Copper Development Association

Earthing Practice

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Earthing Practice

by Trevor Charlton

Preface

Earthing of electrical networks and installations is important to ensure correct operation. It also serves a vital safety role - facts which are amply reinforced in legislation and codes of practice.

Most engineers in power supply, buildings services and instrumentation will need to become familiar with the subject during their career. This may arise when investigating equipment failure, unsatisfactory power quality, interference or ensuring that safe conditions are provided for staff working on electrical equipment.

Despite an obvious need, earthing is barely covered during engineering degree courses. It is also difficult to obtain up to date, reliable information on the subject. For example, if one consults books on building services or electrical substation design, the chapter on earthing is almost inevitably a small one - a situation which is almost reversed when one examines the standards which apply.

Books which attempted to cover the whole subject are generally quite old, were written before detailed computer analysis was possible and before many of the high frequency and other problems being experienced now were fully understood. For these reasons, earthing has developed an aura, such that it is often described as a black art. It is however a science and there is now a range of software tools and measurement techniques with which it is possible to accurately predict performance.

This book has been written to help overcome some of the above difficulties. It is intended to act as an introduction to the subject, explaining the general concepts and providing sufficient background information to help the reader recognise when to seek further advice.

The book starts by discussing

- the reasons for earthing
- the alternative types of earthing system and
- legislation.

The main emphasis is on practical application, so chapters on the type of electrode available, how to install, maintain and measure their impedance are included. Being able to predict performance is important at the design stage, but rather than introduce complex formulae, general design guidance is given and some graphs have been included to illustrate the more important factors influencing performance. The coverage has been broadened to include typical earthing system designs for a range of applications and the problems which can be anticipated. The main focus of the book is towards the earth electrode, i.e. that part of the earthing system which is installed in the ground. An efficient earth electrode is required for lightning protection, domestic electrical wiring and large industrial or power plants. The general installation and design aspects for the earth electrode are similar throughout these applications, although the overall earthing system design will differ significantly amongst them. Copper has and continues to be the most widely used material for earthing. Its successful application is reinforced in standards, such as BS 7430, 'Code of Practice for Earthing', which states "Copper is one of the better and commonly used materials for earth electrodes and underground conductors" In fact, some standards forbid the use of many other metals for this purpose - especially for the buried earth electrode.

Aware of the need for a readily available source of information, the CDA has taken the initiative to provide this book to help users of copper obtain better performance from the material. Two chapters, on the properties of copper and corrosion resistance, have been included to help with material selection.

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1 Introduction

It is well known that most electricity systems need to be earthed and this practice probably started in the very first days of electrical experiments. Then, as now, static was discharged by connection to a plate which was in contact with the general mass of earth. The practice has continued and been progressively developed, such that connections to earth occur at almost every point in the electricity system. This includes the generating station, the lines and cables which distribute electricity and the premises at which it is used. The need for such a connection is sometimes enshrined in legislation. For example in the UK, the Electricity Supply Regulations 1988, clause 5(1), requires all systems (i.e. Generation, Transmission and Distribution) to be earthed at one point. This does not actually extend to the installation within premises and whilst it is still the most common arrangement to earth such installations, the standards (for example via BS 7671: 1992, Amendment 1, 1994, Requirements for Electrical Installations) allow for certain unearthed arrangements.

Whilst earthing forms an intrinsic part of the electricity system, it still remains in general a misunderstood subject and is often referred to as a “black art” - even sometimes by well qualified engineers. In recent years there have been rapid developments in the modelling of earthing systems at power frequencies and higher, mainly facilitated by computer hardware and software. This has increased our understanding of the subject at the same time that the design task has become significantly more difficult and emerging standards are requiring a more detailed, safer design. There is thus an opportunity to explain earthing concepts more clearly and a need for this to be conveyed to earthing system designers and installers so that a greater understanding may be gained.

By earthing, we generally mean an electrical connection to the general mass of earth, the latter being a volume of soil/rock etc., whose dimensions are very large in comparison to the electricity system being considered.

Before discussing definitions, it is worth noting that in Europe we tend to use the term earthing, whilst in north America, the term “grounding” is more common. The IEEE definition of grounding is:

“Ground (ground system). A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or some conducting body of relatively large extent that serves in place of the earth.”

For use within Europe, if the generally accepted terms were replaced as below, then the meaning remains the same.

“Earth (earth system). A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the mass of earth or some conducting body of relatively large extent that serves in place of the mass of earth.”

As will be described later, it is possible to operate an electrical system without an earth, so why is the practice of earthing electricity systems so commonplace?

The most often quoted reasons for having an earthed system are:

- To provide a sufficiently low impedance to facilitate satisfactory protection operation under fault conditions.
- To ensure that living beings in the vicinity of substations are not exposed to unsafe potentials under steady state or fault conditions.
- To retain system voltages within reasonable limits under fault conditions (such as lightning, switching surges or inadvertent contact with higher voltage systems), and ensure that insulation breakdown voltages are not exceeded.
- Custom and practice.

- Graded insulation can be used in power transformers.
- To limit the voltage to earth on conductive materials which enclose electrical conductors or equipment.

Less often quoted reasons include:

- To stabilise the phase to earth voltages on electricity lines under steady state conditions, e.g. by dissipating electrostatic charges which have built up due to clouds, dust, sleet, etc.
- A means of monitoring the insulation of the power delivery system.
- To eliminate persistent arcing ground faults.
- To ensure that a fault which develops between the high and low voltage windings of a transformer can be dealt with by primary protection.
- To provide an alternative path for induced current and thereby minimise the electrical "noise" in cables.
- Provide an equipotential platform on which electronic equipment can operate.

To perform adequately in fulfilling any of the above functions, the earthing system must generally have a low impedance so that in dispersing or collecting current from the ground, an excessive voltage rise does not occur. Of course within installations an earth connection is also necessary to ensure the correct operation of equipment - for example electronic devices, where an earthed shield may be required. It is essential to consider the earthing within a whole installation as one complete system and for this to be designed and installed accordingly.

Earthing of electrical installations is primarily concerned with ensuring safety. The earthing system is normally designed to provide two safety functions. The first is termed bonding. Any exposed conductive metalwork which can be touched is connected together via bonding conductors. Most electrical equipment is housed inside metal enclosures and if a live conductor comes into contact with this, the enclosure will temporarily also become live. Bonding is to ensure that, should such a fault develop, then the potential on all exposed conductive metalwork is virtually the same. In other words, the bonds equalise potential within the site so that the resulting potential differences are minimal. An equipotential 'platform' is thus created.

If a person is in contact simultaneously with two different pieces of exposed metalwork, a bonding conductor should ensure that the person does not receive a shock, as the potential difference between equipment should be insufficient for this to occur. The same principle applies within large electricity substations, factories and houses. In factories, bonding of exposed metalwork would normally ensure that an electrical fault to the frame of one machine did not create a potential difference between that and earthed metalwork on an adjacent machine. In the home, bonding ensures that, should a fault to the frame of a washing machine or cooker develop, someone simultaneously touching either of these and the metal sink would not experience an electric shock.

