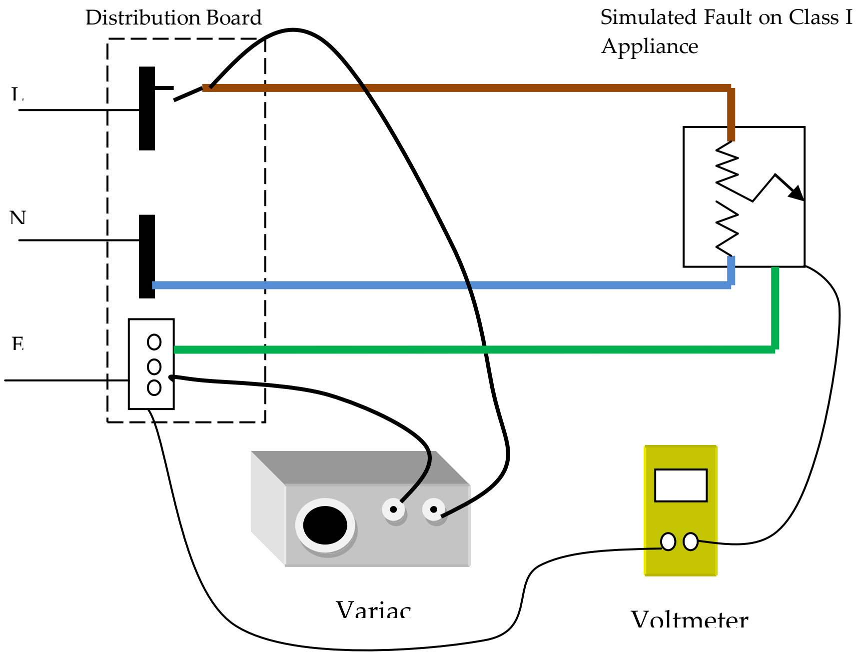


Figure 5-23 Experimental set up for simulation of earth faults to determine touch voltage.

To demonstrate the accuracy of the simulator, three of the simulated faults will be examined and calculations shown.

Fault 1- Earth fault on Class I fixed appliance This appliance is supplied with a standard 2.5mm^2 twin and earth cable. At the faulty appliance prior to simulation, the resistance of the cpc was recorded at 0.09 Ω. Under test conditions, the voltage and current were recorded at 4 V and 16 A respectively. The touch voltage was measured at 1.47 V. Using the recorded values, Z_s = (4V/16A) = 0.25 Ω. Z_e was calculated to be 0.1 Ω. Hence under true fault conditions assuming a U_{oc} of 240 V, the touch voltage would be 240 x (1.47/4.00) = 88.2 V. Using the measured resistance of the cpc, the length of the cable was calculated to be 7.438 m. All the relevant data was then entered into the Touch Voltage Simulator and the results compared to the simulated on site measurement. The output of the simulator was 88.12 V. This gives a simulator accuracy of 99.9 %.

Fault 2- Earth fault on Cooker This appliance is supplied with a standard 6 mm^2 twin and earth cable. At the faulty appliance prior to simulation, the resistance of the cpc was recorded at 0.06 Ω. Under test conditions, the voltage and current were recorded at 3 V and 15.8 A respectively. The touch voltage was measured at 1.02 V. Using the recorded values Z_s = (3V/15.8A) = 0.19 Ω. Z_e was calculated to be 0.1 Ω. Hence under true fault conditions assuming a U_{oc} of 240 V, the touch voltage would be 240 x (1.02/3.00) = 81.6 V. Using the measured resistance of the cpc, the length of the cable was calculated to be 8.097 m. All the relevant data was then entered into the Touch Voltage Simulator and the results compared to the simulated on site measurement. The output of the simulator was 77.86 V. This gives a simulator accuracy of 95.4 %.

Fault 3- Radial socket circuit This circuit is supplied with a standard 2.5 mm^2 twin and earth cable. For this fault the touch voltage was recorded at a socket prior to the faulty socket and also at the fault location. By doing it was possible to determine the transfer touch voltage. At the faulty socket prior to simulation, the resistance of the cpc was recorded at 0.41 Ω. At the other socket the resistance of the cpc was recorded at 0.24 Ω. Under test conditions, the voltage and current were recorded at 12 V and 13.4 A respectively. The touch voltage was measured at 5.63 V and the transfer touch voltage was recorded at 3.36 V. Using the recorded values Z_s = (12V/13.4A) = 0.8955 Ω. The resistance of Z_e was changed for this simulated fault condition and was found to be 0.218 Ω. Hence under true fault conditions assuming a U_{oc} of 240 V, the touch voltage would be 240 x (5.63/12.00) = 112.6 V and the transfer touch voltage would be 240 x (3.36/12.00) = 67.2 V. Using the measured resistance of the cpc, the length of the cable was calculated to be 33.88 m and the distance to the other socket from the distribution board was 19.83 m. All the relevant data was then entered into the Touch Voltage Simulator and the results compared to the simulated on site measurement. The output of the simulator was 111.93 V at the fault location and 65.5 V for the transfer touch voltage. For the touch voltage at the faulty socket, the simulator was 99.4 % accurate and for the transfer touch voltage the simulator was 97.5% accurate.

The discrepancies above are mainly due to experimental error, but the overall result is still within an acceptable margin. It can be seen from these onsite simulations, the 'Touch Voltage Simulator' outlined in this chapter is thus an effective tool for designers and installers of electrical installations to investigate and identify the eventual touch voltage and transfer touch voltages of any electrical circuit under a single fault condition.

5.10 Conclusion

In this chapter the concept of how dangerous touch voltages can develop and also transfer onto healthy circuits in low voltage electrical installations has been analysed. From a designer's perspective, the benefits of designing for safety through the implementation of RCD's and a low touch voltage design using the equations and tools developed by the author should be clearly evident. The major objectives achieved in this chapter include:

- ❖ The underpinning basic theory of the safe touch voltage design equation has been explained and illustrated with examples.
- ❖ A generic circuit diagram is presented illustrating how a touch voltage of a dangerous magnitude could be transferred from a faulty circuit onto healthy equipment located elsewhere within an electrical installation.
- ❖ A touch voltage case study has been used to demonstrate that a dangerous touch voltage could be present in locations where extreme low body resistance may exist.
- ❖ It has been demonstrated that by the use of local supplementary bonding, the danger of any touch voltage transferred from a fault arising from outside the bathroom can almost be completely eliminated even in the event of a fault of long duration.
- ❖ The 'Touch Voltage Simulator' application presented is a powerful tool for designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters.
- ❖ An on-site touch voltage case study verified the validity of the touch voltage simulator as a credible design tool.
- ❖ The generic 'Interactive Touch Voltage Charts' can plot interactive graphs, which can be used as visual aids for engineers to ascertain the touch voltage at the design stage.

A set of touch voltage sensitivity calculation equations has been developed and using an example, the author has demonstrated that the equations can be used by installation designers and installers to investigate and identify the range of resulting touch voltage values that might be the consequence of variation of the four main design parameters U_{oc}, Z_e, R_1 and R_2.

Chapter 6

Software Engineering

6.1 Introduction

Using Virtual reality (VR) for training and enhancing engineering design offers a great alternative to currently used techniques. It also offers a viable alternative for situations that are difficult to replicate or too expensive to set up in real life. VR scenes that previously required bulky and hugely expensive equipment in the past can now operate smoothly on standard modern desktop computers and as such has a potential global audience. However, to develop a desktop VR model that could survive commercially in today's market requires a system that has the ability to develop scenes quickly and reliably with the flexibility to adapt to various scenarios. One of the challenges for this research was to determine a suitable method to develop a VR model and subsequently demonstrate by developing a prototype model the role VR could play in the enhancement of electrical safety and design in the built environment.

In recent times VR has moved away from being a novelty technology to the extent where it is utilised across many disciplines. In the medical field it used as a 3D visualisation tool to aid clinicians and students understand important physiological conditions or basic anatomy. It is also used for surgical simulation and planning. The Military use VR for battle field simulation along with pilot and weapon training while VR based simulators have also been developed for aircraft inspection and maintenance. VR models related to electrical engineering disciplines have been previously developed, however the main focus of this research to date has been on substations and high voltage installations.

Even though VR has reached mainstream status for the delivery of innovative solutions for scientific research, visualisation, education and training, and business, actually developing a VR application still requires much effort and only with properly selected tools is it possible to produce convincing results in a timely manner. The purpose of this chapter is to set out the justification for the selection of the software chosen and to outline the software process behind the development of the prototype model titled 'VES' (Virtual Electrical Services) while the following chapters (7 and 8) will outline and evaluate the scenes and scenarios developed in 'VES'.

6.2 Software Selection

VR applications are one of the most in demand genres for the delivery of innovative solutions for scientific research. In contrast to other simulation and interactive applications, VR allows the user to interact with rich 3D environments and receive instantaneous feedback each time the user interacts with the application. As a result of the demand and commercial potential involved, many companies have developed commercial products for developing VR applications. In contrast to the commercial products on the market, X3D is also available as a low cost alternative. Hence, the first initial decision in choosing the method by which to develop the VR application was to decide whether to opt for a commercial product or the less expensive X3D option and ultimately determine the most practical method of creating 'VES'.

In terms of commercial products for developing 'VES', there are several options including Wirefusion, Quest 3D, Vizard, EON Reality to mention a few, (these will be examined in more detail in section 6.2.3). In general these applications provide the user with a 3D scene similar to what would be encountered in a 3D drawing package and animation is achieved via timelines. Pre-built scripted blocks are used to control behaviours and for non standard or unique behaviours a scripting option is generally available. These commercial products have opened the development of VR applications to a much wider audience; however this comes at a price. Commercial VR applications are expensive typically costing in the €3000 - €12,000 bracket for full professional versions. From a research perspective some companies offer an educational license at a reduced rate, however the results cannot be distributed commercially, but it does allow for the establishment of prototype models to provide evidence for the potential of a unique application.

Due to the significant cost associated with commercial programs, X3D is worth considering as an alternative solution. X3D is the successor to the virtual reality modelling language (VRML) and is an ISO standard XML based file format for displaying 3D computer graphics. The X3D standards allow for the creation and managing of primitives, shaders, atmosphere, texture, imported 3D models and animation and interactivity.

Evidently with X3D it is possible to build a complete interactive VR scene and it appears plausible that similar results comparable to commercial VR applications can be achieved. However an important distinction needs to be highlighted between X3D and commercial packages. If choosing one of the fore mentioned packages such as Wirefusion or Quest3D, the user does not need to concern itself with how the software works per se. In contrast, X3D is a scripting language and not a program and as such requires the developer to write lines of code to describe a 3D scene. Hence for non-programmers, what is realistically achievable in a limited timeframe is a simplistic application viewed via an X3D viewer. Companies such as Vivaty do provide fee based X3D solutions. However, for the development of 'VES', a commercial package was seen as the most practical route that would allow the development of a more comprehensive model with a professional appearance in a limited time.

6.2.1 Requirements for the system

The overall aim and requirement for the commercial software package was to develop a VR model of a domestic dwelling that contains the constituent parts of an electrical installation. The model should have the capacity to simulate the dynamic operations of the electrical circuits in accordance with ET101. The user should be able to explore the domestic dwelling, be able to interact with the VR model, make electrical design decisions and receive feedback and safety advice. Ideally the completed application should run on a standard desktop pc, be capable of being distributed via the web or alternatively downloaded as .exe file, so that it can reach the widest audience possible with relative ease.

In order to compare the available software packages objectively, the requirements for the system were compiled

- Scene modelling and development? Is a modeler contained in the application or is an external application like 3D Studio Max or Google SketchUp required.
- File formats supported for importing 3D models
- 3D libraries, widgets.

- Number of polygons, object scaling, animation, collision detection, extensibility, support for input/output VR devices
- Hardware supported.
- Methods of publishing a completed application.
- Licensing conditions
- Price – Are there educational licenses available?
- Developer support and upgrades?
- Soundness of software provider in terms of future existence.

6.2.2 Software Research Approach

Through literature and internet research, a list of suitable applications was established. From this list, suitably identified providers were reviewed to obtain more detailed information regarding licensing agreements, support and technical features. Following this, the most promising applications were tested (providing a trial version is available) and on the basis of this, one application was selected for the development of 'VES'.

6.2.3 Virtual Reality Software

After undertaking a review based on the requirements stated above. Quest3D was selected as the most appropriate format to develop the application. The table below shows an overview of the other suitable software applications reviewed in terms of developing 'VES'. As the main purpose of this chapter is to detail the justification for the software chosen and outline the mechanics of how the 'VES' model was developed a succinct overview of the other contenders is outlined.

Virtools	
	Virtools [**56**] was founded in 1993 and is a complete 3D development application. In 2005 it was acquired by Dassault Systèmes and since 2006 the software is called 3DVIA Virtools. Similar to Quest3D, Virtools uses building blocks that can be linked together to develop a complex action. Also similar to Quest is the fact that it is possible to make alterations to the scene while running which allows for shorter testing and debugging time. Virtools is capable of importing 3D image formats from3D Studio Max and DirectX. To view simple Virtool scenes a free webplayer is available, however for running content offline a licensed player must be purchased. Virtools is a high end product that comes at a premium price. Also, in many online forums Quest3D appears generally to obtain a superior reaction with the licensing structure of Virtools receiving negative comments.
Vizard	

	Vizard [**168**] is a 3D development platform capable of building interactive and immersive 3D content. It was developed jointly at MIT and the University of California in the early 1990's. The benefit of this linkage is if WorldViz ceases the development of Vizard, all rights return to these institutes. 3D studio Max and Maya 3D models can be imported into Vizard for development. In contrast to Quest3D which uses a graphical form of programming, interaction in Vizard is achieved by programming a script in the python language. Vizard has a much more basic user interface compared to both Quest3D and Virtools and could be possibly considered as not as intuitive as these other two programs. An educational license is priced at approximately $4000 for a single license.
Wirefusion	
	Demicron was founded by students at Stockholm University, Sweden in 1996. Wirefusion [**57**] which is one of their products is a 3D application that quickly allows the development of an interactive 3D presentation for the internet. Strictly speaking it is not recognised as VR software. It is typically used by architects and product companies however it also used for computer based training. Authoring tools such as 3DS max, Maya, SketchUp and Blender can be imported and interactivity added. Sony, Philips and Siemens are examples of the companies who used Wirefusion to date. An educational license can be purchased for approximately €395. Upon reflection, wirefusion appears to be best suited to internet marketing and when contrasted to Quest3D in terms of developing 'VES', it fall shorts on numerous areas including 3D libraries, widgets, user interface and methods of publishing a completed application.

Table 6-1 Overview of alternative VR software applications

Other software applications found but not reviewed include EON Reality, Meta VR, CaveUT, MultiGen, VR juggler and Quantum 3D.

Prior to finalising Quest3D as the software of choice, it was tested using the freely available demo version (the demo version has an unlimited time span however the content cannot be saved). From this trial period it was clearly apparent that a prototype version of 'VES' could be developed to demonstrate the potential use of VR to enhance electrical safety in the built environment. The justification for this selection will now be put forward.

Quest3D [**1**] is a software for creating interactive 3D scenes developed by the Leiden company Act3D since 1998. Quest 3D uses a unique style of visual programming called channelling and in contrast to writing many lines of code, developers can logically combine large set of powerful building blocks to build complex scenes in a timely fashion. This method of programming reduces debugging time and avoids time consuming syntax errors. In addition to this, scene development in Quest3D occurs in real time meaning the developer is constantly working on and viewing the end result. This is a major advantage in that time is not lost compiling code or rendering scenes.

In contrast to packages like Wirefusion for example, Quest 3D contains a much more comprehensive set of default channels or building blocks which are all self-contained within the application allowing for the development of a varied range of programs and scenes. In the event of the application under development requiring more specific needs, a C-based Lua scripting language can be used to create new channels. Also, in addition to the default channels, Quest 3D boasts a suite of graphic features including a number of animated characters, smoke and fire effects and vegetation all of which can be added to a scene with relative ease.

Channels within Quest3D have a parent child relationship whereby each child provides input to its parent channel. To realise the real time rendering, the software scans the channels from left to right in a single frame.

While Quest3D allows the programmer significant flexibility in managing the logic of the application, building blocks can be logically grouped in multiple channel groups and stored in folders to ensure the editor remains uncluttered and is suitable for team development. Also, if programmers use dynamic loading whereby only the portion of the application that is required is called, the potential of the graphic card can be utilised and software such as Quest3D can run smoothly on standard PC's. Programmers can achieve this at the developmental stage by planning their scene and dividing an application into its logical parts.

Overall it would be fair to comment that there is a steep learning curve associated with Quest 3D. However in making that comment, from an engineer's perspective, developing an application from scratch is certainly viable. In fact within a relatively short period of time Quest 3D becomes quite intuitive. One of the driving forces behind this assertion is the editor which is one of Quest 3D's main strengths. The editor in Quest 3D is a 'wysiwyg' what you see is what you get making all changes instantaneously visible in the scene making testing very straight forward, it also allows control of almost every detail of an application and has customizable task interfaces. Indeed almost all elements of what is required when developing a project is visible on the one pane limiting the need to navigate between numerous panes.