The second function of the earthing system is to ensure that, in the event of an earth fault, any fault current which does result can return to source in a controlled manner. By a controlled manner, we mean that the return path is predetermined such that damage to equipment or injury to individuals does not occur. The earth connection is not of infinite capacity and zero impedance. However, the impedance of the earthing system should be low enough that sufficient earth fault current can flow to operate protective devices correctly, which will in turn initiate the operation of circuit breakers or fuses to interrupt the flow of current. The required impedance value is normally calculated by the protection designer via fault analysis programmes and this would be provided to those responsible for the design of the earthing system. In addition, the rise in potential which the earthing system will experience whilst fault current is flowing, should also be limited to a pre-determined value.

These are the functions that the earthing system must provide, but they are required to meet a wide range of different problems. The first is a conventional fault, e.g. that arising from damage to a cable or breakdown of the phase to earth insulation in a piece of equipment. The equipment can be in a substation, a factory or the home. We term these "power frequency" faults, since most of the energy dissipated in the fault will be at mains frequency (50 Hz).

In some locations, such as radio or television transmitters, sites where large amounts of power are rectified or capacitor banks are switched, then energy will be available at higher frequencies than normal. The earthing system must be specially designed to provide a low impedance at these frequencies.

Many electrical installations are prone to the risk of damage as a result of a lightning strike and special arrangements are necessary to reduce the risks involved. An adequate earthing system is a fundamental part of this arrangement. Because a lightning impulse is steep fronted and a source of high frequency currents, special earthing system designs are again necessary. For example, bends in above ground conductors will form a small inductance which will be insignificant at power frequency, but may create a high impedance to lightning current. This may be sufficient for there to be a 'flashover' whereby the current flows through other routes to ground in preference to the designed route - possibly causing significant damage in the process.

The earthing system is also used as a means of achieving safe working conditions during some types of maintenance or construction. Plant which was previously energised has to be switched off and its previously live components are connected to earth before any work can commence. This allows any stored energy to be discharged safely to ground and helps prevent dangerous voltages arising on the equipment being worked on (these could otherwise occur due to induction, errors or power system faults). In some industrial premises the earthing system is required to continuously discharge the build up of static, and thus prevent a fire or explosion risk. Examples include paper manufacturing plants or when explosives or volatile chemicals are present.

A popular misconception is that the earthing system is only required during fault conditions. In fact it also serves a number of vital roles during routine operation. For example, many power supplies now include a connection to earth, through which residual and harmonic currents are dispersed to ground. The previously held belief that these currents could be 'dumped' to earth with no adverse consequences is now known to be false. Currents which flow to ground, in this way must return to source, forming a loop. These loops will create potential differences which, although small, cause 'noise', 'hum' and possible damage to electronic equipment. This process, together with the increasing amount of harmonic current being injected into the public supply network, is a growing cause of significant power quality problems. Some equipment contains earthed screens, which operate continuously to reduce the field produced outside the case or reduce the impact of external fields on the equipment performance.

In recent years, a number of factors have drawn attention to earthing systems. One is the increased use of plastic sheathed underground cables, another the use of plastic water pipes. Plastic water pipes have had a particular impact on domestic properties, which used to place great reliance on the earthing facility provided by the older metal pipes. Plastic sheathed cables are now used instead of the previous types which had a lead sheath and steel armouring in direct contact with the soil. This has had a detrimental effect on the overall efficiency of earthing systems and placed more reliance on the remaining components of the earthing system, including the earth electrodes installed at all electricity substations. It is now more important than before to ensure that the earth electrode systems are correctly designed, installed and maintained.

Clearly, the earthing system performs a wide range of similar functions throughout all the stages of providing electricity, i.e. at the generating station, the electricity company substations (at which the supply voltages are changed) through to the electrical installations in homes, offices and factories. Copper is the most widely used material for these earthing systems. Its well tried and tested properties of relatively low electrical resistance, malleability and good corrosion resistance have ensured that it has been the preferred material for very many years.

2 Standards and Legal Framework

2.1 Philosophy Underlying the Standards

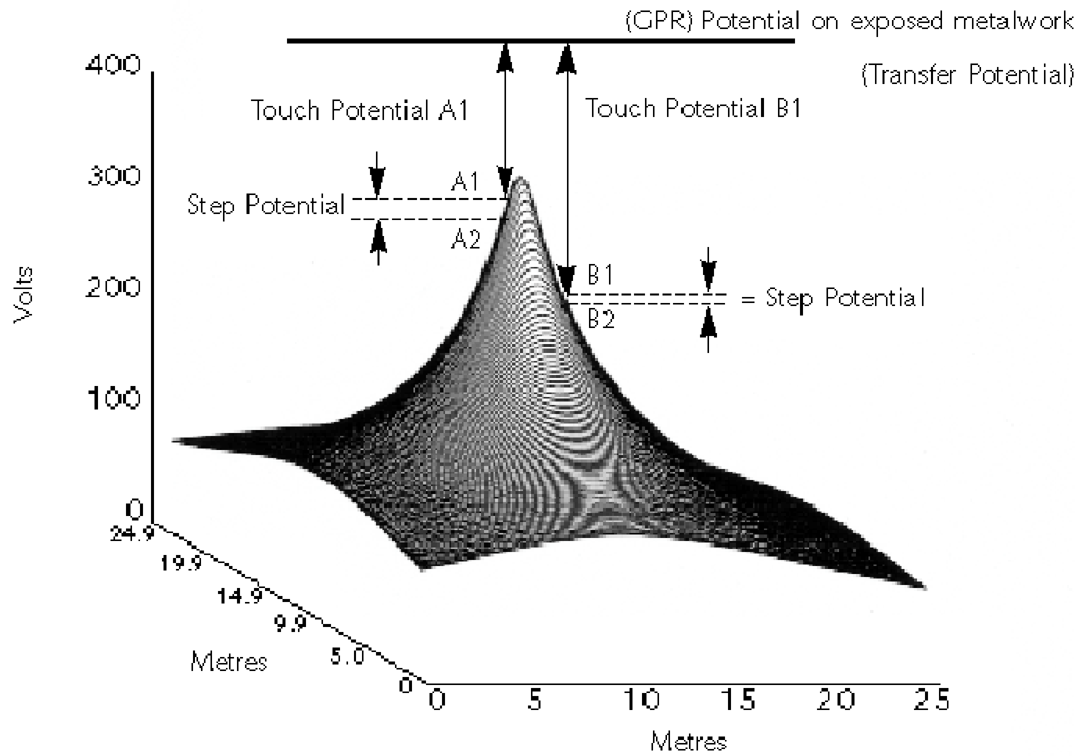
As a general rule, the standards provide the design limits to be met and (together with supporting codes of practice) explain how the earthing system can be designed to meet these. They generally include formulae to enable the necessary calculations to be carried out or detailed guidance on practical aspects - for example, how to connect items of equipment or where to position the electrodes. In this chapter the potentials on which the design limits are based will be described, based on supply industry practice. Readers should note that there are differences in the design limits appertaining to the supply industry and consumer electrical installations. For example, the shock voltage limits are lower within electrical installations than in supply industry substations. It is important to refer to the appropriate standard to check the design limits which apply to each situation.