In terms of modelling in Quest 3D, it is possible to create a scene by adding standard primitives where lighting, texture shading etc can be added however what is achievable is not very sophisticated. To achieve more complex objects, programs such as 3DS Max or Maya should be used. 3D models developed within these applications can then be subsequently imported into Quest 3D using a '.X' exporter.

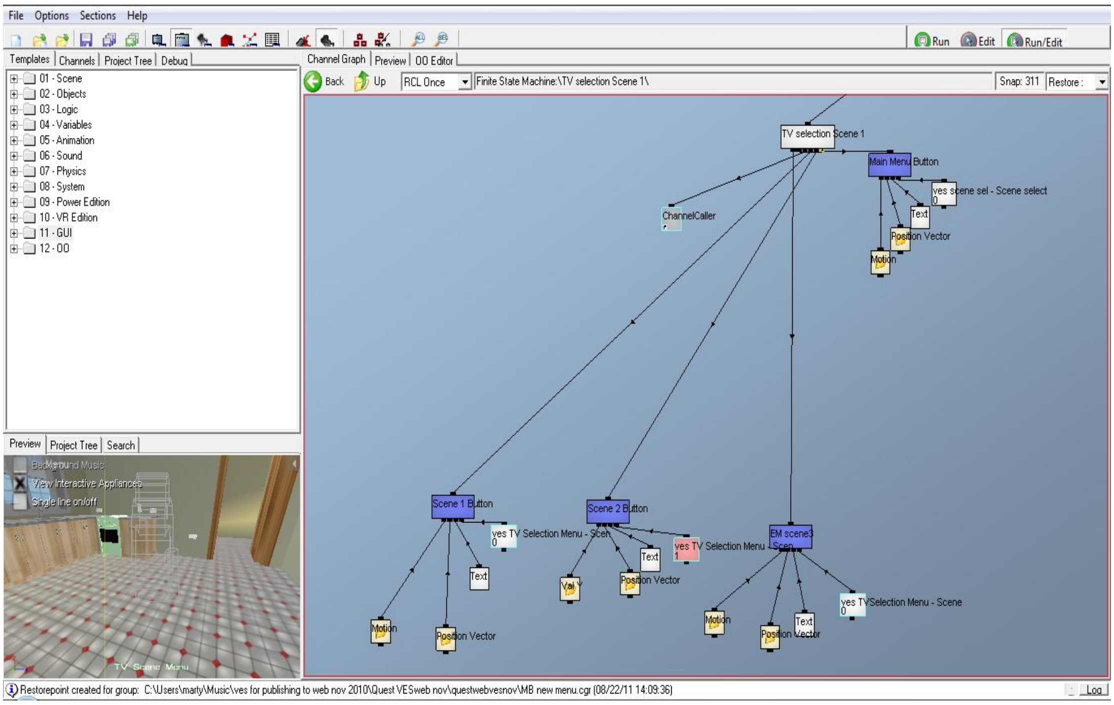


Figure 6-1 Sample channel structure in Quest3D

Once a completed project is tested, there are many methods by which to publish it using Quest 3D. These include a standalone executable file, a player file, a web application or a screen saver. In terms of developing 'VES', the ability to distribute the completed application via the web or as an .exe file was one of the main requirements set down. To run the .exe file on another computer requires the availability of DirectX, however each Microsoft Windows version has this by default. To run the web application requires the user to download a Quest3D player which can be downloaded for free. This is a slight negative and ideally it would be more suitable if the download was not required. That said it is reasonably small and can be downloaded in minimal time. On the upside neither of these methods is bound by additional license fees which are associated with similar commercial products such as Virtools.

To purchase a commercial license for the Quest3D VR Edition costs €9,999. Educational licenses are offered and are very competitively priced at approximately €400 for a single license.[7] Obviously any applications developed with such a license cannot be sold on commercially, but it is ideally suited for research purposes. Notably no further license fees are associated with Quest 3D products. Once you buy the product there are no further hidden charges and extras which is a definite advantage when compared against some of its competitors.

The support and upgrade features associated with Quest3D are also reasonably developed and could be considered user friendly for first time users. Software upgrades are freely available and can be downloaded from the Quest3D website once you are a registered user. Support is offered via the Quest3D manual, video tutorials and also via the very active developer's forum where queries can be posted and support received. Employees of Quest 3D are reasonably active on this forum. Upon reflection the level of support offered is necessary to allow first time developers become competent to a level where developing complex scenes is possible. The support is also of sufficient depth to prevent developers becoming disenchanted with the software.

In conclusion, the justification for the selection of Quest 3D is ultimately based on Quest 3D's ability to afford the author an opportunity to build a prototype model to demonstrate the potential of using desktop VR for enhancing electrical safety and design. In addition, Quest 3D can be purchased relatively cost effectively (educational license) and obtained in a relatively short period. Its user interface is workable and the 'wysiwyg' editor speeds up development time. The number of default channels available makes it possible to find a solution for almost any complex scene required and the ability to publish to the web or as .exe file makes any developed prototype widely available and easily accessed. Therefore in terms of developing a prototype model to achieve the objectives outlined, Quest 3D offers a very good option.

6.3 Modelling Import

As already highlighted what is achievable in terms of modelling using Quest3D is primitive in contrast to more sophisticated programs such as 3DS Max and Maya. Hence Quest 3D is not used to develop complex models. Models are developed in a 3D modelling package and exported to Quest3D for simulation, logic and interactivity.

[7] Quotes for software were received in 2010.

In terms of developing ‘VES’, 3DS Max was chosen as the program of choice to model the 3D scene. 3DS Max is a modelling, animation and rendering package developed by Autodesk. It is frequently used by architectural firms for visualisation, TV commercial studios and by game developers and can be utilised on the Microsoft Windows platform. What was required to be modelled for the development of ‘VES’ was a domestic building which contained the component parts of an electrical installation such as the main distribution board, cables, sockets, isolator switches etc and also the most commonly found electrical appliances in a home such as an electric cooker, shower etc. The practicalities of developing and modelling scenes in 3ds Max is well documented in many text books and on the web, therefore in terms of this research it is unnecessary and of little benefit to the reader to re-trace these steps. However, what may be of interest to the research community is to outline any knowledge gleaned from preparing and importing models into Quest3D which may benefit a fellow researcher preparing to take a similar path.

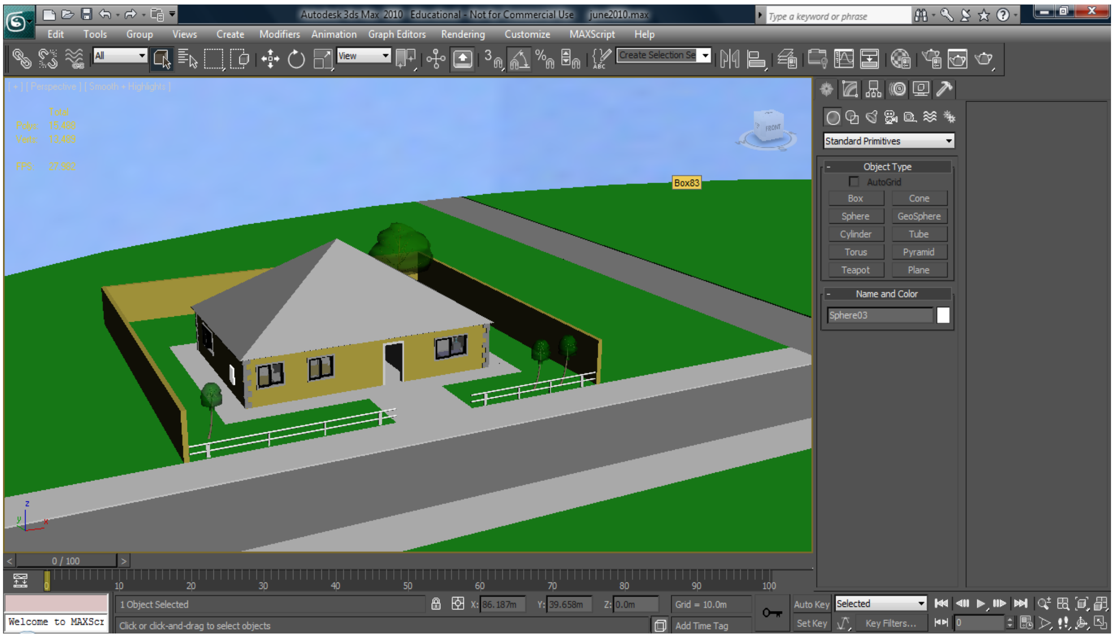


Figure 6-2 3D Model developed in 3DS Max

6.3.1.1 Modelling and Preparation

To begin, as 3D objects form the backbone of 3D scenes, it will be beneficial to outline the principle elements which define the appearance of 3D objects. A **‘**vertex**’** can be defined as a single point in 3D space. Its location is determined by an X, Y and Z coordinate. An example of vertices which define a simple box object is shown above in Figure 6-3. More complex objects such as human characters or buildings may consist of many thousands of vertices. ‘Surfaces’ are built from ‘Polygons’. Generally in real time graphics, polygons have three or four vertices. In Quest3D they consist of 3 vertices, a sample object below illustrates how a cube is broken down into separate distinct polygons.

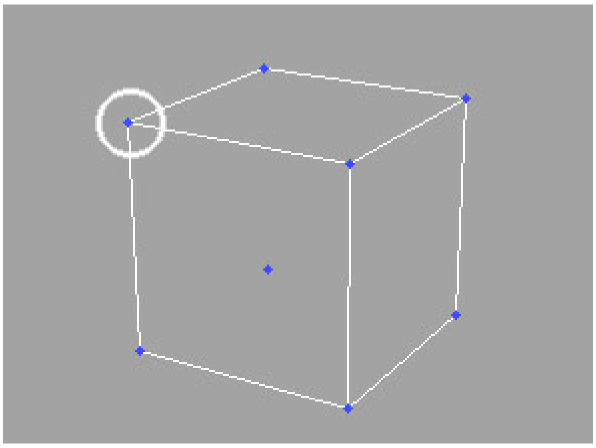


Figure 6-3 Vertices of a simple box object [2]

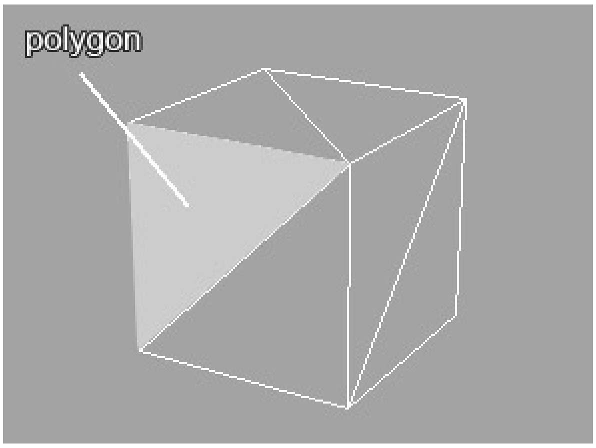


Figure 6-4 Polygons of a cube object [2]

Even though Quest3D does not have a preset limit on how many polygons and objects a scene should contain or how large a 3D scene should be, it is advisable to simplify the scene as much as possible when modelling in a 3D drawing package. A reduction in the number of objects and polygons improves the rendering performance and reduces the file size. However, as a result the visual quality may suffer and in turn decrease the user experience. Hence a balance needs to be struck so that the user experience is not reduced by either the performance or poor visual quality.

In terms of optimising a scene it is worth bearing in mind that Quest3D possesses a real time 3D engine which in effect means that each image is rendered in real time. Therefore in order to maximise the frame rate it is essential that the 3D scene is optimised to its full potential. In order to achieve this, two key areas to focus on include, geometry (as already highlighted should be as simple as possible) and texture size. This can be achieved using the principles of low polygon modelling which combines geometry optimisation with the use of textures to create fake geometry. An example of this can be seen in Figure 6-5 where a texture was used to give the appearance of a tiled roof.

Evidently the use of textures can be quite useful, however when using them there are some useful pieces on information that are worth bearing in mind. JPG textures less than 8x8 pixels may cause DirectX crash. Also, texture sizes must adhere to a power of 2, examples being 8, 16, 32, 64, etc. However it is worth noting that the difference between a 512x512 texture and a 1024x1024 is notable with the latter using 4 times as much memory on a graphics card compared to the former [**2**]. Finally, Quest3D scans the folder where the .X file is exported to for scene textures. If they are absent the textures will not appear in the Quest3D scene. Hence to make sure the textures added in the 3DS Max scene are displayed in Quest3D, it must be ensured that the scene textures are saved in the same folder as the 3D scene.

Figure 6-5 Texture used to give appearance of tiled roof in Quest3D

For the creation of shapes and objects in 3DS Max, parametric surfaces or polygons can be used. However if parametric geometry is utilised, models should be converted to mesh before exporting as Quest3D like most similar products only works with polygon surfaces. Indeed, it is worth bearing in mind that only faces and polygons are visible in Quest3D, lines cannot be exported.

Some other useful modelling tips include:

- Using an 'attach list' which allows many objects share the same material and may shorten editing time in Quest3D. For example if you decide to change the materials of the walls in all the rooms it can be achieved in one step.
- Flickering Scenes in Quest3D - One of the early problems encountered when using Quest3D was flickering, this is caused when two planar surfaces overlap with very little height distance. Being aware of this issue when modelling in 3DS Max can overcome this problem.
- For the creation of complex models such as televisions and sofa's etc many models are freely downloadable from the web and can be directly imported into 3DS Max. This can reduce development time and give the model a more professional appearance. However, regard should be given to the file size in each instance.

Finally before exporting, any unnecessary objects should be deleted from the 3DS Max file and all remaining scene objects should be highlighted. Then using a '.X' exporter which can be downloaded from the web for 3DS Max, export the file to the required folder. '.X' files contain all wireframe, surface, texture assignment and animation data of an object. From here the 3D model can be directly imported to Quest3D. Once imported, Quest3D creates a new channelgroup with the channels that holds the imported data. (For information, Quest3D supports a number of file formats however the '.X' is the main file format of Quest3D) Further advice on making the transition from 3DS Max to Quest3D can be found in [**2**].

6.4 'VES' Software Development

In the final section of this chapter the objective is to give the reader a more in depth overview of how Quest3D operates by detailing the main components and also by demonstrating how program flow is developed. Following on from this, the virtual scenes created in 'VES' will be documented to demonstrate to the reader how the prototype model was developed along with the associated software process.

6.4.1 User Interface

Quest3D's user interface is intuitively configured and is modular in nature meaning the layout can be arranged to suit the developer's preference. By default the editor is partitioned into three main sections, namely the channel, object and animation section. These three sections correspond to the three distinct tasks that are involved in developing a VR application in Quest3D.

The channel section can be considered as the engine of Quest3D. This section which contains the channel graph allows the developer to develop the logic and interdependencies of the channels that are used to develop an interactive scene. The object section allows the developer define the appearance of any 3D objects in a scene. Here, colours, transparency and textures can be added. In the animation section, all objects can be animated and a preview of the end product can be viewed instantaneously. It is also possible to set up cameras and lights in this area.

6.4.2 Channeling

The channel graph in the channel section is the window in which the channel structures are developed. Everything in Quest3D is conceived by inserting links between various components or building blocks which are called channels. Channels which can be seen below in Figure 6-6 can contain any piece of information such as a command, sound or mathematical formula. Each channel type is unique and the base type identifies the channel

functionality. Channels with a similar base type possess the same form of data.

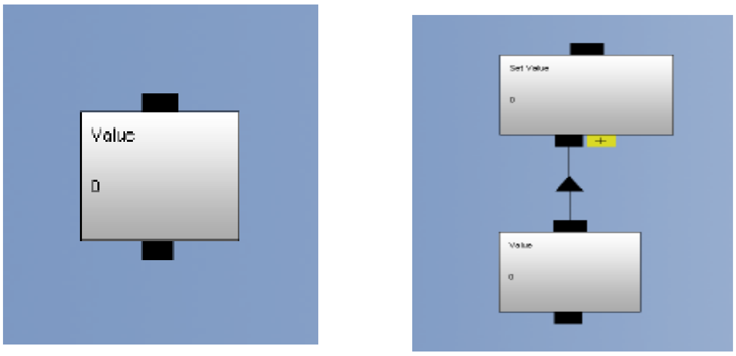


Figure 6-6 Sample Channel in Quest3D (left) and parent child relationship (right)

The term 'channel' comes from, to channel information or functionality, and indeed many channels in Quest3D require other channels to operate. For example a mathematical equation needs input values to produce an output and a camera needs a location in a 3D scene etc., these inputs are called children. The small black squares above and beneath a channel are called link squares. Channels can be linked together by connecting a line between top and bottom link squares. As shown in Figure 6-6, the upper channel is called the Parent and the lower channel is called the Child. However, for a link to be established between a parent and child requires the child type and the parent's available link to be compatible.

New channels can be added to the channel graph by dragging them in from the template list as shown below. Use of templates which are predefined channels or a group of channels can optimise development time. A structured group of channels is titled a channel group and each channel group may have links to other channel groups. Links can therefore end up being established between channels in various files. However, when this occurs i.e. a channel is linked to another channel in another channel group, Quest3D automatically converts it into a Public Channel. Public Channels are channels that can be called from external channel groups and are red in colour to differentiate them from the standard channels.

Creating logic in Quest3D is one of the fundamental components in developing any application. A number of channels in Quest3D are specifically designed to enable this process. Therefore it is worth highlighting a selection of these as they were repeatedly utilised in the development of 'VES'.

The 'If' and 'Ifelse' channels are two of these very useful channels. The 'if channel' only calls its children when a certain condition is met such as the value of the first child link becoming one or alternatively not equal to zero. If this occurs, this channel calls its children. The 'ifelse' channel works in a similar vein except it calls the channel connected to the second child link position if the condition is met and if the condition is not met the channel connected to the third child link position is called. 'Trigger' channels are also very useful and also have similarities to the 'if' channels with two notable exceptions. They only execute their children once and secondly the input condition required to initiate this channel can be varied from a '0' or '1' input requirement in the properties window for this channel. 'Channel switches' allow developers to choose between various channels of almost any type. However it must first be set to the base type of its children. Finally the 'user input' channel can register interactivity from a number of sources including an analog input from a joystick, a binary input from a key or mouse button press or a screen coordinate value such as mouse movement. These inputs can serve as conditions for the 'if' and 'trigger' channels.

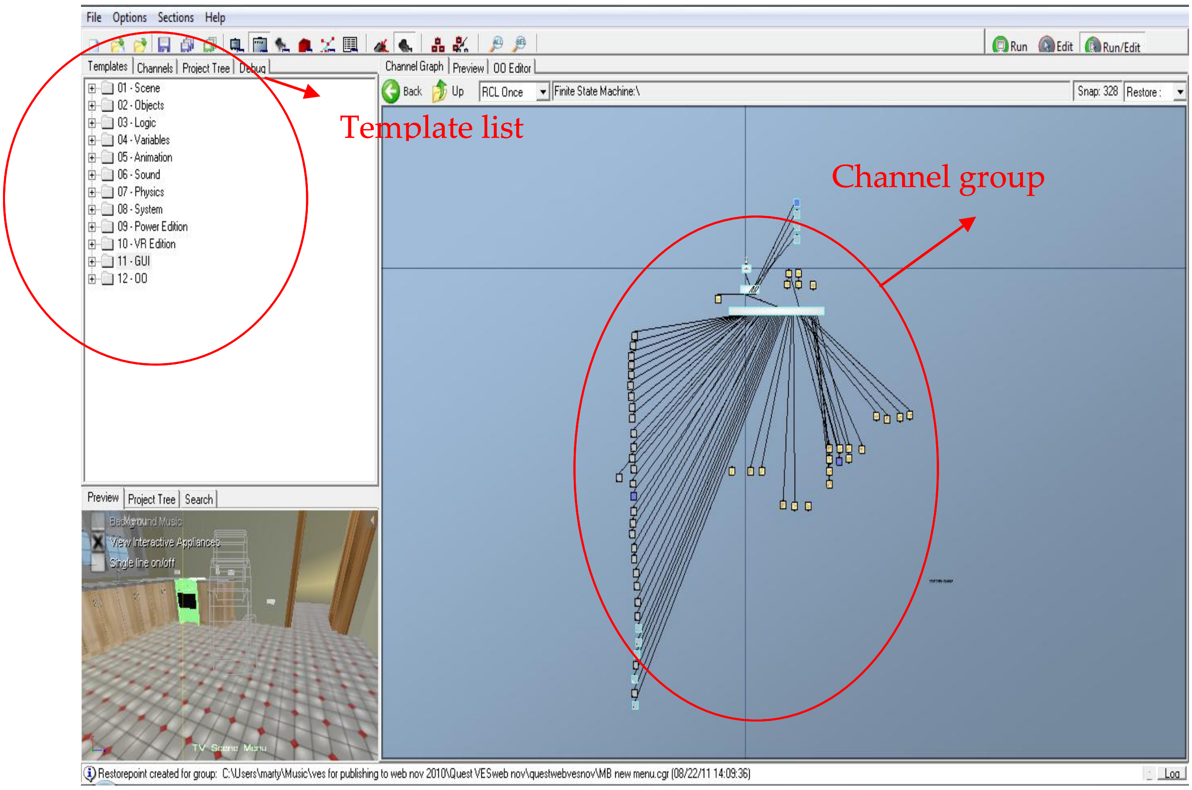


Figure 6-7 Channel Graph in Quest3D

6.4.3 Program Flow

Every channel group in Quest3D has a starting point and every entire project has a start group inclusive of a start channel which alerts Quest3D to where execution of an application should begin. 'Channel Callers' which quite simply call the channels linked to them are used to add structure to a project and allow an application to be logical grouped into its component parts similar to chapters in a book. In Quest3d a channel caller calls its children from left to right. This is significant when developing program flow as triggered actions or data processing may be required to be performed before another action can occur and if this does not occur in the correct order the application will fail to produce the desired result. Cognisance of this detail can save time when debugging any issues.

Once the initial execution of an application occurs, the start channel triggers a response from all its children and all these children trigger their children and so forth. Once initialised, the application can be viewed instantaneously in the animation window.

As already highlighted Quest3D operates in real time which means it continually executes an entire application and revises the preview. One complete loop through an entire projects channel structure is called a frame. The frame rate determines how many times an application is executed per second. A poor frame rate may lead to a jerky display and can result from a highly complex application or alternatively inadequate computer hardware to render a scene correctly.

6.4.4 Development of 'VES'

The purpose of this section is to detail the development of the 'VES' project and to outline the software process involved in its development. 'VES' is broken into three main scenes titled 'Touch Voltage Simulator', Electrical Safety' and 'Electrical Rules and Standards'. The background, objectives and justification for the development of each of these three scenes are detailed in chapter 7 and hence the emphasis here is on the development of such an application using Quest3D. The earlier chapters in this thesis which examined the effects of electricity on humans, how electrical accidents occur in domestic properties, current concerns regarding electrical safety and a touch voltage case study within which a simulator was developed and tested for accuracy using experimental data collected from simulating earth faults in residential premises provide the foundations and knowledge upon which 'VES' is developed. Chapter 1 provides a more detailed methodology which details the research design leading to the development of the 'VES' project.

In terms of the overall design heuristics of 'VES', the ambition was to create an intuitive user friendly project that required minimal instruction for the user. By aiming to do this, it was hoped that the user will experience a unique method of enhancing their knowledge of electrical safety and design that is widely accessible on personal computers via the web. It was thought that a sense of immersion and intuitive interaction was necessary to invigorate the user. Many studies have highlighted the usability problems associated with virtual environments [**81**]. Hence, cognisance is required when developing 'VES' of the art of human computer interface and the methods required to achieve a positive user experience. Sutcliffe and Gault [**161**] provide a good overview of the heuristics required to engage the user effectively.

In an attempt to give the entire project a professional appearance and to give the user clear entry and exit points, it was thought prudent to develop a menu style format to provide a seamless transition for the user between scenes in 'VES'. This was achieved using the 'Finite State Machine' channel, which provides a method to manage complex menu structures. It is possible to create similar transitions using logic channels, however as a project becomes more complex, this can become quite elaborate and cumbersome if future expansion is required. The figure below shows a screenshot illustrating the scene menu in 'VES'. By hovering over the scene titles and left clicking the mouse, access to the scene is granted.

Figure 6-8 Scene menu in 'VES'

The Finite State Machine channel in Quest3D has a number of child links. State changes are triggered by checking the values connected to the first child link. The actual states are connected to the seconded child link, while the third child link can be triggered once on specific state changes. The properties window of the Finite State Machine as shown below in Figure 6-9 is where the design development occurs for this channel. The various states are represented by the blue circles and the black line and arrows determine the transitions possible within a project. Use of this channel which requires a certain familiarity with Quest3D certainly optimises development time.

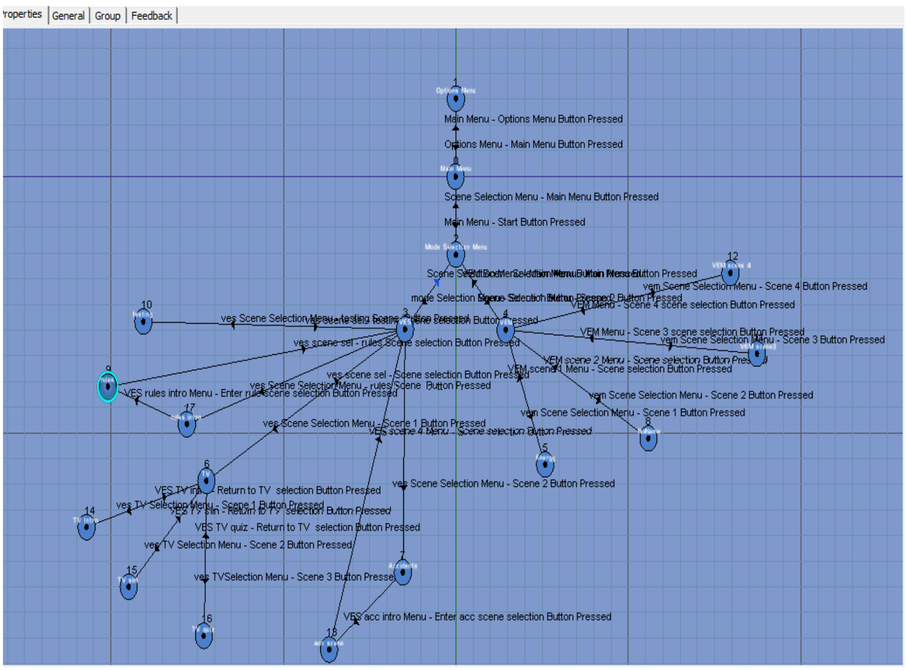


Figure 6-9 Finite State Machine properties window

Another important aspect when developing an application is camera selection as this defines the point of view in which a scene is presented and as such directly influences the user experience. Quest3D offers a selection of camera templates to select from including animation camera, animation camera with target, object inspection camera and 1st and 3rd person walkthrough camera. For 'VES' a 1st person walkthrough camera was selected as this allows the user to walk freely through the scene at standard eye level. As this offers a view as close to real life as possible it provides the user with the highest level of immersion.

Touch Voltage Simulator

Building upon the touch voltage analysis outlined in chapter 5, this scene integrates the simulator developed earlier and allows the user navigate through a residential home and simulate an earth fault under various conditions on numerous household appliances and socket outlets. Upon initiating a fault, the user receives feedback with regard to the touch voltage that could develop under such conditions and also the transfer touch voltages that may possibly develop on healthy appliances. In addition to this, the user can vary the circuit parameters and view the impact of such design decisions. To prevent user frustration a check box can be ticked to identify the 'interactive appliances' in the scene while a single line diagram is also provided to ensure the user is aware of the electrical layout of the installation.

Upon selecting the 'Touch Voltage Simulator' from the initial scene menu, the user is confronted with a further sub menu offering three options; 'Touch Voltage Introduction', which gives the user background information on the theory of touch voltages and navigation advice for the user, 'Touch Voltage Simulator', which grants access to the virtual world and finally 'Touch Voltage Quiz' where the user can evaluate his/her knowledge in this area. All of the above transitions between scenes is developed using the finite state machine channel already explained. Once inside the virtual world the user can navigate through the scene using a mouse and arrow keys. It is acknowledged that this method of navigation can at times be cumbersome and will require a brief adjustment period from the user. However, early in the development stage, accessibility was deemed one of the most important design characteristics. Therefore it was decided on balance that this method was the most appropriate for user navigation as it meant no additional hardware requirements and hence the user audience would not be limited by such a design decision.

In all the scenes, the use of a 'Head Up Display' or Graphical User Interface (GUI) is integral to the development of the project as it allows for user interaction and the ability to provide feedback. In Quest3D the GUI is rendered on top of the original scene. In essence, it is a second 3D scene which is rendered with its own unique camera. Therefore for each frame, the 3D scene is rendered followed by the rendering of the GUI layer which is overlaid on the original 3D scene. To prevent interference between these two separate entities the Z buffer is cleared. For the user to achieve mouse interaction with any of the GUI elements, developers can utilise the 'mouse over' and 'user input channels'. The 'text out' channel can be used to promptly produce 2D text on the screen while 2D images can be rendered using the 'copy image' channel [**2**]. A variety of GUI tools are available from the template list in the channel graph section.

Once inside the virtual world interactive appliances can be viewed by clicking the check box on the top left hand corner of the screen as shown in Figure 6-10. Check boxes are available from the GUI items folder in the template list. By doing this the appliances gently flash green and become clearly identifiable to the user. To create the flashing green appearance a value operator channel is selected which can perform operations on vectors and matrices. By selecting 'loop relative value' the value operator loops between two values. To perform this operation the channel requires three input values. The first value is used as the start point of the looping value. The second is the end of the loop while the third is the value by which the loop is increased or decreased. An example of this can be seen in the figure below where the cooker in the Kitchen is in the process of flashing green.

Mathematical operators such as the one outlined above are used throughout the development of the 'VES' project and are generally used to allow the scaling, movement and rotation of 3D objects in VR scenes. These very useful 'Operator channels' allow developers affect each of these elements dynamically in real-time. Many of the functions of the Value Operator base channel are used to access information from other channels. Examples include use of a Value Operator to obtain a distance (vector, vector) or alternatively a 'Vector Operator' base channel may also be used to retrieve information from other channels such as 'Get Translation position from Matrix'. Transformation of vectors is achieved using 'Vector Operators'. This may range from basic addition and subtraction to multiplication and division of two vectors. 'Matrix Operators' can be used to turn vectors into matrices, such as 'Create Translation Matrix'. Information can also be retrieved using 'Matrix Operators' such as 'Get Current Camera Matrix'. 'Damping' is a unique type of operator which can be used for values, vectors and matrices. Over a period of time it dampens a variable, providing a smooth transition from the current state to the new. The speed can be adjusting using the second child link position and the effect is logarithmic in nature [2].

The single line diagram which can be selected from the check box in the top left hand corner of the scene was included to give the user a visual representation of the electrical installation. It was developed using a separate 3D render channel with its own basic camera and is called by the program after the main scene and only if the check box is selected. The detail of the diagram is developed using Quest3D's primitive 3D objects.

To carry out a touch voltage study, the user can move the mouse over any of the interactive appliances and left click the mouse to bring up the GUI associated with whichever appliance is chosen. From here the user can select to simulate an earth fault from this point in the installation and receive feedback on the value of touch voltage that could possibly develop. The option of carrying out a touch voltage sensitivity analysis and viewing the impact of varying any of the design parameters is also possible. This is achieved using dropdown menus as shown for the various parameters which include, the external fault loop impedance, the open circuit terminal voltage of the supply transformer, the size of the phase and protective conductor and the distance the appliance is from the distribution board. An option also exists to calculate the transfer touch voltages which may develop on healthy appliances which share the same protective conductor.

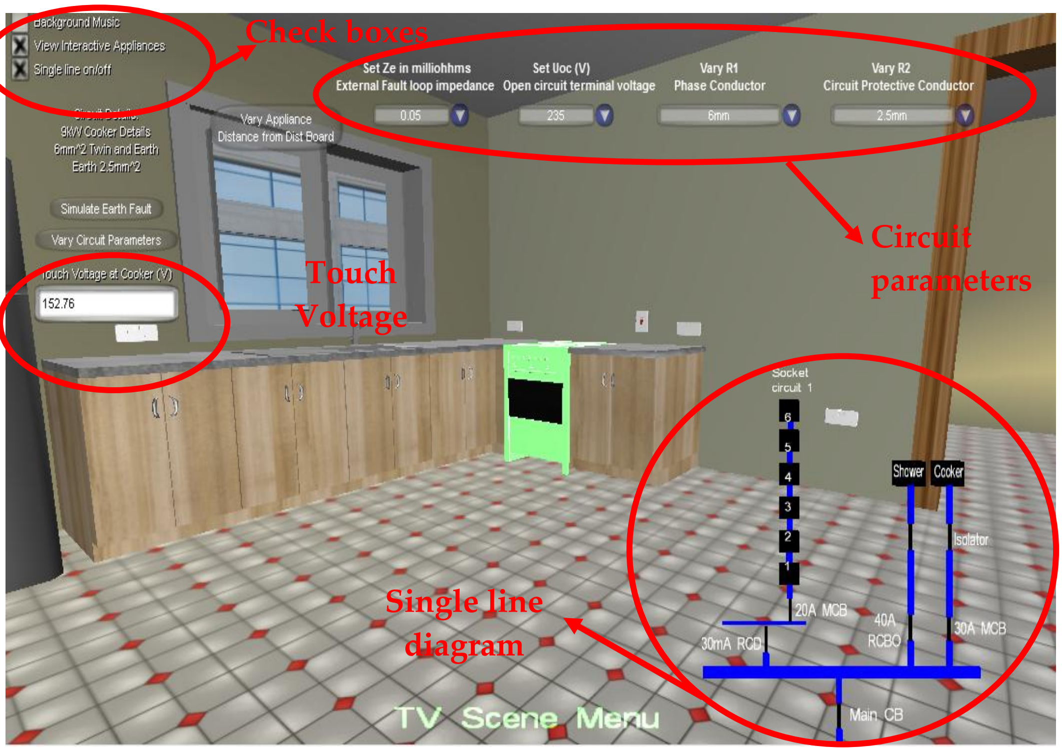


Figure 6-10 Scene from 'Touch Voltage Simulator'

The 'Expression Value' is the channel utilised to formulate the mathematical expressions required to develop the simulator in this scene. Its properties window which is shown in Figure 6-11 is where the mathematical expressions are entered. The actual value of the expression value channel is determined by the result of the entered expression.