Previously, it was established practice to design the earthing system to achieve a certain impedance value and the main electrodes were usually positioned near the equipment where fault current was expected to pass (for example transformers). This has changed during the last ten years, as the approach in the standards has moved towards that of north American practice. The most significant change is that now the earthing system must be designed to ensure that the potentials in its vicinity during a fault are below the appropriate limits. When an earth fault occurs and current flows to ground via the earth electrode, the potential on the electrode and any equipment connected to it, will rise above true earth potential. The potential reached under severe fault conditions, can be several thousand Volts. As the earth fault current flows into the soil surrounding the electrode, the potential within the soil and on its surface will rise. Moving away from the electrode system towards a remote point, the potential will progressively reduce until eventually it becomes that of true earth. This situation is shown in Figure 2-1, where the potential rise on the surface of the soil surrounding a single vertical earth rod, has been illustrated in three dimensions. This attempts to explain the potentials involved, in a semi-structural way.

Reference to Figure 2-1 shows that the rate of reduction of soil surface potential, or the potential gradient, is greatest near the rod and reduces as one moves away towards a remote point. Imagine that a person is walking away from the rod in a straight line towards a remote (reference) earth, i.e. down the potential "slope", taking equally spaced steps. The potential difference between the feet would be higher near the rod (for example at position A1, where it would be the potential difference between points A1 and A2) and would fall rapidly with each successive step (for example it is lower at position B1, i.e. B1-B2) before leveling out some distance away. This effect is recognised in the standards and is the basis of the term "step potential", which is the potential difference between two points on the surface of the soil which are one metre apart. The situation described for a single rod is similar to that for all electrode systems and the step potential is highest in the area immediately beyond the buried electrodes, in uniform soil conditions. Step potential is a directional quantity and calculations are required to find the highest value in a full 360 degree radius.

We have recognised that the potential on the surface of the soil differs according to the position in relation to the electrode system. This has implications for the second type of potential difference, the "touch" potential. Whilst fault current is flowing through the impedance of the earthing system, all of the exposed metal connected to this will experience a rise of voltage. For small systems, this is assumed to be the same value on all metalwork and is referred to as the GPR (Grid Potential Rise). In the example shown in Figure 2-1, the GPR is approximately 420V. The potential at a point on the surface of the soil will be lower than this, by an amount dependent on the buried depth of the electrode and the horizontal distance away. If a person is in contact with exposed metalwork and is standing on the soil, then their hands will be at same potential as the GPR, whilst their feet will be at a lower potential. This potential difference will be lowest if the feet are directly above the buried rod and will increase as they move further away. For example, Figure 2-1 shows that the touch voltage is significantly higher at position B1 than at position A1. The touch potential is normally the potential which dictates the design of the earth electrode system within an outdoor substation and it will be greatest in areas furthest away from buried electrodes where it is still possible to touch exposed metalwork. In chapter 7, examples of earth electrode arrangements are discussed and the new arrangements attempt to reduce touch voltages. It is also important to ensure that a potential difference cannot be experienced between hands which are in simultaneous contact with different pieces of exposed metalwork and this is catered for by inter-equipment bonding as discussed in chapter 4.

Figure 2-1 Touch, Step and Transfer potentials around an earth rod electrode

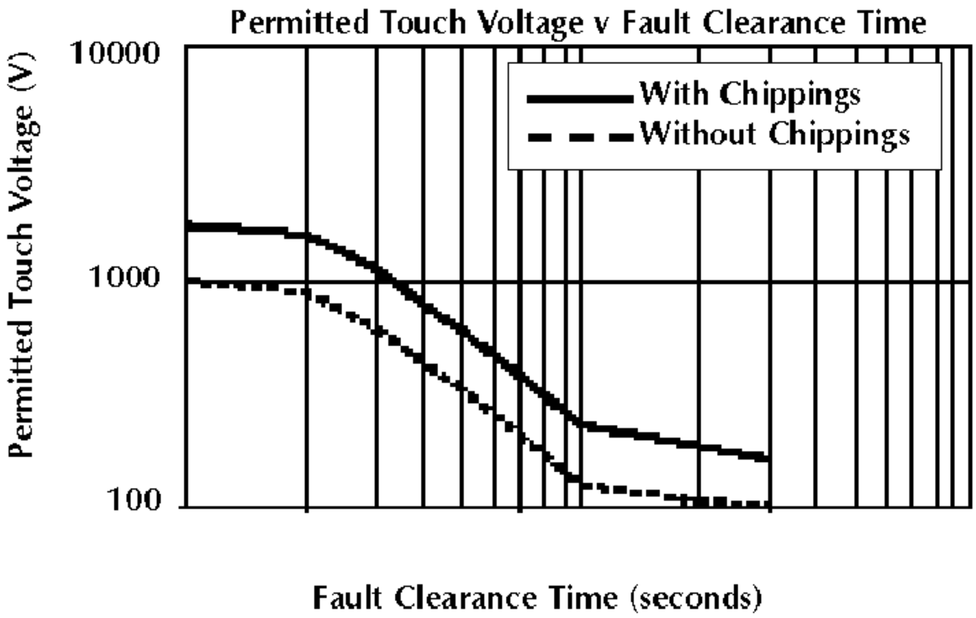


Finally, if an insulated cable which is connected to a remote (reference) earth, is brought near the rod, the potential difference between the cable and the rod is called the "transfer potential". The same transfer potential would be present if an insulated cable were taken from the rod to a remote point, where metalwork connected to a remote (reference) earth electrode system was present. The highest value of transfer potential is thus the GPR and this is the value normally used for calculations. At present, transfer potential limits are set by communication directives. They are 430 V and 650 V in the UK, depending on the type of installation, above which additional precautions are required.

Whether a person experiencing any of these potentials is at risk depends on a range of factors, including the GPR. The standards attempt to take these factors into account and establish limits, below which the design is considered acceptable. The ultimate risk of these potentials is that they will be sufficient to cause an electric shock which causes ventricular fibrillation of the heart. In arriving at the present limits, it was necessary to predict the proportion of current which would flow in the region of the heart and then establish limits based on its magnitude and duration. In UK standards, curves C1 and C2 of IEC 479-1, 1989 (International Electrotechnical Committee, Effects of Current Passing Through the Human Body) are used. These curves illustrate, for two probability levels, the current required for different time durations to cause ventricular fibrillation in a human.

The design limits are stated as voltages and in arriving at appropriate limits, it is necessary to consider the impedance through which the current will flow. This comprises of the human body impedance, hand contact resistance, any footwear resistance and the resistivity of the surface material underneath the feet. These factors are all taken into account in the standards and Figure 2-2 has been included to illustrate typical limits. This shows the tolerable voltage limits according to EA TS 41-24 (see section 2.3.2), assuming 100 Ohm-metre surface soil, a 1,000 Ohm body impedance, 4,000 Ohm footwear impedance and a foot contact resistance of 300 Ohm. A second curve shows the effect of having a high resistivity surface covering on top of the soil. Curve C1 of IEC 479-1 is used, but note that the x and y axes have been transposed in this figure to make it easier to understand. From Figure 2-2 it is evident that a relatively high voltage can be tolerated for short periods. It should be pointed out that voltage limits are presently being debated in both European and National Standard making committees. There are presently differences between the limits stated in Standards and it is hoped that one set will soon be available.

Figure 2-2 Permitted touch potential, in accordance with EA TS 41-24



In designing the earthing system, the designer would use the formulae and techniques described in the standards or codes of practice to arrive at a design which has touch potentials lower than the applicable limits.

2.2 The Legal Situation in the UK

The main three pieces of safety legislation applicable are the 'Health and Safety at Work etc. Act, 1974', the 'Electricity at Work Regulations, 1989' and the recent 'Construction (Design and Management) Regulations 1994'.