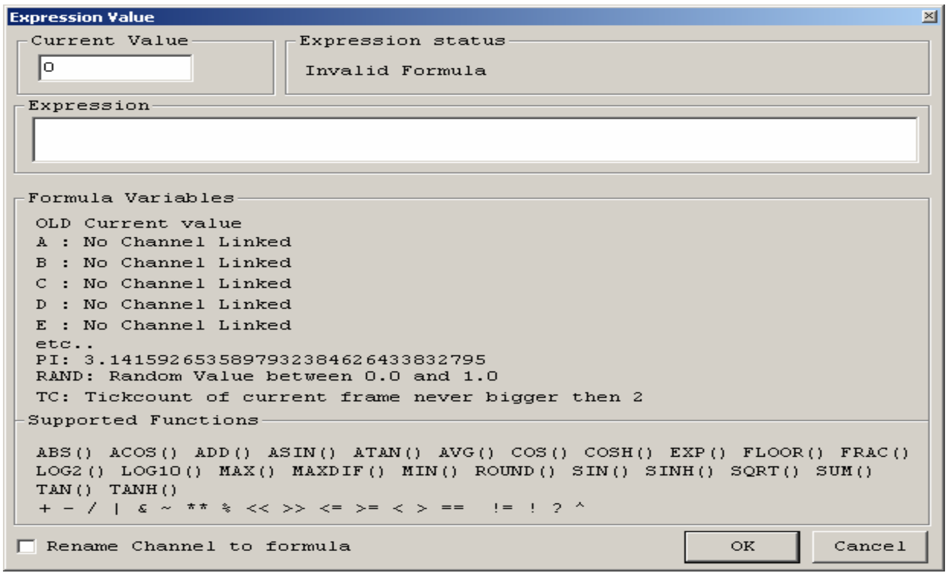


Figure 6-11 Expression Value Channel properties window

Electrical Safety

Collating the electrical accident and safety data examined in earlier chapters, this scene allows users to navigate through a domestic home and receive electrical maintenance advice, safety advice, and also information on electrical accident case histories associated with various rooms within the home.

As the user navigates into the different rooms within the home a GUI with data that is unique to that location is presented. Triggering of each GUI in the various rooms in this scene is initiated by the 'Collision Ray Check' channel. A separate primitive object was inserted under each floor area in the various rooms for the collision ray channel to detect. This ray is determined by the movement vector children and the original position vector [**2**]. Once detection is achieved the value of the channel is set to one and the GUI appears on the screen. Contained in the GUI are three options for the user to utilise; accident scenarios, room safety tips and appliance tips. For accident scenarios an 'array channel' was used to compile a database of accidents associated with that location, once selected the user can select from a range of narrative reports for various accidents within that location. If room safety tips are highlighted the user receives general safety advice specific to that location and finally if appliance tips are selected the user receives electrical safety advice for the interactive appliances that are flashing within the scene as can be seen in Figure 6-12 shown below

Figure 6-12 Scene from Electrical Safety

Electrical Rules and Standards

Using a selection of regulations which were recently updated in ET101 (the national rules for electrical installations in Ireland), this scene illustrates a unique way of disseminating this information. This form of information transfer can benefit installers of installations or aid designers when carrying out electrical designs to inform them of regulations in place at that time.

Initially a sidebar menu was developed in this scene to allow users to transfer between the various regulations highlighted. This was created using the command channel in Quest3D. This channel sends a command to DirectX to set DirectX to a different state and is the first channel called by the 'channel caller' channel in this scene. Subsequent to this the, 3D scene is rendered followed by the logic created within the scene to display the relevant regulations. The regulations highlighted relate to wiring systems, overcurrent protection, switchgear and accessories and zones within bathrooms.

As an example, a screen shot from the wiring system regulations is illustrated in Figure 6-13. Upon selecting this option the user is confronted with two further options to select from, which include 'protection against impact' and 'protection against corrosive substances'. In the figure shown the user can clearly identify the areas of reduced risk for wiring systems highlighted by the dotted lines where mechanical protection is not required. The dotted lines are achieved using Quest3D's primitive objects. Using the radio buttons the user can obtain the regulations associated with solid or hollow walls. The ‘textout’ channel is used to display the text of the regulation on the screen, while the ‘slider’ channel from the GUI template list is utilised to control the physical properties of the wall and make it transparent so the user can visualise the cables which would not be visible under normal conditions.

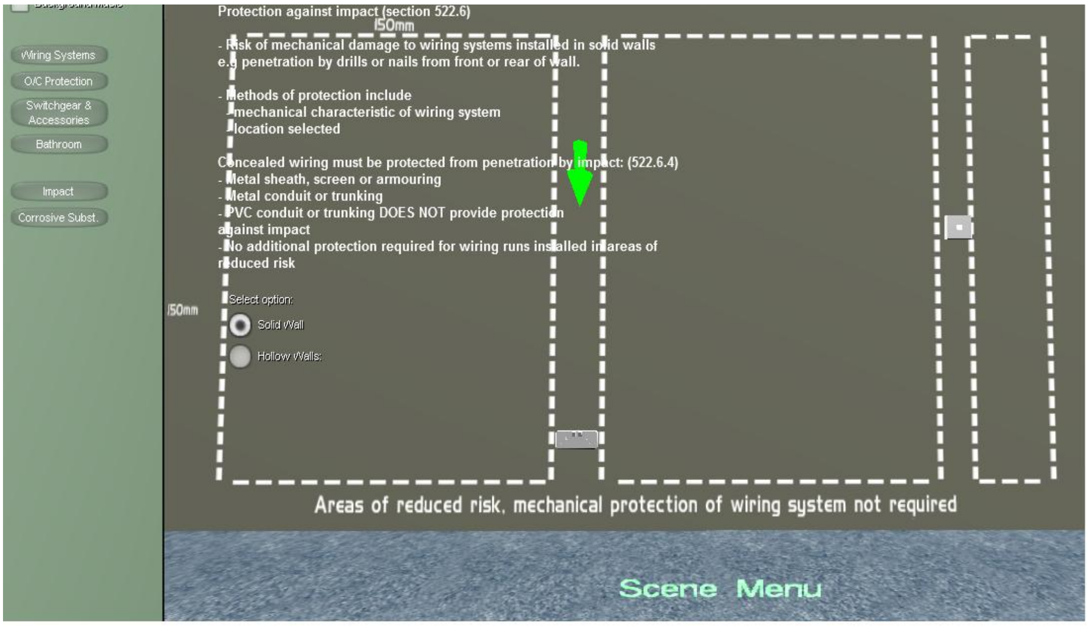


Figure 6-13 Scene from Electrical Rules and Standards

For the various regulations outlined in the different menu options available, the 3D primitive objects used to illustrate each regulation are individually called by different renderers, otherwise every scene would include all the regulations programmed even if they were not selected. This logic is achieved using the ‘channel switch’ channel which alternates between the channels required dependent on the menu option selected.

Ultimately, from prototype scenes such as this and the others which were outlined earlier, it is hoped that the potential for using VR as an educational aid or as a design tool for a practising engineer is identifiable.

6.5 Conclusion

The ‘VES’ prototype application designed to enhance electrical services design and safety in the built environment using a desktop VR system has been set out in this chapter. Justification for the selection of the software chosen was detailed along with an insight into software process involved in the development of ‘VES’. Evidently, developing a VR application still requires significant enterprise particularly if developed on an individual basis, however with properly selected tools such as those set out in this chapter, it is possible to produce convincing results in a relatively short time frame.

The major objectives achieved in this chapter include:

- ❖ A review of available VR systems suitable for the development of an application such as 'VES' is presented.
- ❖ Clear justification for the selection of Quest3D is given.
- ❖ The underpinning basic theory of developing an application using Quest3D is outlined.
- ❖ A prototype VR model is presented which has the potential to improve electrical services design and enhance electrical safety.
- ❖ The scenes developed within 'VES' are illustrated to give the reader an appreciation of the application developed.

Chapter 7

Using Virtual Reality to Enhance Electrical Safety and Design

7.1 Introduction

Virtual reality (VR) can be described as a technology that allows users to explore and manipulate computer-generated, three dimensional, interactive environments in real time [**155**]. Since its origins which can be dated back to [**162**], VR has developed significantly and has gained widespread use across many disciplines e.g. [**7**] [**38**] [**39**] [**91**]. Seen initially as an expensive tool, that required vast investment, it is now possible to illustrate complex, expensive or dangerous systems economically on a computer screen [**126**].

VR systems are generally considered strong in both visual and spatial representation of physical environments. Consequently disciplines that require training in inspection tasks and procedural training [**137**] should benefit from this type of system. VR also offers the advantage of being safe for both user and equipment, while at the same time offering the user an opportunity to be exposed to a range of scenarios that are hazardous to recreate or occur infrequently. The culmination of these factors suggests that VR should not only be an ideal system to enhance the training and understanding of electrical services engineers and electricians but can also play a significant role in creating awareness of electrical safety issues and reducing accident rates within the general public.

This chapter presents the design process of a desktop VR prototype, "Virtual Electrical Services" (VES), which was developed to demonstrate how VR technology can be applied to the electrical services industry and used to enhance electrical safety and design in the built environment. Three interactive scenes using a domestic dwelling as the virtual environment were developed to illustrate this point. The first interactive scene, 'Touch Voltage Simulator' allows the user to carry out a touch voltage analysis of a domestic dwelling and is based on previous studies into touch voltage [**10**]. The second interactive scene 'Electrical Safety and Accidents' demonstrates how electrical accidents occur in domestic premises and provides safety guidance to the user based on the findings of [**12**]. The third scene 'Electrical Rules and Standards' outlines the potential of VR for the dissemination of Electrical Regulations and standards to the electrical services industry to allow for greater understanding and rapid transfer of knowledge.

Electricity is one of the most convenient forms of energy that is used in every building today. The added comfort that it brings to our daily lives in addition to the advances in electrical safety have contributed significantly to our well being in the built environment. However, the inherent risks associated with its use will always exist and will continue to be a priority for the electrical services industry. Previous electrical safety studies have identified the home as one of the leading locations for electrical injury and death to occur [**138**] [**12**] and in recent times greater attention has been drawn to domestic electrical safety due to an ageing housing stock, lack of maintenance and inspection and the increasing use of electrical appliances [**15**]. Consequently, the importance of safe design and the ability to recognise how accidents occur are of the utmost importance. VR is a technology that provides an opportunity to enhance our understanding of these issues, train the user how to interact safely with equipment, while also giving the user an opportunity to interactively design an environment and investigate the consequences safely. Desktop VR has the added advantage that it can be utilised universally due to the widespread availability of computers. In short, VR can add value to the electrical services sector and has the potential to become an integral part of training for third level students, electricians, design engineers and a valuable electrical safety tool for educating the general public.

This chapter presents an overview of VR development systems and tools concentrating on the software used in this prototype model. It reviews previous VR engineering applications, outlines the development of this prototype model and presents an in depth explanation of each scenario developed. A discussion is then presented of the potential for future development of this VR prototype and concludes by presenting the findings of this chapter and outlining the benefits of using VR in this sector.

7.2 Virtual Reality Technologies

Previously, public expectations exceeded the ability of VR to deliver realistic applications within meaningful timescales. The root causes of this can be attributed to inadequate PC hardware, costly investment requirements and over optimistic coverage in the media. User disappointment resulted in the practical benefits of VR being questioned and the consequent drifting of funds to new and emerging fields of interest. However, steady progress by small groups of scientists who continued their VR research [**30**] led to the rebirth of VR in the late 1990's [**148**]. The main contributory factors for this re-emergence can mainly be attributed to the rapid advancements in PC hardware which occurred during this time. Central processing units became much faster along with speeds of PC base graphic accelerators. As such, this meant that VR was much more accessible and the consequent growth inevitable. To emphasise this point VR went from a $50 million dollar industry in 1993 to $1.4 billion dollar industry in 2000 [**30**] and this is estimated to reach $4.3 billion by 2012 [**70**].

VR systems are generally classified into four main categories which are determined by their display technology; immersive, semi immersive, projected and desktop. Immersive VR systems aim to completely immerse the user inside a virtual environment ensuring the user has no visual contact with the physical world. This is generally achieved by using a Head Mounted Display (HMD). With this device, the user views the virtual environment through two small screens placed in front of his eyes and motion trackers monitor the user's movements and update the virtual scene via the attached processor accordingly. Immersive VR systems generally offer the greatest sense of immersion in a virtual environment, and allow the user move around in an intuitive manner in comparison to other systems. Nevertheless, there are commonly acknowledged shortcomings related to immersive VR and side effects such as eye strain, nausea and dizziness associated with its use are well documented [**92**] [**154**]. Semi immersive VR combines a virtual environment with a physical model. A car driving simulator would be one such example, whereby the drivers use a head mounted display to view the virtual environment and a physical steering wheel, gearstick and pedals etc to control the simulated driving experience. In projected systems such as CAVE (Cave Automatic Virtual Environment) the user is surrounded by stereo images which are projected onto screens. The user can walk freely within the CAVE and view the virtual environment with stereo glasses. In a similar fashion to immersive VR systems, motion tracking devices adjust the projection of the images onto the screens to account for a change in user position. Despite the truly impressive nature of some of the applications developed using the systems outlined above, cognisance must be taken of the significant initial investment in specialist equipment required to develop such applications and also in the ability to make them accessible to a far reaching audience.

Desktop VR systems display their virtual environments on a conventional pc monitor and interaction is generally achieved by using the associated mouse and keypad. However, it can support other visual and interaction devices such as 'shutter glasses' and 'joysticks' to name a few. In contrast to the systems outlined above, desktop VR offers a much more simplistic, versatile and less expensive method to develop a VR system, albeit at the expense of a more immersive experience. As outlined by [**45**], desktop VR systems have received criticism for not utilising the full potential of the three dimensional and 'presence' qualities of higher end VR systems, as images are essentially still two dimensional. In addition, desktop VR systems uses a screen of limited size in a fixed location, it does not fill the user's complete field-of-view, and hence it is possible to get distracted by objects in the peripheral view which ultimately impacts on the user's feeling of presence. However, since desktop VR systems can be utilised on standard computer systems and also projected onto larger screens for group instructional training, its relatively simple and inexpensive set up costs added to the accessibility offered via the World Wide Web makes it a very appealing system. Undoubtedly, the global accessibility by multiple users to desktop VR is one of its major proponents and for many VR applications, desktop VR will continue to be the way forward.

7.3 Virtual Reality Development Tools

Selecting the most appropriate VR development tool is an essential component in developing a VR application. The level of flexibility and pre-programmed components can vary substantially between packages. Many features require careful consideration from a developers point of view such as file formats supported for importing 3D models, number of polygons, object scaling, animation, collision detection, extensibility, support for input/output VR devices, 3D libraries, widgets, developer support and methods of publishing a completed application.

As outlined by [**158**] VR development tools can be categorized into three main groups, Application Program Interfaces (API's), Software Development Kits (SDK's), and Authoring tools, the latter being the tool utilised in the development of the 'Virtual Electrical Services' application outlined in this chapter. Generally, an authoring tool is an icon-based application coupled with a graphical user interface (GUI) that enables the author to develop a unique style of programming. The tool is designed for users with nominal programming knowledge. Instead of having to write lines of code, developers make use of a set of building blocks. This approach significantly widens the market for VR applications development. Developers in various fields suitable for VR applications can enhance understanding, transfer of knowledge and learning potential for employees, clients, students or the general public in their areas of interest. Typically, to develop a fully operational inviting VR application, a user links together objects such as 3D objects, lights and cameras etc. in a graphical interface and defines their relationship in a sequential and logical structure. Many authoring tools also support some form of a scripting language that will allow for more elaborate interactivity and icon development. Examples of authoring tools currently available in the market are: Virtools, Eon Studio and Wirefusion.