Breaches of these constitute a criminal offence and would leave an individual or company liable to prosecution. The Health and Safety at Work Act places duties on the employer and employee regarding health, safety and welfare. Clearly this applies to the situation where an employee is required to work in a location where adverse electrical potentials may be experienced during fault conditions.

The Electricity at Work Regulations deal with safety during the installation and use of electricity. In Regulation 8 they specifically refer to earthing. Suitable precautions and metal casings around machinery are discussed.

The CDM regulations apply to all projects and require that a safe working environment is provided during construction and maintenance. Maintenance is normally an on-going task, so the regulations apply over the lifetime of the installation. Since earthing is a fundamental component in providing safety in relation to electricity, it undoubtedly means that the earthing system comes within the scope of the regulations. Potential risks during maintenance, repair or renovation should be highlighted in a Health and Safety file which is retained by the occupier/duty holder of the site. Adequate records are required in the form of drawings and a historical record of maintenance.

Electricity companies are required to adhere to the ‘Electricity Supply Regulations, 1988, as amended’ and are licensed to enable them to distribute electricity within their geographical area. The licence, called the ‘PES licence’, requires companies to advise on the method of earthing it has adopted and that they abide by the Electricity Supply Regulations and the ‘Distribution Code’, amongst others. Earthing is covered in regulations 4 to 8 of the Electricity Supply Regulations. Regulation 5 requires that high and low voltage systems are earthed. It refers to solid and impedance earthing but does not mention unearthed systems. Regulation 8 requires that exposed metalwork (such as that enclosing or supporting equipment) is to be earthed where necessary to prevent danger. Where a dangerous occurrence takes place, the earthing system condition is one of the factors covered in the reporting procedure. The Distribution Code states "Arrangements for connecting the system with earth shall be designed to comply with the Electricity Supply Regulations 1988". The code covers earthing and refers specifically to a number of British Standards and other Codes of Practice, which are described below.

The standards, codes of practice and regulations are in the regulatory and commercial domain. Failure to abide by them could have serious financial consequences.

2.3 Summary of Contents of Main Standards and Codes of Practice

2.3.1 Domestic, commercial and industrial premises

(i.e. installations up to 1,000 V ac and 1,500 V dc - between phases, with some minor exceptions).

2.3.1.1 Existing

BS 7671 1992, Amendment 1, 1994. Requirements for Electrical Installations. (This is also known as the IEE Wiring Regulations, 16th Edition). Applies to all aspects of new electrical installations and requires that older installations are re-appraised when they are extended. Whilst it applies to all aspects, earthing comprises a significant part of the document because of the safety implications.

There is not a formal code of practice to support the BS, but there are a number of publications produced by the Institutions which serve this purpose. They help to illustrate practical arrangements which satisfy the regulations.

The Institution of Electrical Engineers publish a series of guidance notes. Guidance note number 5 concerns protection against electric shock and a significant amount of the text is concerned with earthing. The Institution of Incorporated Executive Engineers also publish an illustrated Guide to the IEE Wiring Regulations, which helps explain many practical applications.

2.3.2 High and medium voltage electricity substations

2.3.2.1 Existing

BS 7354:1990 Code of Practice for Design of high-voltage open-terminal stations, Section 7: Earthing

This covers substation construction and design considerations and includes some formulae. Some safety limits are introduced.

BS 7430:1991 Code of Practice for Earthing

This is, in effect, the technical supplement to BS 7354. It covers construction and measurement and includes resistance formulae, ratings, and material selection. Guidance is given for the earthing of many specific applications including protection of solid state devices against static electricity. It applies to all land based systems except medical equipment.

EA Technical Specification 41-24:1992 (Issued 1994)

Guidelines for the design, testing and maintenance of main earthing systems in substations. This document is intended to be used in conjunction with BS 7430, and ER S.34. It supersedes ER S5/1 and covers the design of substation earthing, including some formulae. Guidelines are given for the construction, maintenance and measurement of the earthing system.

EA Engineering Recommendation S.34:1986

A guide for assessing the rise of earth potential at substation sites. The core technical reference document for the electricity supply industry in Britain. It includes resistance formulae, current distribution formulae and nomograms.

2.3.2.2 Future

prEN 50179 Power Installations Exceeding 1 kV ac or 1.5 kV dc

This is a new European standard, presently in near final draft form and currently called CLC TC/112. Chapter 9 deals with earthing systems. This is an attempt to standardise earthing practices in Europe and is likely to come into effect in 1996 as a framework type document. It is likely to establish general rules but not include detailed technical application guidance. It will be necessary for all the present British Standards and Codes of Practice to be reviewed and amended once this comes into force. One possible change involves the allowable potentials, and draft documents indicate that this may be lower than the present ones. In turn, this will require a more detailed design of the earthing systems, probably involving additional electrodes. Minimum cross sectional areas for earth conductors are 16 mm^2 for copper, 35mm^2 for aluminium and 50 mm^2 for steel.

Other relevant standards are:

DIN VDE 0141: 1989 Technical Help to Exporters Translation

Earthing systems for power installations with rated **voltage**s above 1 kV. The German earthing standard. General principles are introduced and some resistance formulae given. The basis of the design of the earthing system is a series of tables giving the relevant criteria for different systems. Construction, inspection and maintenance are also covered.

ANSI/IEEE Std. 80: 1986

IEEE Guide for safety in ac substation grounding. A comprehensive USA standard which covers design and technical aspects. It covers soil modelling, fault current distribution, worked examples and special considerations, e.g. Gas insulated switchgear (GIS). This standard is generally considered to be stringent in its approach.

CCITT Directives

These mainly involve electromagnetic interference in telecommunication cables, arising from power and electrified rail systems.

3 Methods of Earthing

3.1 Main Power Network

Earthing on the power network will be considered first, as the method of earthing this strongly influences the method subsequently chosen within buildings. In theory, the main power network does not have to be earthed and sometimes arguments are put forward that an unearthed network may be more reliable. In some cases this can be true but, in general, unearthed networks can become unreliable due to over-stressing of the insulation which surrounds cables or lines. This can arise due to static, induction or intermittent faults.

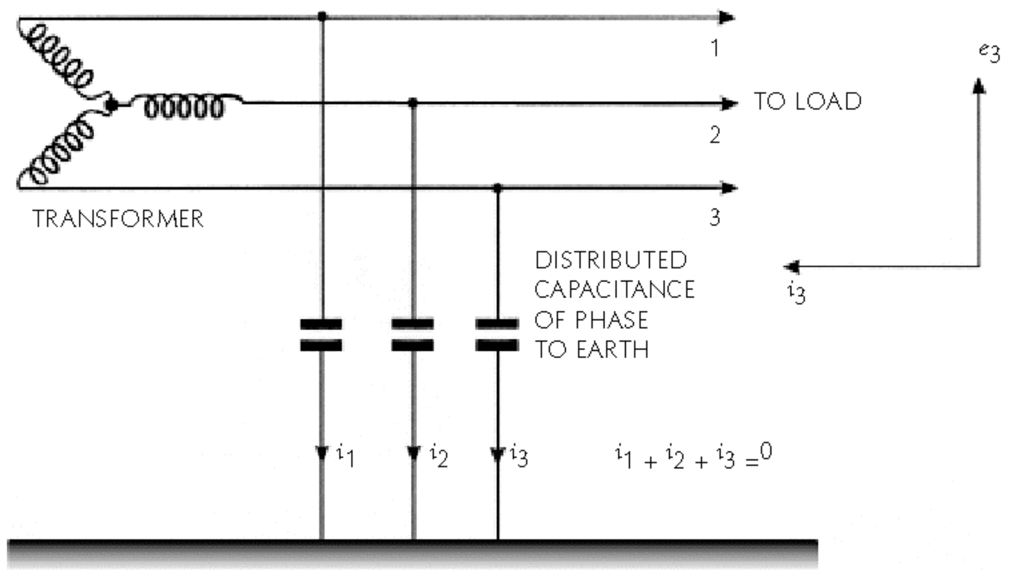
In the UK and most of Europe, the main power networks are earthed. For example, in the UK, the Electricity Supply Regulations 1988, Regulation 5 concerns connection with earth. This requires that each part of the power network (i.e. each voltage level) be connected to earth. In the case of high voltage systems, the earth connection should be as near as possible to the source of voltage. Generally, a separate earth is required at each voltage level, although the earths from different voltage networks are often combined.

There are a number of ways in which the power system can be operated. These include unearthed, high impedance earthed and low impedance earthed arrangements. They are quite different concepts and to those who are familiar with the relatively large earth conductors and low earth values on traditional systems, use of small earth conductors and high impedances on other systems can come as a surprise. These different arrangements are described in more detail below:-

3.1.1 Unearthed or insulated system

This does not have a deliberate, formal connection to earth. There may be some high impedance connections for instrumentation, for example the coil of a measuring device. Under normal conditions the capacitance between each phase and earth is substantially the same. The effect is to stabilise the system with respect to earth so that, with a three-phase system, the voltage of each phase to earth is the star voltage of the system. The neutral point, if any, is then at, or near, earth potential, (see Figure 3-1).

Figure 3-1 Capacitive currents in a three-phase system



Faults on overhead distribution lines are not uncommon, particularly during bad weather conditions when branches of trees may fall onto the lines. When the first incident occurs, involving, say a contact between a conductor and earth, there may be no damage as there is not a complete metallic circuit to enable current to flow. This is different to an earthed system, where a significant current would flow. At first sight, the unearthed system may appear to be a safer and more reliable system. In reality a current would flow in the unearthed system, returning via capacitive coupling to the other two phases. The capacitive current flowing at the fault point is three times the normal capacitive current to earth from each phase of the whole system. The damage due to the first fault is likely to be slight, since the total current is still relatively small. However, the current could be sufficient to risk electrocution if someone was to touch the damaged conductor. Power companies often find that it is time consuming to locate faults on this type of system. The introduction of an unearthed system into the UK would require a change in the Electricity Supply Regulations.

The probability of a second fault is higher than generally thought, as the voltage across the remaining insulation will be phase to phase level rather than phase to earth (i.e. an increase of $\sqrt{3}$ in magnitude). This will stress the phase to earth insulation and may cause accelerated ageing and breakdown. A second fault is likely to involve considerable fault energy and damage. It is thus important to remove the first fault as quickly as possible.

Resonance can cause over-voltages on this type of system. The system already has a high capacitance and if a phase conductor is connected to earth via a connection having a high inductance (e.g. an instrument transformer), then resonance, high circulating currents and over-voltages can occur. An intermittent arcing fault which has a high impedance can cause similar high voltages leading to equipment failure. This is due to a trapped charge effect on the neutral. The charge is progressively built up with each subsequent arc and can produce voltages which can be sufficiently high to overseers insulation by 6 to 7 times (in theory), of that occurring at normal voltage. In practice, due to weather conditions, dust etc., the actual voltages measured have been 3 or 4 times the normal voltage.

If continuity of supply is an important factor for the distribution system, then an ungrounded system may have some advantages. However, the insulation applied between each phase conductor and earth is likely to need increasing to at least the same as that between different phases, in order to deal with single phase to ground faults, and the trapped charge scenario.

3.1.2 Earthed systems

An earthed system has at least one conductor or point (usually the neutral or star point) intentionally connected to earth. For reasons of cost and practicality, this connection is normally made near the position where the three individual transformer phase windings are joined, i.e. the star point or neutral. This method is adopted if there is a need to connect line to neutral loads to the system, to prevent the neutral to earth voltage fluctuating with load. The earth connection reduces the voltage fluctuation and unbalance which would otherwise occur. Another advantage is that residual relays can be used to detect faults before they become phase to phase faults. This can reduce the actual damage caused and the stresses imposed on other parts of the electrical network.

The type of earthed system is classified according to the type of connection provided. The main types are:-

3.1.2.1 Impedance earthed system

Resistors and/or reactors are deliberately inserted in the connection between the neutral point and earth, normally to limit the fault current to an acceptable level. The impedance can, in theory, be high enough that little more fault current flows than in an unearthed situation.

In practice, to avoid excessive transient over-voltages due to resonance with the system shunt capacitance, inductive earthing needs to allow at least 60% of the 3 phase short circuit capacity to flow for earth faults. This form of earthing has a lower energy dissipation than resistive earthing.

Arc-suppression coils, also known as Peterson coils or ground fault neutralisers, can be used as the earth connection. These are tuned reactors which neutralise the capacitive coupling of the healthy phases, so that fault current is minimal. Due to the self-clearing nature of this type of earthing it is effective in certain circumstances on medium voltage overhead systems, for example, those which are prone to a high number of transient faults, e.g. the Hungarian 20 kV system. The use of auto reclosing circuit breakers has reduced the use of this method of earthing generally in high and medium voltage systems.

Resistance earthing is more commonly used, because it can allow the fault current to be limited and damp transient over-voltages, if the correct value of resistance is chosen. In UK distribution systems, particularly those at 11 kV, it is common to find 750, 1,000 or 1,500 A liquid earth resistors (LERs) installed in various combinations to limit the earth fault current. In new installations, it is now more common to use ceramic type resistors. These require less space, have significantly lower maintenance costs and cool down more quickly than liquid resistors following the passage of fault current.

3.1.2.2 Low impedance (solidly) earthed system

This is the most common arrangement, particularly at low voltage. Here the neutral/earth connection is through an adequate connection in which no impedance has intentionally been added. The disadvantage of this arrangement is that the earth fault current is normally high, but the system voltages remain suppressed or low under fault conditions.

The prime example on newer supply systems in the UK is PME, (Protective Multiple Earthing) where there is no separate formal earth conductor. The neutral conductor carries unbalance current and acts as the earth conductor. To protect against the possible loss of the neutral/earth connection from the source, the neutral is earthed at several positions (thus the term "multiple").

3.2 Earthing on LV Systems and Within Premises

Having dealt with the type of earthing available on the Power System, the low voltage system and the wiring within premises must be considered.