The VR application presented utilises the authoring tool Quest3D as discussed in detail in chapter 6 developed by ACT-3D B.V. As previously highlighted Quest3D allows for a relatively short development time and low development cost when using an educational license. This was a significant factor in choosing this particular application for the development of VES. In addition, Quest3D does not generate pictures or 3D models; instead the developer creates a repository of pictures, 3D meshes and sounds in a separate program and imports them into Quest3D. The basic building blocks in Quest3D are the so-called 'channels'. In brief, a channel is a reusable component that contains a piece of application logic. This component is able to interact with the Quest3D interface engine and other channels.

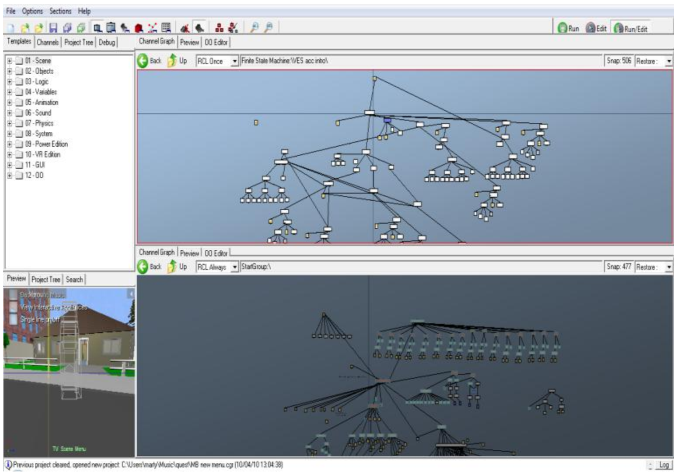


Figure 7-1 Overview of the Quest3D user interface

By creating a hierarchical logical framework of linked channels (see Figure 7-1) an interactive application can be developed. Quest3D contains many default channels, allowing for the development of a wide range of applications. If more functionality or interactivity is required, the C-based Lua scripting language can be used to create new channels. In general, by employing this graphical form of scripting, experimentation with program flow is easier and there is also no concern regarding syntax errors. Quest3D also affords realtime feedback with no need to compile code. The ability to create successive iterations of your application with instant visual feedback is a beneficial feature and it shortens debugging time. Quest3D use a DirectX 9 game engine and hence is supported by all DirectX 9 compliant graphic cards and operating systems. The hardware requirements to run the VES application are Intel Pentium III or Higher or AMD Athlon processor, 512MBytes RAM, Hardware accelerated DirectX compatible graphics card and 1024x768 display resolution [**140**].

Finally, accessibility and ability to communicate with the published VR application is often a major concern for developers. Quest3D supports a large number of delivery formats including web, executable, installer and windows screensaver but it requires the user to download and install a plug-in in order to view the content. However, the size of the plug-in is relatively small and its installation does not require technical competence.

7.4 Virtual Reality in Engineering Training

The application of VR technologies for engineering design, training and education has generated much interest across many sectors of the engineering community. This is not surprising as using VR technology to build virtual training systems has the advantages of being safe, economical, controllable and repeatable [**124**]. Virtual Reality also offers the ability to expeditiously attain proficiency and knowledge which is a critical factor for the profitability and sustainability of companies, governments and training organisations. In an era where regulatory practices are amended on an ongoing basis there is a requirement on the part of industry and higher education institutes to provide training methods that will allow trainees to quickly and cost effectively up-skill and attain knowledge to adapt to the new and rapidly emerging practices and associated technologies.

Both educational theory and cognitive science support the role of VR as a training tool [**137**]. According to [**37**], the main pedagogical driver that motivates the educational use of VR is constructivism. Constructivists assert that individuals learn through their experience of the world, through a process of knowledge construction that takes place when learners invest intellectually in meaningful tasks [**41**]. From this it can be concluded that interaction with an environment or process is key to the learning process and perhaps outside of actual reality, VR offers one of the most appropriate methods to create a contextualized trainee activity. It is also recognised by [**174**] that using VR can enhance cognitive learning through active participation in tasks, increased motivation and flexibility in terms of time and location. Through active participation, trainees in VR can make decisions without real world consequences and they can effectively learn by doing and hence become active in their own learning. This in many respects is in contrast to traditional educational methods which rely on the trainee attaining knowledge from teachers and literature and then subsequently attempting to apply this knowledge to the real world. Situated learning theory also suggests that VR maybe an advantageous tool as it asserts that knowledge should be learnt through contextualised activities in authentic situations that reflect the way in which the knowledge will be used [**118**]. In any case, research in human learning processes to date outline that humans acquire more information if more senses are involved in the acquisition process and as such VR can be a beneficial tool.

VR has been employed with varied success across many engineering disciplines, examples of such systems include; a VR safety-training system for construction workers [**172**], application of VR for the teaching of semiconductor device physics [**156**], using virtual reality to enhance the manufacturing process [**129**] and VR technology applied in Civil Engineering education [**151**]. VR systems specifically related to the electrical industry include; VR systems used to train electrical sub-station operators [**147**] [**26**] [**5**] [**169**], a VR training tool developed to allow electricians and builders better understand each other's concerns in an attempt to prevent costly mistakes [**158**]. [**174**] outlines the development of a prototype simulator to support electrical safety awareness in construction, while a VR system for training electricians in electrical inspection and testing is currently in operation in the UK. [**133**]. No known VR systems, considers the applications developed in this thesis.

7.5 Virtual Electrical Services

The fundamental objective of VES (Virtual Electrical Services) is to develop a prototype VR simulator to demonstrate the potential benefits of employing virtual reality to enhance electrical services design and safety in the built environment. The potential market for which the VR system could add value includes undergraduate engineering students, practicing electrical services engineers and the general public, who perhaps could benefit from the electrical safety advice and instruction contained in a potential virtual electrical safety manual. From an educational viewpoint, VES is not seen as a replacement for traditional teaching methods, but merely as a complementary teaching resource that could significantly enhance student understanding and motivation. VES has the potential to engage students and present problems which they can investigate and solve in their own time. This offers encouragement to students to become more active in their own learning in an environment which relates to the problem. Practicing engineers could use the application to grasp emerging technologies or recent changes in regulations that could influence their designs. VES could also be utilised as a continual professional development application for industry.

In order to provide the user with the highest degree of realism the following were set as the benchmarks for the VES application; 1) visual representation of an electrical installation in the built environment, 2) simulation and representation of the functionality of the installation, 3) strict adherence to the appropriate electrical rules governing the installation under investigation. In addition the VES application had to ensure the provision of interactivity in an intuitive manner and provide accessibility to the application across the widest range of platforms and interested parties.

The following sections describe the creation of the virtual environment and the applications developed within VES.

Figure 7-2 Virtual environment created for VES application

The initial development stage required the construction of 3D models of the residential building, surrounds and the different components of the electrical installation using a conventional 3D modelling software, 3D *Studio Max* (See Figure 7-2). Detail in the geometrical modelling was sacrificed to ensure optimisation of the real time rendering capabilities of the software which can be adversely affected by complex geometry and excessive texture sizes [**58**].

Many real-time 3D applications use the principles of Low Polygon Modelling. This is the amalgamation of geometry optimisation and the use of textures to create bumps [**58**]. Using 3D Studio Max, it is possible to develop a model with polygons or with parametric surfaces. If parametric geometry is used, all objects should be converted to 'editable mesh' before exporting because Quest3D like many similar applications work with polygon surfaces. Once complete, the 3D models are exported from the animation software to .X format and imported into the development environment.

The VES prototype application consists of three interactive scenes. A user interface allows the user to enter and exit each scene in an intuitive manner. Each of the applications developed are now discussed.

7.5.1 Touch Voltage Simulator

Protection against electric shock by earthed equipotential bonding and automatic disconnection of supply which gives rise to touch voltages is a universally agreed protective measure used by electrical designers for general applications and implemented in approximately 95% of all electrical installations. As protection against electric shock is one the most important design criteria for electrical services engineers, the ability to understand how touch voltages develop and how they are calculated is imperative.

For the purpose of this chapter, we shall define 'touch voltage' as a difference in voltage potential experienced by a person who makes contact simultaneously with more than one conductive part, which is not normally energised. The touch voltage U_t can be calculated using a simple voltage divider circuit:

$$U_t = U_{oc} \frac{R_2}{Z_e + R_1 + R_2}, (V) \tag{7.1}$$

Where,

U_t = touch voltage,
U_{oc} = Open circuit voltage of the mains supply
R_2 = circuit-protective-conductor resistance
R_1 = phase-conductor resistance
Z_e = Earth-fault-loop impedance external to the faulty circuit

From IEC 60479 part 1 [**97**] (Effects of current on human beings and livestock), when the touch voltage is 50V a.c. or less under normal dry conditions, the body impedance of a person is high enough to prevent a touch current of high enough magnitude to cause any injury.

One of the principle objectives of VES is to allow users enter a virtual electrical installation and investigate the touch voltage that could develop under different design parameters for various earthing conditions. It has been developed primarily as an educational training tool for third level students in Dublin Institute of Technology (DIT) who wish to enhance their understanding of touch voltage design. However, designers and installers of electrical installations may also find this simulator beneficial. In any case, users who familiarise themselves with the simulator can quickly immerse themselves in touch voltage design, identify the potential touch voltage under fault conditions and investigate the necessary design criteria to achieve a safe touch voltage design.

The touch voltage simulator application itself is broken up into three separate components. Initially the user is presented with an introductory scene which informs the user what touch voltages are and how they develop. This section also gives instructions how to manoeuvre in the virtual environment. The second section is the touch voltage simulator itself. Here the user is situated in the virtual environment. By moving through the environment using a mouse/keyboard interface the user can enter the virtual home and interact with the electrical installation. The third component presents the user with a multiple choice assessment exercise to examine some of the fundamental design questions related to touch voltage design.

To make the touch voltage simulator as intuitive as possible the user is presented with two check boxes which can be activated and de-activated on the graphical user interface (GUI). One of the check boxes allows the user to view a single line diagram of the electrical installation on screen via a head up display (HUD). The second check box allows all interactive appliances to flash on screen. Previous usability studies of virtual environments have demonstrated that users have a tendency not to recognise or be oblivious to what is or is nor interactive [**3**]. Making the interactive appliances clearly visible can potentially improve usability and help prevent user frustration which could ultimately reduce its effectiveness as a training tool.

Within the simulator the user can walk around the virtual electrical installation and interact with or simulate an earth fault on any of the interactive appliances, such as the main distribution board, cooker circuit, shower circuit, socket circuit etc. For example in the case of a socket circuit when the user points and clicks at one of the interactive sockets in the virtual installation s/he is presented with the circuit details and a menu of options via the GUI. Assuming that the chosen option is to simulate an earth fault then the potential touch voltage under these circuit conditions is presented. If the user wishes, it is possible to vary the four major design parameters U_{oc}, Z_e, R_1 and R_2 that govern the value of the touch voltage. By varying any of these parameters the touch voltage automatically updates and the user can immediately view the impact of any design decisions. It is also possible to view the transfer touch voltage that could develop on the other socket outlets related to that circuit under fault conditions and any variance in the design parameters will also update the transfer touch voltages in realtime. A visual example of the GUI and the interactive cooker appliance can be seen in Figure 7-3.

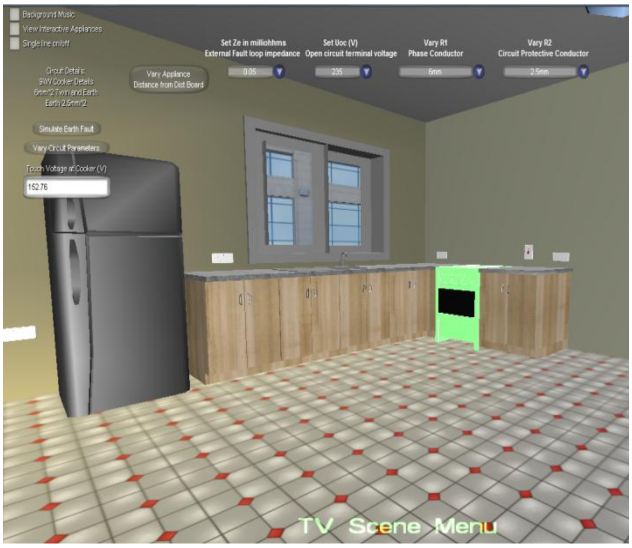


Figure 7-3 View of kitchen and GUI in VES

Familiarity with the virtual environment can allow users to quickly become absorbed in touch voltage design. In this way the user can easily identify if a potentially dangerous touch voltage will develop and the possibility of designing a circuit to have a transfer touch voltage not exceeding 12 V to provide protection against electric shock for a person with very low body resistance in a special location (e.g. bathroom) and 50V for all other dry locations. Adopting the use of the 'touch voltage simulator' as an educational tool is a more student centered approach and shifts away from conventional learning techniques to one where students can self learn by investigating the touch voltage outcomes for their own inputted data in their own time.

7.5.2 Electrical Safety and Accidents

Electricity is one of the most clean, convenient, easily distributed and reliable sources of energy that is used in every building today and the comfort that it brings to our daily lives has greatly improved our standard of living. In addition to this, advances in protective devices and wiring practices in conformance with modern standards have all contributed to higher levels of electrical safety since the introduction of electricity into buildings more than a century ago. Nonetheless, the implicit risks associated with the use of electricity will always exist and will therefore continue to be of major concern to the electrical services industry.

Statistically it has been shown that domestic properties are one of the leading locations for electrical injury and death [**138**]. A further investigation into electrical accidents by the author [**12**] also singled out domestic properties as one of the prime locations for electrical accidents to occur. This investigation highlighted over the years investigated that approximately 46% of all fatalities due to electric current in England and Wales occur in domestic premises and identified 25–34 year olds as the main at risk group to electrical injury. Worryingly 0–4 year olds were also highlighted to be a vulnerable group. The investigation concluded that accident rates can be reduced if electrical installations are designed correctly, adhere to current wiring standards, maintenance is performed correctly and periodically and occupants are aware of the dangers of electricity and how accidents occur. In addition, a report produced by five international organisations details the growing concerns for electrical safety across Europe [**15**] and it suggests that more can be done to make premises safer. Therefore the ability to raise awareness, recognise how accidents occur and enhance electrical safety knowledge among residents, landlords, building managers and owners is vital.

VR provides an opportunity to deepen society's understanding of these issues, raise awareness of potential dangers, train the user how to interact safely with equipment and instruct owners how to carry out maintenance safely. The prototype VES application addresses these concerns and emphasizes the potential benefits of using VR for this purpose.

When the user enters the virtual environment, s/he is presented, via the GUI, with an array of general electrical safety statistics derived from [**12**]. The purpose of this information is to give the user a general overview of how electrical accidents occur in residential dwellings and to outline statistically who are the most likely victims. Subsequently, if the user chooses to navigate through the virtual home, electrical safety guidance associated with the user location can be obtained via the GUI. The unique information provided for the user in each location is broken into three sections. The first presents a database of accident scenarios associated with that location based on information obtained from a HASS/LASS report that was compiled by interviewing patients who attended Accident and Emergency units in hospitals across the UK. [**59**]. The ability to select from a range of electrical accidents in the database enables the user to see how accidents occur and the measures required to prevent such accidents. The second section provides general safety advice related to the users' location and the third section provides safety guidance and maintenance advice for the electrical appliances installed in that location

Ultimately, enhanced communication via VR can highlight the main risk activities associated with the use of electricity in the built environment. It can also provide education on good maintenance practices and enhance the prevention of injury. Owners and occupiers who can identify key safety issues, which allow them to monitor the condition of their installation and carry out minor repair work safely, can significantly improve safety levels [**12**]. Also, heightened levels of awareness among the public of the potential dangers may improve the renovation rate of electrical installations and hence electrical safety in the built environment

7.5.3 Electrical Rules and Standards

Electrical rules and standards are the fundamental guidelines for all electrical installations to ensure a safe environment in which to live and work. The use of a virtual reality training tool to educate students, contractors and engineers on these regulations is an exciting and novel prospect. In Ireland, ET 101 [**74**] is the national rules for electrical installations. On occasion these rules are updated to enhance electrical safety and to ensure harmonisation with CENELEC and IEC standards. Dissemination of the rules via VR can perhaps assist the electrical services industry in the transition between standards and also provide for a clearer interpretation and deeper understanding of the rules amongst practising engineers and students.

Electrical rules and standards such as ET 101 [**74**], BS 7671 [**101**] and IEC 60364 in their current format are well documented and each section is clearly defined. However, the language used in these documents is technical and often complex and the precise interpretation of the rules on the part of the reader requires experience and a strong technical knowledge. The use of visual aids to assist in understanding and interpretation must be viewed in a positive light. It is this author's opinion that a virtual representation of the rules and standards will enhance the method by which knowledge is currently transferred and help students and practising engineers develop a greater appreciation of the rules and standards

Furthermore, as standards evolve from one version to the next it is incumbent on governing authorities to disseminate information pertaining to the updates often in the form of multi-location seminars. The time and cost involved in this process could perhaps be reduced if Web based VR applications such as 'VES' are utilised as a companion training tool by the relevant governing bodies. The fact that desktop VR applications are reusable, convenient to update, can potentially reduce training budgets and can be distributed via the web presents a very attractive option for the industry.