3.2.1 Types of System

There are a number of methods by which an earth connection can be given and there are now standard definitions for these in Europe. They are each identified by a coding which contains the following letters:

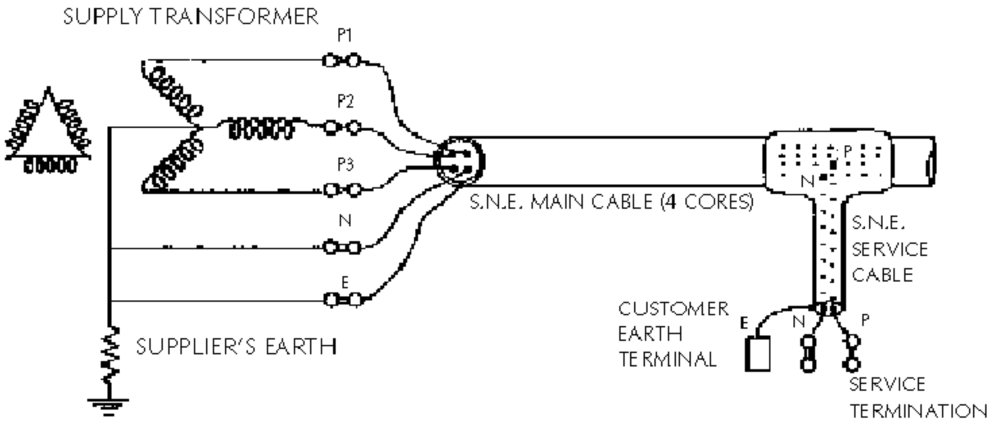
T : terre, direct connection to earth
N : neutral
C : combined
S : separate

The main types are described below and diagrams have been provided to explain these in more detail. Please note that the earth electrodes in the diagrams include a resistor symbol to show that the electrode has an impedance, which is predominantly resistive.

TN-S The incoming supply has a single point of connection between the supply neutral and earth at the supply transformer. The supply cables have separate neutral and earth protective conductors (SNE) Generally the neutral conductor is a fourth 'core' and the earth conductor forms a protective sheath, or PE conductor. The customer may be provided with an earth terminal connected to the sheath of the service cable or to a separate earth conductor. This was a standard arrangement prior to the introduction of protective multiple earthing (PME) systems. The arrangement is illustrated in Figure 3-2.

Figure 3-2 Typical T N-S system

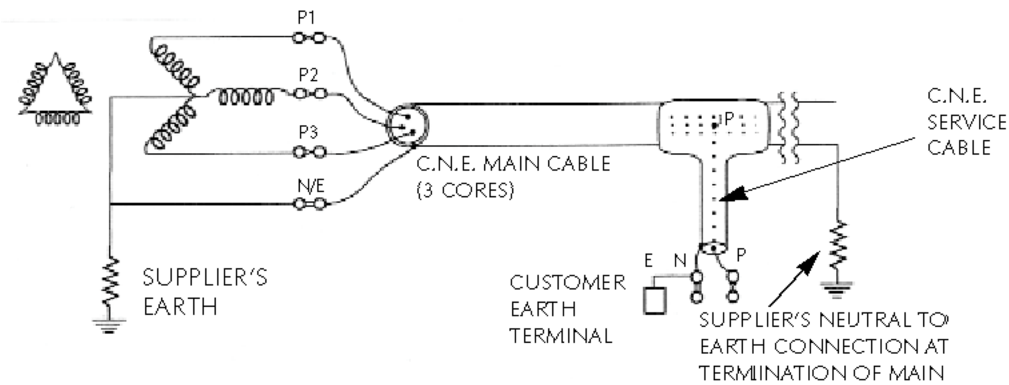
Supply Single Point Earthed. SNE Mains and Service Cables. Customer provided with earth terminal from the sheath of the service cable.



TN-C-S The supply neutral is earthed at a number of points. The supply cables have a combined neutral and earth metallic outer sheath with a PVC covering (they are termed CNE cables). The combined neutral earth sheath is the PEN (protective earth neutral) conductor. An earth terminal, which is connected to the supply neutral, is provided by the electricity supplier. The supply within the customers premises would be TN-S, i.e. the neutral and earth would be separate, linked only at the service position. Before the customer is allowed to make use of the earth terminal, the supplier must be satisfied that all internal, normally exposed metalwork (such as water, gas, central-heating pipes etc.), is bonded together in the manner prescribed in the Regulations. The arrangement is illustrated in Figure 3-3.

Figure 3-3 Typical TN-C-S (Protective Multiple Earth) Supply

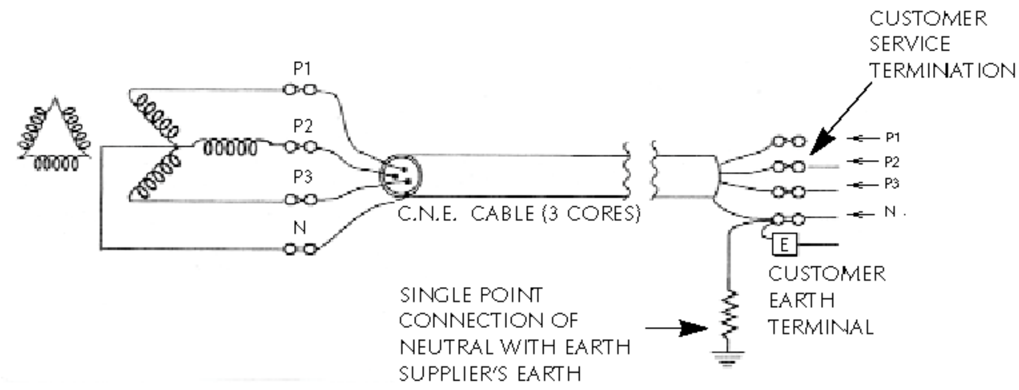
Neutral earthed by Supplier at a number of locations. CNE Mains and Service cables. Customer provided with earth terminal connected to the service neutral.



PNB Protective Neutral Bonding. This is a variation of the TN-C-S system in that the customer is provided with an earth terminal connected to the supply neutral, but the neutral is connected to earth at one point only, normally at or near to the customer's supply point. This arrangement is reserved for use when a customer has an individual transformer and is no longer listed in BS 7671. The arrangement is illustrated in Figure 3-4.

Figure 3-4 Typical P N B System

Customer has own transformer. Single point neutral earth CNE cables used.

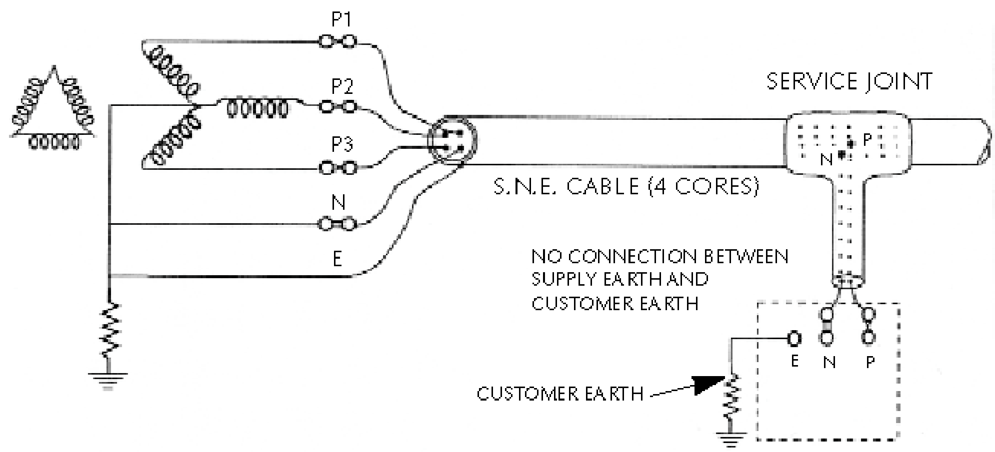


The remaining two systems are:-

TT This is a system where the supply is earthed at one point only, but the cable sheaths and exposed metalwork of the customer's installation are connected to earth via a separate electrode which is independent of the supply electrode. The arrangement is illustrated in Figure 3-5.

Figure 3-5 Typical TT System

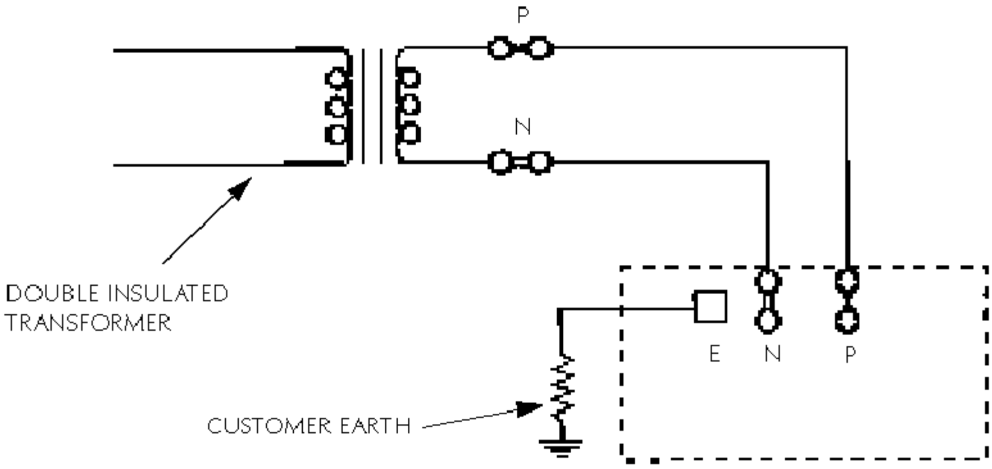
Supply is earthed at one point only. Customer provides own earth which is independent of the supply earth.



IT This is a system having no direct connection between live parts and earth, but with the exposed conductive parts of the installation being earthed. Sometimes a high impedance connection to earth is provided to simplify the protection scheme required to detect the first earth fault. See Figure 3-6.

Figure 3-6 Typical IT System

Source isolated from earth or connected to earth through a high impedance. All exposed conductive parts of the installation are connected to an independent earth. Not remissible for public supply in the UK.



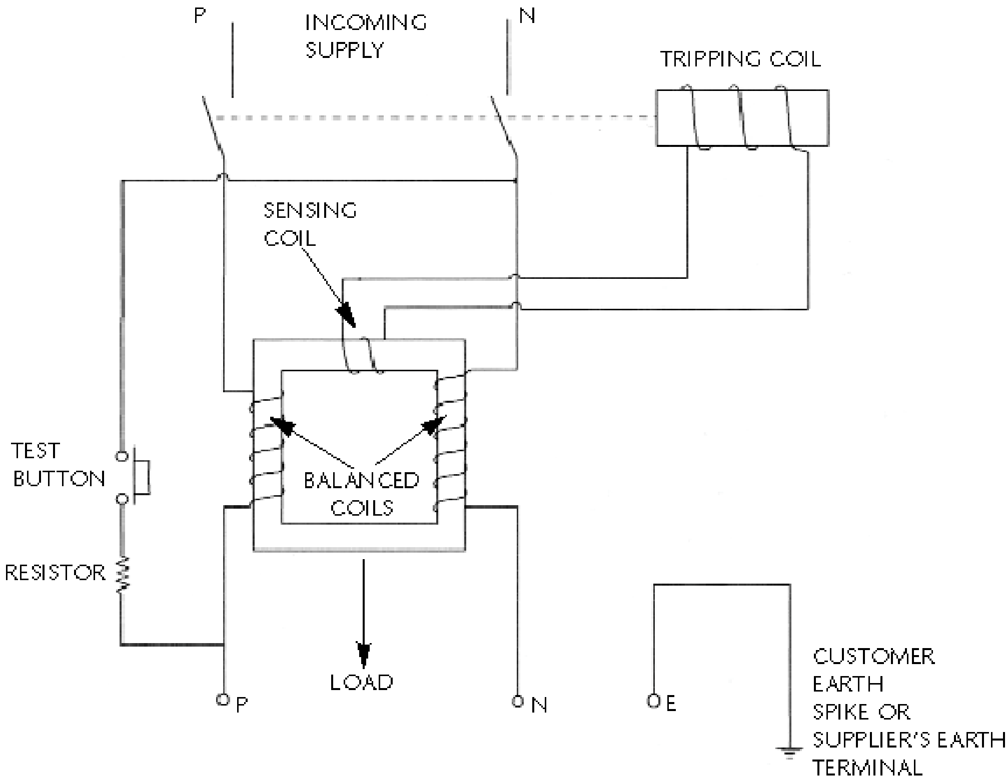
Earthing arrangements within buildings in the UK should conform to British Standard 7671. This standard is based upon the 16th edition of the Institution of Electrical Engineers Regulations for Electrical Installations. The Electricity Supply Regulations 1988 do not apply, where the installation does not form part of the public network, so an earth connection is not a statutory requirement and unearthed systems (IT) are permitted and used in special circumstances. However, BS 7671 still requires a main earth terminal and the Electricity at Work Regulations will probably be applicable.

The underlying principle is first to take all reasonable precautions to avoid a direct contact with live electrical parts, and secondly to provide measures to protect against indirect contact. The latter involves effective earthing and bonding, and a system of protection which removes the fault condition. The principle is more commonly known as protective bonding and will be covered in a little more detail in chapter 4. It is not however the intention of this book to describe earthing within buildings in detail as there are already a large number of publications which cover this. Readers are referred to the publications listed in chapter 16, where they will be able to find the subject adequately covered.

Although it is now normal practice for all electricity suppliers in the UK to provide each customer with an earth terminal, for a variety of reasons not every customer has been given this facility. The customer must, however, provide his own protection against the dangers of an earth fault. One way in which this can be achieved is by using an earth leakage detector and circuit breaker. This device still requires a connection to earth and detects when an earth fault occurs in a circuit. It then causes a circuit breaker (or trip) to operate and isolate the faulty circuit.

The recognised device is the current operated detector known either as the Residual Current Device (RCD) or the Residual Current Circuit Breaker (RCCB). This unit operates by detecting the residue, or difference, between the current flowing into and returning from a source. (See Figure 3-7). When the residual current exceeds a predetermined value, the RCD contacts open. The unit can be designed to be ultra sensitive, with very high speed operation for use in special situation, e.g. hospitals. A test button is incorporated. Initially, the detectors were voltage sensors i.e. they detected a rise in voltage on the earthed structure. However, for many years, the voltage detecting device has been considered to be unreliable, it did not protect against phase to neutral faults and its use is no longer recognised by BS 7671.

Figure 3-7 Residual current detector



In addition to providing main earth fault protection, RCDs are also used extensively in conjunction with conventional protection, such as fuses or miniature (over-current) circuit breakers. A particular application for RCD protection is on the circuit providing supply to equipment which uses a trailing lead - such as a lawn-mower or hedge trimmer. When used in this way, RCDs provide “Supplementary Protection against Direct Contact”. It should be noted that RCDs do not react to overload, so additional protection is required for this.