To demonstrate the potential of this novel approach a number of the current rules in ET 101 are demonstrated in the VES prototype. Examples of these include: protection against impact required for wiring systems installed in solid and hollow walls; in the area of switchgear and accessories, the mounting heights of light switches, control devices, socket outlets and distribution boards are demonstrated; in relation to bathrooms in residential dwellings, the zones and the equipment permissible in each zone for these *special installations* are clearly identified (see Figure 7-4).

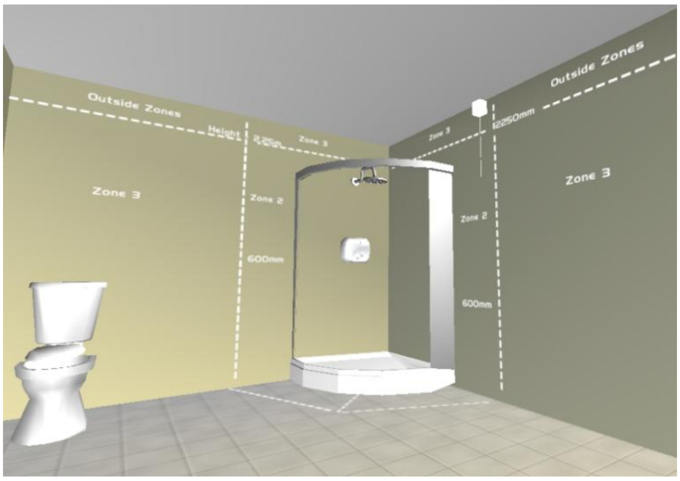


Figure 7-4 View of Zones in bathroom in VES

Currently there are no known electrical governing bodies or training colleges utilising VR in this fashion. One of the objectives of this thesis is to highlight the potential VR offers the industry with regard to enhanced understanding of the regulations. If the view is taken that VR can enhance the learning effect, one could perceivably argue that through enhanced understanding, VR could lead to increased adherence to standards and hence an overall improvement in safety.

7.6 Discussion

'VES' constitutes a first attempt at attaching a new dimension to the training of electricians and electrical services engineers. Although in its infancy, the successful development and early implementation of this prototype desktop VR application suggests that 'VES' could be a valuable tool for the industry and could also enhance electrical safety awareness and knowledge of the general public. Based on the initial developments outlined in this thesis, it is worth highlighting the potential for future growth to progress VR in this sector.

It must be acknowledged that desktop VR does not utilise the full 3D potential recognised in other more immersive virtual environments. However, it does offer a very useful tool for training that can be widely distributed and easily accessed via a personal computer. Desktop VR also offers a proficient substitute for situations that are either impossible or too expensive to set up in a commercial company or training facility. Modern computers have added impetus as VR scenarios that previously required large and expensive equipment are now possible and graphical programming environments provide for an efficient method to develop an application. Hence the ingredients required, to make desktop VR commercially viable such as swift scene creation, platform reliability and flexibility are arguably here.

'VES' demonstrates the potential for a virtual electrical services design training application. An enhanced application could be used to educate students over a wider variety of design areas. Currently one of the most significant drawbacks for engineering students who attend university immediately after second level is a lack of experience of real world engineering situations. VR offers an opportunity to bridge this gap and provide a safe environment that is less critical should an incorrect decision be made. A virtual design environment such as this allows the user to investigate different scenarios and become more active in a learning environment. The facility also exists to set tasks for the user and let the training simulator carry out an evaluation of the user's performance in real time.

A comprehensive virtual guide to electrical rules and standards could be developed. This could prove to be a very useful tool for governing bodies and electrical contractors associations as a way of communicating with installers and designers of electrical installation. The clear instruction that can be obtained from a virtual demonstration could lead to greater understanding and adherence to the regulations.

Although every dwelling contains an electrical installation none are equipped with a safety manual. A virtual electrical safety manual for the general public could be developed based on existing manuals such as an operating manual for an intruder alarm. This virtual manual could outline how to operate, maintain, test and isolate electrical systems and appliances and could easily be adapted to give feedback on electricity consumption within the home. It could also be used to demonstrate where cable runs are in walls and hold a general safety record of the installation. Bearing in mind the fact there is no requirement for periodic inspection of domestic properties unless perhaps they are tenanted or communal properties, a virtual electrical safety manual could reduce accident rates, increase renovation rates and improve overall electrical safety. A similar virtual safety manual could also be brought to a commercial level whereby facility managers could have a virtual operating manual for the building under their control.

7.7 Conclusion

An application designed to enhance electrical services design and safety in the built environment using a desktop VR system has been set out in this chapter. The system allows full navigation of a virtual environment and interaction with many of the electrical elements. 'VES' can be used as a training tool to improve electrical services design, enhance electrical safety and provide a unique method to disseminate electrical rules and standards. The 'VES' prototype is in its early stages and an in depth evaluation of the system with students from Dublin Institute of Technology is outlined in chapter 8.

The establishment of VR training systems similar to the prototype discussed in this chapter can add value to the electrical services industry. Some of the key advantages are:

- VR offers the user an opportunity to be exposed to a range of scenarios and conditions that either occur infrequently or are hazardous to replicate.
- VR offers a low-cost alternative to creating full-scale real life training mock ups.
- VR is reusable, convenient to update, readily customised and can potentially reduce training budgets.
- Using VR as an educational tool shifts away from conventional learning techniques to one where users can self learn.
- VR can motivate and encourage students to become more active in their own learning
- Use of VR as an educational electrical design tool can enhance designers understanding and improve electrical safety
- VR can play a significant role in creating awareness of electrical safety issues and reducing accident rates within the general public
- VR can increase awareness and understanding of electrical rules and standards among practicing engineers and students.

Undoubtedly the capacity to replicate electrical installations in a virtual environment which affords the same functionality is a very interesting option and it is hoped that the prototype outlined in this thesis can provide impetus to the electrical industry to use VR technology to further enhance electrical safety and design in the built environment.

Chapter 8

Virtual Reality Model Evaluation

8.1 Introduction

Over the last decade advances in technology have brought about significant development across a broad spectrum of our social, cultural, physical and educational systems. These developments are clearly emphasised by the notable growth and advancements of computer technology applied to a diverse range of applications such as smart phones, cameras, medical devices and communication systems [**72**]. One facet of this metamorphosis is Desktop VR which is steadily establishing itself as a popular medium to transfer knowledge in modern education and training facilities due to its capacity to afford real time visualisation and interaction within a virtual world that closely mirrors a real world [**121**].

Previous research [**78**] has demonstrated that computer based instruction and training can be an effective learning and design tool. Virtual reality can further enhance the effectiveness and realism of these systems via the additional interactivity and immersion offered. Successful working examples have been developed in diverse fields from medical [**116**] to engineering [**69**] to aiding children with development disabilities [**40**]. Historically however, these systems were generally limited to the minority and not widely accessible. In recent times this trend has diminished, mainly due to the culmination of significant price reductions, rapid advancements in computer processing power along with the proliferation of broadband connections. Consequently the use of desktop VR for research and development has escalated and become widely accessible as VR systems can now operate on relatively cheap systems such as the ubiquitous PC. Furthermore, with the development and maturity of commercial VR packages such as Quest3D [**140**] and Virtools [**56**], it is now possible to create professional VR applications in a relative short time span that have the flexibility to support the development of an online training and design environment.

This chapter presents an evaluation of the prototype desktop virtual reality model titled 'VES' (Virtual Electrical Services) developed to demonstrate how VR technology can be applied to the electrical services industry and used to enhance electrical safety and design in the built environment. In the considered context, users can navigate through a domestic home using a mouse and keyboard, interact with electrical appliances, carry a touch voltage study and sensitivity analysis, determine the most dangerous location of electrical accidents within the home and receive safety and maintenance advice for various electrical appliances. 'VES' was developed based on the findings of [**12**] [**11**] [**10**] and a complete description of the design process and the scenes developed is given in [**9**].

Use of desktop VR in this manner can provide an appealing training and design environment, allow users to operate in a safe environment and may potentially reduce training costs and enhance electrical safety. In addition, current educational thinking suggests that the form of activity supported by this technology will enhance student's ability to retain and acquire a heightened appreciation of new knowledge when they are actively involved in constructing that knowledge [**107**]. A note of caution is warranted however as an underlying assumption can often exist among researchers and developers that their VR application is intrinsically useful and usable just because it is developed using a novel and exciting technology [**80**]. Admittedly significant progress has been made in this area and usability engineering and evaluations are more routinely implemented to afford users with virtual environments that are more effective and productive and not merely contemporary and different. An objective of this chapter is to assess the prototype model developed using a cohort of final year undergraduate students from Dublin Institute of Technology. Users' attitudes toward VR learning environments will be evaluated along with the usability of the prototype model developed. This will serve as useful feedback to determine the characteristics of the prototype model which can be enhanced in future developments.

This chapter presents an overview of the unique characteristics of desktop web based VR technologies. It reviews the educational affordances offered by working in such an environment and outlines a case study carried out to evaluate 'VES'. A discussion is then presented of the case study findings and the potential for future development and concludes by formulating some guidelines for the effective use of desktop VR.

8.2 Unique characteristics of virtual reality

Virtual reality is generally defined as the use of computer graphic systems with various display and interface devices to provide the effect of immersion in an interactive three dimensional environment [**29**]. From the above, it is apparent that the commonly perceived characteristics or VR namely interactivity and immersion are recognised. Burdea and Coiffet [**30**] go further however, and define the three I's of VR, namely 'Immersion, Interaction and Imagination' and suggest that VR has applications that involve solutions to real world engineering, medical and military problems. In doing so they theorise that the extent of an application to perform well depends equally on the human imagination. 'Imagination' referring to the minds capacity to perceive nonexistent things, which may reflect the user's perception of engagement.

From a pedagogical perspective virtual reality offers a unique set of characteristics in contrast to other learning environments which have the potential to offer an enhanced learning experience. In this context Hedberg and Alexander [**90**] cite increased 'immersion', increased 'fidelity' and a higher level of 'active learner participation' while Whitelock et al [**171**] cite 'representational fidelity', 'immediacy of control' and 'presence' as the distinguishing characteristics. Each set of characteristics having identifiable similarities as identified by Dalgarno [**46**]. Previous research has shown that technological features could influence learning outcomes [**150**]. Most notably, as identified by [**121**] the degree of realism of the scenes along with the level of control the user has on activities, which dictate to some degree the interaction experience (usability) and learning experience. Hence the desktop VR features evaluated in this study will spotlight these characteristics.

Representational fidelity is the level of realism afforded by the 3-D image content of a desktop VR model. Two important visual aspects of this characteristic are realistic display of the environment and smooth display of object motion and view changes [**46**]. A further aspect to this characteristic is the consistency of the behaviour of objects and their response to user interaction. Consequently, frame rate is significant. Quest3D which was used to develop 'VES' operates in real time meaning it continually executes an entire application and revises the preview. One complete loop through an entire project channel structure is called a frame. Even though Quest3D does not have a preset limit on how many polygons and objects a scene should contain or how large a 3D scene should be, it is advisable to simplify the scene as much as possible when modeling. A reduction in the number of objects and polygons improves the rendering performance and reduces the file size. However, as a result the visual quality may suffer and in turn decrease the representational fidelity. Hence a compromise needs to be struck so that the user experience is not reduced by either the performance or poor visual quality.

Real-time interactivity is another feature of virtual reality. This can be defined as a virtual reality systems ability to detect a users input and respond instantaneously. Designed correctly, a well refined interface used to capture and respond to users commands can afford a heightened sense of immersion. Depending on the VR system various forms of user interface can be used. For 'VES' a mouse and keyboard is utilised. A further aspect of VR systems which can also affect a users experience is immediacy of control which refers to a user's ability to alter their viewing position or change direction while giving the impression of smooth movement through a VR scene. In order to afford the expected cohesion and flow, user's action should be suitably overt. In terms of 'VES' it is acknowledged that using the keyboard arrow keys and mouse for navigation can at times be cumbersome and will require a brief adjustment period from the user. However, early in the development stage, accessibility was deemed one of the most important design characteristics. Therefore it was decided on balance that this method was the most appropriate for user navigation as it meant no additional hardware requirements and hence the user audience via the World Wide Web would not be limited by such a design decision.

Immersion and presence are often stressed in distinguishing VR systems from other various forms of computer applications. According to Dalgarno et al [**46**] presence relates to the subjective sense of being in a place and immersion as the objective and quantifiable properties of a system that conspire to give a sense of presence. [**46**] argues that a strong sense of presence in a VR system occurs as a result of the high degree of immersion offered by the fidelity of the representation in conjunction with the type of interactivity available. Hence it could be assumed that presence is determined by human response to immersion on an individual basis and as such it would appear the level of presence experienced for the same system may vary for a range of people. In contrast to more immersive systems, Desktop VR systems have received criticism for not utilising the full potential of the 3-D and 'presence' qualities of virtual environments [**45**]. Nunez however [**134**] argues that desktop VR can provide a high presence experience. In any case, the ability of developers to exploit and harness the immersive properties VR offer can only be advantageous in securing and retaining user attention and consequently inducing learning and understanding.

8.3 Virtual Reality in Training and Education

The flexibility and portability offered by Web based Desktop VR systems allow developers design applications for a broad range of disciplines. As outlined by Chittaro et al [**37**] the context for development within these disciplines can be quite diverse with successful working examples spanning across many areas such as formal education in universities, informal education in cultural sites along with distance learning, vocational training and special needs education. In contrast to more traditional learning practices educational use of Desktop VR offers learning affordances to users with certain advantages that perhaps could never be achieved using standard methods. As an example VR systems can facilitate enhanced spatial knowledge in disabled children [**157**] and diversely aid in the visualization of the physical evolution of work in civil engineering projects [**151**]. In addition well designed VR systems with specified learning tasks may more effectively engage learners and increase motivation. Desktop VR can also provide a broad range of experiences that may perhaps prove impossible to replicate in the real world due to danger, inconvenience, cost, distance or impracticability.

A growing body of research alludes to constructivism as the main pedagogical driver that underpins the educational use of VR [**37**]. This is a philosophy of learning that suggests knowledge is constructed by learners through experience and activity [**121**]. In this regard Desktop VR is ideally suited to affording constructivist learning as it provides an interactive environment in which learners may actively participate. Predicated on this belief that knowledge can be closely related to experience researchers have argued that freshly obtained knowledge will be realized more effectively in the real world if the context of the modeled learning environment is equivalent to where the knowledge shall be applied. This is based on VR systems ability to provide visual realism and interactivity that closely replicates the real world and hence knowledge obtained within the virtual system should be more readily recalled and applied in practice [**46**]. In contrast to more conventional educational methods which is often dependent on learners acquiring knowledge from books and teachers and subsequently applying this knowledge to real situations [**37**], Desktop VR is student-centered and focuses on meeting the learners' needs by allowing users control their learning pace and become responsible for their learning in a contextualised simulated environment. Bell and Fogler [**14**] also assert that VR offers an environment where students can exercise the higher levels of Bloom's Taxonomy which is unique from any other educational methods. This is argued due to the freedom users have to explore an environment and the ability to analyse problems and assess alternatives in ways that were previously not possible. Hence the activities supported by Desktop VR promote current educational thinking that students are more adept at mastering, retaining, and generalising new knowledge when they are actively involved in constructing that knowledge in a hands on learning environment [**107**]. Evidently the learning affordance offered by VR are abundant and the potential to develop enhanced systems for widespread use will become even more accessible as desktop VR technology continues to advance and become even more economical to develop. However it is important that developed applications are user centered and focus is brought to bear on how the technology can foster learning and not just on what can be achieved using the technology.

In academic areas such as engineering very often the ability of a student to visualize and interpret abstract information determines how successful they will be in fully comprehending the material under study. Developing ways to enhance this learning process through multi sensory 3D visualisation environments with the ability to control dynamic models at the user's own pace can only be positive. The practical application of 'VES' which is the desktop VR model under scrutiny in this research is to provide support in Electrical Services Engineering design and training and is specifically focused on disciplines relating to enhancing electrical safety. The model is not developed to replace traditional methods of training but rather to provide an additional tool that may enhance understanding and learning and as a result increase safety. The virtual model can be manipulated interactively to allow users assess the impact of their electrical design decisions, interact with the electrical components and visualise many of the current rules for electrical installations along with providing electrical safety accident and maintenance advice. By providing an environment where users can interact with a simulated environment in an intuitive manner, repeat tasks until the required proficiency is attained and work safely constitutes a marked shift in conventional learning and design techniques in the area of Electrical Services Engineering. The role VR can possibly play in this field of engineering can be summarized as follows.

❖ Enhance the learning effect by demonstrating through an immersive medium in a contextualized environment the design features, processes and electrical components involved in an electrical installation.

- ❖ Reduce capital investment by solving the issues surrounding space and time for training institutes.
- ❖ Provides a safe training environment for users to work in.
- ❖ May enhance user motivation and subject interest
- ❖ It offers an alternative to site visits and allows users become familiar with inaccessible locations that may pose a health and safety risk
- ❖ VR offers a training system that is reusable which may allow users master a task.
- ❖ It may be convenient to update.
- ❖ Allow users to experience a sense of immersiveness in electrical installation design and concepts
- ❖ Allows users attain a better understanding of complex ideas, systems or environments

8.4 Case Study

8.4.1 Software

Virtual Electrical Services (VES) is a Web-based Desktop VR interactive system that is designed for engineering students to obtain knowledge regarding electrical safety and design in the built environment. It may also have practical applications for electrical design engineers. The Web-based VR system is designed in three parts: Touch Voltage Design, Electrical Safety and Electrical Rules and Standards. The system was developed using Quest3D to create the VR content and utilises Autodesk 3DS Max to create the virtual environment. 3DS Max is a commercial software package used to create 3D models while Quest3D is software for creating interactive 3D scenes developed by the Leiden company Act3D since 1998. It uses a unique style of visual programming called channeling and in contrast to writing code, developers can logically combine large set of powerful building blocks to build complex scenes. This method of programming reduces debugging time and avoids time consuming syntax errors. In addition to this, scene development in Quest3D occurs in real time meaning the developer is constantly working on and viewing the end result. In the virtual environment created, users can navigate through a domestic home, examine many of the electrical components, receive electrical safety advice and interactively carry out electrical designs and view the impact of their decisions [**9**].

8.4.2 'VES' Model Evaluation

Through the ongoing advancements of virtual environments, usability has increasingly become a major focus of system development. Usability can be broadly defined as the ability to carry out tasks: effectively, efficiently and with satisfaction [**127**]. Hence the more successfully users can complete their task in a manner which satisfies them, the more usable this system will be considered to be. Terms such as "usefulness" or "ease of use" are often cited [**25**] when VR systems are considered. Such terms resonate strongly with the widely accepted Technology Acceptance Model (TAM) which was developed with the primary aim of identifying the determinants involved in computer acceptance [**18**] and has been used extensively by various researchers to explain or predict the use of different technologies. This model suggests that the perceived ease of use (expectation that a technology requires minimum effort) and perceived usefulness (perception that the technology can enhance his/her performance of a task) can determine the intention to use a technology. In addition, both Salzman et al [**150**] and Lee et al [**121**] outlined that the unique features VR offer such as immediacy of control, representational fidelity and presence which collectively can influence the interaction experience are significant in determining the usability of a system.

Various methods of evaluations are often used to ascertain the usability of a computer-based system. In this chapter a questionnaire following a usability evaluation period is the primary technique utilized to acquire the user's findings. Bowman et al [**25**] in their survey of usability evaluations consider questionnaires to be good for collecting subjective data that can often be more convenient and consistent than personal interviews. Within the survey users were afforded the opportunity to express their thoughts on the model and to highlight any perceived areas of strength or weakness. Post evaluation discussion groups were also held with class groups to provide additional feedback. Furthermore in order to assess the users' understanding of the learning content, a set of problems which are coded into the VR system are taken by all participants prior to entering the virtual environment receiving only basic tutor instruction on the material. Subsequently using the interactive environment of the 'VES' model where learners can actively participate, the user's are posed the same problems in what is effectively a problem based learning exercise. This task is in line with the thoughts of Dalgarno et al [**46**] where it is suggested that a virtual learning environment with a good representational fidelity and immediacy control, developed around a real world system will not automatically lead to conceptual understanding and therefore appropriate learning tasks are required so that the user will be encouraged to undertake learning activities that will lead to a greater understanding of the learning content. Additionally, by engaging the user in the 'VES' model and encouraging active participation should result in a situation where the users will be in a more effective position to perform a usability evaluation.

The questionnaire was developed in order to primarily answer two research questions (1) evaluate the usability of the prototype model and (2) to assess the users' attitudes toward Desktop VR as a learning environment. Users are assessed over 11 measurement items as shown in Table 8-1. Items 1-5 set out to primarily evaluate the usability of the system, closely monitoring the unique VR characteristics as they are often cited as being intrinsic in establishing the usability of the system while items 6-8 will provide feedback on the psychological factors that affect the learning experience which in conjunction with items 9-11 should provide a platform to establish user attitudes towards VR as a learning environment. The questionnaire was drafted by referencing survey questions used in published literature. The individual questions corresponding to each measurement item are set out in Appendix A.

Measurement Items	References
1. Immersion	Huang et al (2010)
2. Representational Fidelity	Dalgarno et al(2002), Lee et al (2010)
3. Immediacy of Control	Dalgarno et al(2002), Lee et al (2010)
4. Perceived Usefulness	Davis (1989), Lee et al (2010)
5. Perceived Ease of Use	Davis (1989),
6. Presence	Lee et al (2010)
7. Motivation	McAuley et al. (1989)
8. Cognitive benefits	Antonietti et al. (2000)
9. Intention to use system	Huang et al (2010)
10. Perceived Learning Effectiveness	Lee et al (2010)
11. Satisfaction	Chou and Liu (2005)

Table 8-1 Questionnaire Measurement Items and Sources

8.4.3 Participants and Procedures

Participants consisted of final year undergraduate students studying Electrical Services Engineering and Energy Management from the School of Electrical Engineering Systems in Dublin Institute of Technology. A total of 101 students were given a brief demonstration on how to use the VR system. Students were then allowed to access the system via the web or as a downloadable executable file. Subsequently an on line questionnaire was distributed to the participants. All subjects were asked to respond to the questionnaire and their responses were guaranteed to be confidential. The questionnaires contained the users' background, age and qualification. Furthermore the questionnaires also provided the opportunity to highlight the strengths and weaknesses of the system along with suggestions for improvement. There were 14 uncompleted responses leaving 87 completed responses for analysis. Males made up 100% of the subjects surveyed. The questionnaire had 41 questions that were evaluated using a 7-point Likert scale ranging from 1 which means ''strongly disagree'' to 7 which means ‘‘strongly agree’’. After completing the experiment, group discussions were used to provide additional qualitative feedback during debriefing sessions.

Measurement Items		α	Mean	S.D
1. Immersion	VR Features	0.7	5.3	0.9
2. Representational Fidelity		0.78	5.2	0.99
3. Immediacy of Control		0.76	5.96	0.82
4. Perceived Usefulness	Usability	0.71	5.84	0.81
5. Perceived Ease of Use		0.85	5.5	1.1
6. Presence	Learning Experience	n/a	5.05	1.37
7. Motivation		0.86	5.5	0.97
8. Cognitive Benefits		0.81	5.61	0.8
9. Intention to use system	VR model Measurement outcomes	0.77	5.51	1.04
10. Perceived learning effectiveness		0.85	5.42	0.84
11. Satisfaction		0.82	5.41	0.77

Table 8-2 Questionnaire Measurement Item

8.5 Data Analysis and Results

The internal consistency reliability for the measurement items was assessed by computing Cronbach’s αs. The alpha reliability was considered acceptable with values ranging between 0.7 and 0.86. The mean coefficient associated with each measurement item and the standard deviation is outlined in Table 8-2. The individual coefficients of each questionnaire item are presented in Appendix A. Additionally a Spearman correlation was carried out between each measurement item and the results are presented in Table 8-4. PASW Statistics 18 software package was used for the analysis of the results.

Prior to further analysis of the results obtained it will be useful to examine the participants to highlight the context and background in which the results were obtained. The academic programme from which the participants were taken from is an advanced level entry programme which contains a significant number of mature students with many years of industry experience alongside a number of standard entry students that have continued their formal education through since second level. This is reflected in the age profile of the participant’s where the user’s ages range from 21-57. The average age of the participants is 29. Of the 87 participants, 82% of them have already obtained a BEng Tech in Electrical Services Engineering or an equivalent electrical degree. The remainder also have an equivalent engineering degree; however the focus on electrical engineering is to a lesser extent. Considering that ‘VES’ is developed to potentially aid electrical design and safety for both industry and university students and in light of the knowledge and experience of the user group, the participants should provide a very good representative sample of the target audience and therefore the feedback received should provide much more useful information in contrast to obtaining feedback from a less mature/knowledgeable audience. Table 8-3 gives a picture of the VR knowledge of the users.

Virtual Reality knowledge of the users	%
No knowledge	25%
Some Knowledge	47%
Medium knowledge	26%
A lot of knowledge	2%

Table 8-3 Virtual Reality knowledge of the users

8.5.1 Interaction Experience

Analysing the usability of the model, measurement items 1-5 are primarily analysed. Items 4 and 5 which measure the perceived usefulness and perceived ease of use provide feedback on the interaction experience while items 1-3 will provide feedback on the VR characteristics of 'VES' and their influence on the usability of the system. Perceived usefulness which can be used to indicate whether the technology can enhance his/her performance of a task attained a slightly higher mean score (5.84) than perceived ease of use (5.5). There was a strong, positive correlation between perceived usefulness and all three VR features which was statistically significant as shown in Table 8-4. Perceived ease of use which can be used to indicate the accessibility of the system and the expectation that a technology requires minimum effort showed a small to medium correlation effect with the VR features. Examining the correlation effect between the perceived usefulness and the user's intention to use the system and satisfaction with the system shows a strong correlation, which is statistically significant. A medium to strong correlation also exists between perceived ease of use and satisfaction.

In agreement with Lee [**121**] and Salzman [**150**] findings, the VR features in this study can be considered to play a significant role and indicate a positive influence in terms of the usability of the system. VR features that were measured by immersion, representational fidelity and immediacy of control which refers to the user's ability to interact and control the virtual objects collectively impact on the interaction experience of the participants. One could indicate from these findings that with enhanced control components and realism, users will be offered an enhanced interaction experience.

Analysing the influence the usability measurements items have in relation to the psychological factors associated with the learning experience shows a strong correlation that is statistically significant. This indicates that the usability of 'VES' model has an appreciable effect on the learning experience, which in turn will influence the learning effectiveness of the system. These finding are consistent with the findings of Lee et al [**121**] and Sun et al [**160**] where it is suggested that Desktop VR models that consider closely the perceived usefulness and ease of use will positively influence the learning experience and learning effectiveness

Measurement Items	1	2	3	4	5	6	7	8	9	10	11
1. Immersion	1										
2. Representational Fidelity	.568	1									
3. Immediacy of Control	.412	.292	1								
4. Perceived Usefulness	.571	.543	.519	1							
5. Perceived Ease of Use	.264	.243	.187*	.174*	1						
6. Presence	.495	.471	.173*	.431	.370	1					
7. Motivation	.461	.493	.329	.611	.229	.437	1				
8. Cognitive Benefits	.423	.379	.401	.665	.199*	.374	.576	1			
9. Intention to use system	.54	.498	.434	.628	.059*	.242	.649	.686	1		
10. Perceived Learning Effectiveness	.51	.501	.485	.649	.304	.342	.606	.724	.671	1	
11. Satisfaction	.506	.363	.416	.571	.413	.348	.511	.648	.598	.636	1

Table 8-4 Spearman correlation between the measurement items *Denotes where ($P > 0.05$)

Using the VR measurement outcomes as outlined in Table 8-4 as a benchmark to evaluate the impact usability has on the system clearly demonstrates that the satisfaction of the user group with the 'VES' model is strongly correlated to the usability of the VR system, while more specifically the perceived usefulness of the system can be seen as very influential in determining one's motivation and intention to use the VR system. Consequently, based on the findings of this research, VR designers and developers should be cognisant that the tasks and activities encountered within a VR model should be considered 'easy to use' and particularly 'useful' to fully exploit desktop VR's learning potential.

8.5.2 Learning Experience

In determining the user groups attitude towards VR as a learning environment, items 6-8 were used to assess the psychological factors that affect the learning experience while items 9-11 were used to benchmark the user groups perceived effectiveness and satisfaction with the 'VES' prototype model as a learning environment.

Sense of presence received the lowest mean score (5.05) of all the measurement items. However, the score is not so low as to indicate that low immersion systems are not capable of providing a sense of presence. As highlighted by [**46**] and noted earlier, presence is a subjective feeling that is induced by the level of immersion, interactivity and fidelity offered by the model. This suggestion is consistent with the findings of this research by virtue of the medium to strong positive correlation that exists between presence and the VR features as outlined in Table 8-4 indicating that with increased fidelity and interactivity a heightened sense of presence will be realised by the user. Furthermore by correlating the sense of presence to perceived learning effectiveness a positive medium size effect exists suggesting that a heightened sense of presence can offer an enhanced learning effect. To emphasise the subjective nature of presence in a VR system one participant interestingly noted the following;*"After a prolonged time using the VR model I felt a sense of nausea from the constant movements and tracking using the VR model"*, the same participant also commented *"The good features which I found from my use of the VR model, was the feeling of been physically present in the application"*.

Motivation as defined by [**111**], is an internal state or condition that activates, guides, and maintains or directs behaviour. Sutcliffe [**161**] suggests that motivation is a major factor that influences learning and thus better-motivated users can learn more effectively. In this study motivation was found to be an influential psychological factor that is positively related to the VR measurement outcomes. This is consistent with previous related studies [**121**] [**94**] thereby demonstrating the plausible effect motivation can have on learning effectiveness. VR features were also found to be significant in influencing user motivation, this is in keeping with the findings of Huang [**94**]. Additionally, usability and in particular perceived usefulness was found to be significant in terms of user motivation indicating that a useful, easy to use system will enhance user motivation. This serves to highlight the negative impact a poor interaction experience could have which may lead to user frustration and ultimately negatively impact on a user's intention to use the system.

Cognitive benefits were found to have a strong positive correlation with the perceived learning effectiveness of the VR model, satisfaction and also the intention of the participant to use the system. This is consistent with the findings of Lee [**121**] and Antonetti [**4**] suggesting that users see VR as advantageous in terms of understanding and memorisation. The significant influence perceived usefulness has on the cognitive benefits in contrast to the VR features may also indicate that it is the usefulness of the task set within the model more so than representational fidelity which perhaps will heighten user conceptual understanding. This emphasises the critical nature of the role instructional content plays in fully capturing the cognitive benefits VR can offer.

Analysing the VR model measurement outcomes in Table 8-2 highlights that perceived learning effectiveness attained a relatively high mean score (5.42). This finding can be substantiated by the results of the problem based learning exercise developed for the participants, where it was found that by using the

VR model users' scores increased on average by 31%. This emphasises further and provides evidence for the assertion made by Dalgarno that in order to facilitate conceptual understanding a well designed set of learning tasks is crucial. From the evidence of this research it would appear that the learning activities contained in a VR model have a significant influence on the cognitive benefits which in turn strongly influence the perceived learning effectiveness.

In general, the overall attitude toward VR as a learning environment was found to be positive. The evidence to support this claim can be ascertained by reviewing the mean scores received for the measurement items 'Satisfaction' and 'Intention to use the system' which can justifiably be argued as indicative benchmarks. The qualitative feedback received from the questionnaire and also the debriefing sessions also support this claim where the majority of users observed the usefulness of the model in addition to the perceived positive influence that VR could have on their learning. Examples of positive feedback from the users include; (1) *"The good features are that the model makes it more interesting to learn the topic. I found it a lot easier to understand than having to look at schematics of the same scenario."* (2) *"The VR model provides a realistic environment that allows the user to make learning more interesting and practical."* (3)*"The model showed a different approach to a common technical proposition and it does drive home the message. The immediacy of the response to a change in design made the learning process easy and encouraged further manipulation.*

The potential for enhancing electrical safety and design through the use of VR is evident from the above analysis. There appears to be general agreement from previous studies and the findings of this research that VR can have a strong motivational impact on users. This research suggests that this leads to a greater learning effect that evolves into a potentially greater understanding of the concept or task in hand. One could conclude from this that through the use of a well designed VR model, users will be more competent in the area under study and the net effect in this instance will be to enhance electrical safety in the built environment. However it must be noted that if the usability of the system is poor and the instructional content and tasks are flawed the ability of the system to achieve its objective will be significantly diminished.

8.6 Limitations and Implications

Evaluation of the prototype 'VES' model, especially in terms of its usability and learning experience is very important to the successful uptake of the system. To enhance the prototype to a point where it could be successfully commercialised or integrated seamlessly into an educational module in a third level programme will require further development taking account of the feedback received via the questionnaire and debriefing sessions. To this end a number of the issues highlighted will be addressed and some guidelines for the effective of use of VR will be put forward.

A number of the user's encountered problems navigating through the system. There were a couple of explanations to account for this. Firstly, difficulties were noted in terms of adjusting to using the arrow keys and mouse for navigation. In general this appeared to be a short lived effect and that after using the system for a period of time users overcame this control issue. However it is noted that this could add to user frustration and weaken the interaction experience. Using a control pad is a viable alternative. Secondly, some users encountered an unsmooth jumpy display navigating the scene. When this issue was discussed with the relevant users, it became apparent that they were using older machines with a reduced processing power in contrast to more modern PC's. In future versions it may be worth highlighting a minimum requirement specification, above which this problem would not be encountered as an issue.

Although many users noted their satisfaction with the representational fidelity of the system, some users did comment on how the graphics of the system should be enhanced. In making this comment, most users reflected on the contrast between this system and current video games that are on the market. It is evident from these comments that users who are familiar with these video games consider this level of detail as the perceived benchmark and the level of expected quality. To bring 'VES' to this standard would require a dedicated development team. However it does highlight the level of detail that would be expected from the current generation and improvements in this area would undoubtedly increase the fidelity, usability and satisfaction with the system.

Other areas the user group highlighted was the contrast of text with the 3D display which made it difficult to view in places. This can be easily overcome in future versions by using dialog boxes. Finally, users commented on the wish for more interactive appliances and additional scenes and scenarios such as commercial and industrial electrical installations. Based on the findings of this research where it appears the use of VR improves users' ability to analyze problems and explore new concepts, further development as suggested by the group can be justified.

In order to widely deploy VR for electrical safety and design, developers need to appreciate the challenges of utilising VR technology for instruction rather than relying on the novelty of the technology. Based on the findings of this research some suggested guidelines for the effective use of VR in this field are listed below.

- A well designed set of applicable tasks or activities that are considered to be useful and easy to use is vital in enhancing the perceived learning effectiveness.
- VR features play a significant role in user satisfaction and perceived learning effectiveness
- Usability of the interface design. Rather than ensuring basic functionality, developers should attempt to ensure the interface design is understandable and the user interactions are easy to understand.
- The perceived usefulness of the application appears from this research to be significant in establishing user satisfaction and their intention to use the system
- Affording the user the ability to interact with the environment while providing real time feedback significantly enhances engagement and increases motivation leading to increased learning outcomes

8.7 Conclusion

Engineering education and design can be greatly enhanced and facilitated by the use of virtual reality. Evaluation of the model by a representative sample of potential users indicated that a) the developed prototype has the potential to increase understanding of issues related to electrical safety and hence could potentially help to cut down on accidents and fatalities related to electrical shock and electrocution, b) it was found that users were receptive to using VR as a learning and design tool and c) 'VES' the prototype model offered a reasonably acceptable interaction experience. The findings of this research should also make a significant contribution to understanding the role desktop VR can play in supporting learning and design in engineering while also highlighting some of the important aspects in determining the user's 'satisfaction', 'intention to use the system' and the 'perceived learning effectiveness'. Generally, Desktop VR has reached the level of development where it should be seriously considered by the electrical services industry to support designers, contractors and training personnel in increasing understanding, improving safety and potentially improving productivity.

Chapter 9

Conclusions and Further Development

9.1 Introduction

Electricity and the dangers associated with its use in the built environment have long since been a priority for the electrical services industry and also the general public who live and work in this environment. For electrical safety to continuously progress, it is incumbent on those within the industry to consistently strive for enhanced regulation, improved systems of work and enhanced methods to allay these risks. Such efforts will not just benefit those working and training to work in this industry but all of society.

In this research, a prototype application designed to enhance electrical services design and safety in the built environment using a desktop VR system has been set out. The system allows full navigation of a virtual electrical installation environment and interaction with many of the electrical elements. This constitutes a first attempt at attaching a new dimension to the training of electrical services engineers. Although in its infancy, the successful development and early implementation of this prototype desktop VR application suggests that 'VES' could be a valuable tool for the industry. The model presented has the potential to be used as an educational tool for third level students, a design tool for industry, or as a virtual electrical safety manual for the general public. Unlike traditional design or training methods virtual reality has the advantage of being safe for both the user and equipment. In addition, it offers the user an opportunity to be exposed to a range of scenarios and conditions that either occur infrequently or are hazardous to mimic.

Virtual Reality also offers the ability to expeditiously attain proficiency and knowledge which is essential for the profitability and sustainability of companies, governments and training organisations. For electrical services engineers this is achieved by providing an environment where users can interact with a simulated environment in an intuitive manner, repeat tasks until the required proficiency is attained and work safely which constitutes a marked shift in conventional learning and design techniques used currently within the industry. Additionally, in an era where regulatory practices are amended continuously there is a requirement on the part of industry and higher education institutes to provide training methods that will allow trainees to quickly and cost effectively up-skill and attain knowledge to adapt to the new and rapidly emerging practices and associated technologies. In this context, Desktop VR as developed through this research provides a viable solution.

9.1.1 VR Development Process

Electrical safety in the built environment can be defined as the process of eliminating the risk of incident or injury from electrical installations. As part of the effort to heighten safety, a Desktop VR prototype model is set out in this research as a plausible tool to aid in this ongoing process. The foundations upon which to develop the model were realised in the early sections of this research (chapter 2-5). Chapter 2 focussed on establishing how humans respond to a.c. 50/60 Hz and documented how the pertinent standards have evolved. For designers it is important to appreciate factors which influence the severity of an electric shock, these include the physical condition of the subject, the duration and path of the current flow, the frequency of the supply, the magnitude of the current and also the magnitude of the voltage causing the shock. This analysis proved useful in assessing the published current and voltage limits and their affect on current regulations. Following this, chapter 3 provided a body of evidence which outlined the current concerns regarding electrical safety in the built environment. This provided clear justification for the development of a virtual reality model to feed into the ongoing effort to improve electrical safety levels. Chapter 4 investigated fatal and non-fatal electrical incidents from electric current causing shock or burn in domestic properties. This study highlighted the at-risk groups that could benefit from improvements in electrical safety, the main risk activities in domestic properties, the products involved and the outcome of the injured patients. The data collected from this study provided the electrical accident data and scenarios for use in the VR model. Chapter 5 summarised the theory of transfer touch voltage and analysed the significant factors related to the development of a safe touch voltage design. The 'Touch Voltage Simulator' application developed allows designers and installers of low voltage electrical installations to test and evaluate the resulting touch voltage for various design parameters. Upon confirming the validity of the touch voltage simulator through an on-site touch voltage case study, the simulator was deemed suitable to be included in the VR model.

More generally, the approach taken in the development of these early chapters highlighted three predominant factors related to preventing electrical accidents in the built environment namely *design*, *maintenance* and *persons*. These factors formed the basis of the proposed electrical safety concept as outlined in chapter 1. From the findings of this research, it would appear that VR is well placed to address the overall safety concerns highlighted by this concept and has the potential to play a significant role in addressing many of the individual factors such as allowing designers investigate the impact of their designs, allowing persons become more aware of the dangers of electricity by virtue of the collected accident scenarios, while also allowing a skilled or non skilled person become more informed or virtually instructed before carrying out maintenance. The latter half of the thesis focussed on the development and evaluation of the VR model. The evidence of which suggests that it can be a valuable tool for both academia and industry and is worthy of further research and development.

9.2 Research Findings Contributions to Aims and Objectives

As outlined through this work and the work of many others, there is ample evidence to highlight the dangers associated with the use of electricity. Therefore, the continued commitment of the industry to put electrical safety at the forefront of engineering decisions is vitally important. This signifies the context in which this research is motivated which is to highlight the growing concerns in the field, aid regulatory decisions in the development of standards and promote methods and techniques to enhance our understanding and reduce the number of fatal and non fatal electrically related incidents

9.2.1 Addressing the main research questions and their wider implications

The main aim of this research is the design and implementation of a prototype virtual reality application designed to enhance electrical services design and safety in the built environment using a desktop VR system. By successfully developing a novel prototype, a new dimension is added to the field, which if utilised to its potential can significantly add value in terms of training engineers, heightening safety and reducing the potential of fatal and non fatal accidents.

The application of independent analysis in the evaluation of the VR model should benefit any further development of the model in addition to providing supporting evidence to VR practitioners. This analysis makes a significant contribution to understanding the potential of Desktop VR technology to support and enhance understanding in engineering applications. This analysis can also guide the future development efforts of Desktop VR-based learning environments applied to the field of electrical services engineering. In a broader context, it will make a significant contribution by edging the VR community closer to understanding the potential of desktop VR technology to support and enhance learning. It may also enlighten developers on the capability of desktop VR to enhance learning and to support developers in identifying the essential characteristics Desktop VR-based learning environments should entail.

The study of original unpublished data investigating fatal and non-fatal electrical incidents from electric current causing shock or burn in domestic properties should prove useful in enhancing knowledge in the field. This data was used to trend electrical injury for various categories and groups. This determined at-risk groups that could benefit from electrical safety interventions and highlighted the high-risk activities, which lead to receiving an electric shock in a residential home. The benefits of the narrative reports that accompany each individual incident is also exploited to forge an insight into incident causes that may indicate where specific types of remedial action can be implemented namely engineering controls and safety awareness campaigns which may aid in tempering the number and severity of domestic electrical incidents. The wider implications of this study may influence regulatory bodies in the development of standards in the relevant wiring rules. It may also provide supporting evidence for governmental safety agencies in promoting safety.

The original touch voltage sensitivity equations developed can be used by installation designers and installers to investigate and identify the range of resulting touch voltage values that might be the consequence of variation of the four main design parameters. It is demonstrated by example that the equations can be used by installation designers and installers to investigate and identify the range of resulting touch voltage values that might be the consequence of variation of the four main design parameters U_{OC}, Z_e, R_1 and R_2. In addition the concept of how dangerous touch voltages can develop and also transfer onto healthy circuits in low voltage electrical installations has been analysed. From a designer's perspective, the benefits of designing for safety through the implementation of RCD's and a low touch voltage design using the equations and tools developed by the author should be clearly evident.

9.3 Limitations

The development of the prototype model and the subsequent evaluation highlighted that the users perceive the prototype to be a useful tool and are receptive to using VR as a learning and design tool. However, it would be remiss in terms of this research not to acknowledge that the prototype, albeit fully functional, is limited in its current format and could benefit from further research and development. Even within the most comprehensive and large scale studies, there are limitations by virtue of the practical realities. In the context of this research, the VR model served its purpose, in that it demonstrated the concept of utilising VR in the electrical services industry and highlighted the potential to heighten safety as a result. However for a package of this nature to be commercially realised in an expedient manner, a team consisting of 3D artists, software developers and electrical services consultants would be required.

On a micro level the VR prototype could be enhanced by utilising an alternative method of navigation, enhancing the graphical display and by employing more content for the user to investigate including additional scenes, staged in industrial and commercial installations. However, it is worth acknowledging that if the prototype in its current format suggests that VR can be successfully employed in the industry, enhanced content, display, user navigation and so forth will only serve to reinforce this point.

9.4 Recommendations

The following are some recommendations, which arise from the research work:

- ❖ It would appear prudent that electrical codes such as ET 101 and BS 7671 have less stringent requirements for voltages less than 25 V instead of 50 V. This argument can be made based on accident investigations involving incidents where less than 50 V was reported but also on the findings of the IEC 60479 standard where touch voltage thresholds for ventricular fibrillation below 50 V is possible for various scenarios.

- In the home, the electrical injury rate for males is 1.5 times than that for females. However, the fatality rate due to electricity-related accidents is nine times higher for males than the corresponding rate for females. This topic warrants further investigation. In addition it is recommended that the accident interviews should be made mandatory as part of A&E's normal record.

- The new 4th edition of (ET101:2008) by ETCI or 17th edition IEE Wiring Regulations (BS7671:2008) coupled with best practice of de-energising equipment before maintenance/repair and corrective maintenance on electrical appliances could significantly reduce injury and death rates.

- For domestic dwellings, a certification process based on periodic inspections would ensure best practice with the added benefit of giving the occupant a heightened sense of security, increased convenience using electricity and an increased property value.

- Virtual reality environments should be introduced to the electrical services engineering industry to enhance electrical safety and design and strengthen current training programs.

- The development of virtual reality based learning environments for integration in educational electrical services programmes should be pursued. Virtual reality systems can allow users to attain a better understanding of complex ideas, systems or environments and helps users develop capabilities, skills and competencies essential for further study and future employment. Additionally, Desktop VR can enhance the learning effect by demonstrating through an immersive medium in a contextualized environment the design features, processes and electrical components involved in an electrical installation.

- Further development of the 'VES' prototype model should include increased electrical installation content in a layered format. For example clicking on a component could potentially bring the user to an inner layer which gives a more magnified view of the component and relevant information, while also allowing dynamic electrical simulations in order to improve the realistic representation of the actual systems. In addition the integration of commercial and industrial scenes would increase the usefulness of the program.

- Multidisciplinary teams consisting of software engineers, electrical services engineers, 3D artists and psychologists would be best suited to developing a commercially viable system.

9.5 Final Note

Virtual reality is identified as a rapidly developing computer based technology that is widely used for a diverse range of applications. Over the past decade, computer systems have rapidly evolved and significantly improved the quality and accessibility of virtual reality systems and also reduced the cost associated with such systems. The net effect has prepared the way for virtual reality technology to be considered in a variety of engineering areas.

The intent of electrical safety is to eliminate as far as reasonably possible the potential of electrical accidents occurring. One potential method of addressing this issue is to use virtual reality. Through a virtual environment designers can view and investigate the impact of their designs, persons can become more aware of the dangers of electricity, while a skilled person can become more informed or virtually instructed before carrying out maintenance. By providing a format to develop and address each of these elements will only serve to heighten awareness and encourage people to use safe electrical practices. It is hoped through the development of this novel prototype, that the potential of virtual reality will be exploited by the industry and the overall research findings will aid in enhancing electrical safety in the built environment which can benefit all of society.

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Appendix – VR Evaluation Measurement Questions

Measurement Item	Question	Mean	S.D
Immersion	1. The 3D simulation system creates a realistic-looking environment.	5.64	0.96
	2. I feel immersed in the 3D simulation system.	4.75	1.23
	3. I feel that the 3D simulated environment makes me concentrate more while learning.	5.47	1.4
Representational Fidelity	1. The realism of the 3-D images motivates me to learn	4.97	1.27
	2. The smooth changes of images make learning more motivating and interesting	5.17	1.18
	3. The realism of the 3-D images helps to enhance my understanding	5.33	1.12
Immediacy of control	1. The ability to manipulate the objects within the virtual environment makes learning more motivating and interesting	6.11	0.89
	2. The ability to manipulate the objects in real time helps to enhance my understanding.	5.8	0.94
Perceived usefulness	1. Using this type of computer program as a tool for electrical services/will increase my learning and academic performance	5.76	1.02
	2. Using this type of computer program enhances/will enhance the effectiveness of my learning	5.72	1.03
	3. This type of computer program allows/will allow me to progress at my own pace	5.91	1.00
	4. This type of computer program is useful in supporting my learning	5.97	0.92
Perceived ease of use	1. Learning to operate this type of computer program is easy for me	5.66	1.28
	2. It is easy for me to find information with the computer program	5.37	1.20
	3. Overall, I think this type of computer program is easy to use	5.37	1.26
Presence	1. There is a sense of presence (being there) while learning with this type of computer program.	5.05	1.37
Motivation	1. It was enjoyable using the VR system for learning purposes	5.52	1.23
	2. The system can enhance my learning interest	5.61	1.06
	3. The system can enhance my learning motivation	5.32	1.11
Intention to use the system	1. I think this system can strengthen my intentions to learn	5.20	1.30
	2. I am willing to continue using this system in the future	5.22	1.40
	3. Overall, I think this system can to be a good learning tool	6.13	1.05
Cognitive Benefits	1. This type of computer program makes the comprehension easier	5.68	0.96
	2. This type of computer program makes the memorization easier	5.39	1.21
	3. This type of computer program helps me to better apply what was learned	5.76	1.01
	4. This type of computer program helps me to better analyze the problems	5.68	0.98
	5. This type of computer program helps me to have a better overview of the content learned	5.56	1.02
Perceived Learning effectiveness	1. I was more interested to learn the topics	5.26	1.10
	2. I learned a lot of factual information in the topics	5.18	1.16
	3. I gained a good understanding of the basic concepts of the materials	5.52	0.89
	4. I learned to identify the main and important issues of the topics	5.56	0.88
	5. I was interested and stimulated to learn more	5.26	1.08
	6. The learning activities were meaningful.	5.56	1.01
	7. What I learned, I can apply in real context	5.59	1.12
Satisfaction	1. I was satisfied with this type of computer-based learning experience	5.01	1.19
	2. A wide variety of learning materials was provided in this type of computer-based learning environment.	5.40	1.41
	3. I don't think this type of computer-based learning environment would benefit my learning achievement ***(R)**	5.49	0.89
	4. I was satisfied with the immediate information gained in this type of computer-based learning environment	5.30	1.04
	5. I was satisfied with the teaching methods in this type of computer-based learning environment	5.54	1.00
	6. I was satisfied with this type of computer-based learning environment	5.63	1.10
	7. I was satisfied with the overall learning effectiveness	5.50	1.10

Measurement questions and mean scores received
***(R) Ranking Reversed**