There are some locations where special earthing arrangements are necessary. These include:-

(a) Mines and Quarries. Under the 1989 Electricity at Work Regulations, the Health and Safety commission have issued two approved Codes of Practice:-

(i) The use of Electricity in Mines.

(ii) The use of Electricity at Quarries.

Detailed direction is given in these documents on the earthing arrangements which must be made.

(b) At Petrol Filling Stations. The Health and Safety Executive have issued Publication HSE (41) covering the electrical installations at petrol filling stations. A new Institute of Petroleum document is presently being prepared on this subject.

(c) Lightning Protection of Buildings. This is covered in BS 6651, 'Protection of structures against lightning'.

(d) Lift Installations. This is covered in BS 5655, 'Safety rules for construction and installation of lifts'.

(e) Temporary installations.

(f) Caravan sites and marinas.

4 Earth Conductors

Having introduced the wide variety of earthing arrangements possible, it is now necessary to consider the earthing system itself. The most important functions of the earth conductors are explained and some definitions introduced. The different types of earth electrode available are described and surprisingly the same types are generally used whether the earthing system is for a house, factory or generating station.

4.1 Requirements of the Earthing System

The function of the earthing system is two-fold.

- To provide a low enough impedance path, via the earth conductors, back to the supply source so that in the event of a failure to earth of a live conductor, sufficient current will flow safely along a predetermined route to enable the circuit protective device to operate.
- To limit the potential rise on all metalwork to which persons and animals normally have access, to a safe value under normal and abnormal circuit conditions. The bonding together of all normally exposed metalwork, such as gas, water, central-heating pipework etc., and the connection of that bond to the earth terminal, will prevent the possibility of a dangerous potential difference arising between adjoining pipework under both normal and abnormal conditions.

There are two main types of earth conductor, which are "bonding" (also referred to as protective) conductors and earth electrodes.

4.2 Bonding and Protective Conductors

Within the regulations, a number of definitions have developed to describe the different types of earth conductor used. The practical application of these conductors within buildings will be discussed again in chapter 8. The types are:-

Circuit Protective Conductor (CPC)

This is a separate conductor installed with each circuit and is present to ensure that some, or all, of the earth fault current will flow back to source along it. It may be an individual conductor, the metal outer sheath of a cable or the metalwork formed by a conduit or trunking.

Bonding Conductors

These ensure that exposed conductive parts (such as metal enclosures) remain at approximately the same potential during electrical fault conditions. The two forms of bonding conductor are:-

- Main equipotential bonding conductors which interconnect together and to earth, exposed conductive parts which do not normally carry current, but could do so under a fault condition. These bonds normally connect exposed incoming metal gas and water pipes, the main services and main structural steelwork to the earthing system. Within installations, to comply with BS 7671, these bonds must be of a certain minimum size (at least 6 mm^2), and generally do not need to be greater than 25 mm^2 copper, unless the supply is PME. If the supply is PME, then the required size will be related to that of the incoming neutral conductor (see BS 7671, table 54 and Note).
- Supplementary bonding conductors are to ensure that electrical equipment and other items of conductive material in specific zones are bonded together and remain at substantially the same potential. They are used in addition to the main equipotential bonding conductors and circuit protective conductor.

Bonding and earth conductors within electricity substations need to be of sufficient size that they can carry a certain amount of fault current for three seconds, without damage. The table below shows some of the more common sizes of tape used for both bonding and "in ground" electrodes. The current rating shown is that calculated according to the formula in EA TS 41-24. The ratings are based on an ambient temperature of 30°C, three seconds fault duration and maximum temperatures of 375°C and 295°C for copper and aluminium respectively. Different formulae are applicable, according to the situation, so the standards should always be consulted before assigning a current rating. Also, an allowance for some material loss by corrosion over the life of the installation should be made.

Maximum current kA	Tape cross section (mm) Copper	Tape cross section (mm) Aluminium
12.0	4 x 25	4 x 40
18.5	4 x 40	6 x 40
22.0	4 x 50	6 x 50

For bonding conductors, it is essential that the conductor size chosen is capable of dealing with the full value of anticipated fault current. If a fault develops, the whole of the fault current may flow through via the earth conductor through to the "in ground" electrode system. Once there, it will normally be split up between the various electrodes, so these can often have a smaller cross sectional area than the main earth or bonding conductor.

4.3 Earth Electrodes

The earth electrode is the component of the earthing system which is in direct contact with the ground and thus provides a means of releasing or collecting any earth leakage currents. In earthed systems it will normally be required to carry quite a large fault current for a short period of time and so will need to have a cross-sectional area large enough to be able to carry this safely. Electrodes must have adequate mechanical and electrical properties to continue to meet the demands on them over a relatively long period of time, during which actual testing or inspection is difficult. The material should have good electrical conductivity and should not corrode in a wide range of soil conditions. Materials used include copper, galvanised steel, stainless steel and cast iron. Copper is generally the preferred material for reasons described later. Aluminium is sometimes used for above ground "bonding", but most of the standards forbid its use as an earth electrode due to the risk of accelerated corrosion. The corrosive product - an oxide layer - is non-conductive, so could reduce the effectiveness of the earthing.

The electrode can take a number of forms. These include vertical rods, plates and horizontal conductors, the most common of which are described below.

4.3.1 Rods

These are the most common form of electrode, because they are relatively cheap to install and can be used to reach into deeper, low resistivity soil with only limited excavation and backfilling. They are available in a range of lengths, diameters and materials complying with the Electricity Association Technical Specification 43-94.

The rod is either of pure copper or copper plated steel. The plated type is normally used when mechanical driving is necessary, since the steel used has high tensile strength. The copper plating should be of high purity copper and electrolytically applied. The latter helps ensure that the copper plating does not slip off during driving! Solid copper rods are used in more aggressive soil conditions, for example when there is a high salt content. Stainless steel rods (austenitic steel to BS 970, grade 316S12) are more anodic than copper and can be used where galvanic corrosion is possible. However, stainless steel has poor current carrying capabilities in comparison to copper and this must be taken into account.

There are threaded portions at each end of the rod which allow a pointed spike, a hardened (high strength steel) driving head or additional rods to be screwed on. Rolled threads are stronger than cut threads and it is important for plated rods that the plating is intact across the threaded section. Some manufacturers also have a cross head drilling spike which is particularly useful if the rod couplings have a greater diameter than the rod. It is claimed that this type of head permits driving to greater depth. Rods are readily available in diameters of 15 mm to 20 mm diameter (solid copper) and 9.5 mm to 20 mm diameter (Copper Bond). Lengths are 1.2 to 3 metres for individual rods.

Shielded sections of rod are also available for use when, for example, there is a highly corrosive layer of soil through which a deep driven rod must pass. The shielding would be of, say, PVC to prevent contact between the rod and the corrosive soil. Of course this section will not contribute towards reducing the impedance value, because it is not in contact with the soil.

4.3.2 Plates

There are several types of plate used for earthing purposes, but the only type which is generally considered as an electrode would be solid and of substantial size. Lattice type plates, as illustrated in Figure 4-1 are used for potential grading and would not be expected to pass significant amounts of fault current. They are normally made of copper or steel mesh.

Figure 4-1 Earth Plates (courtesy A N Wallis and Co)

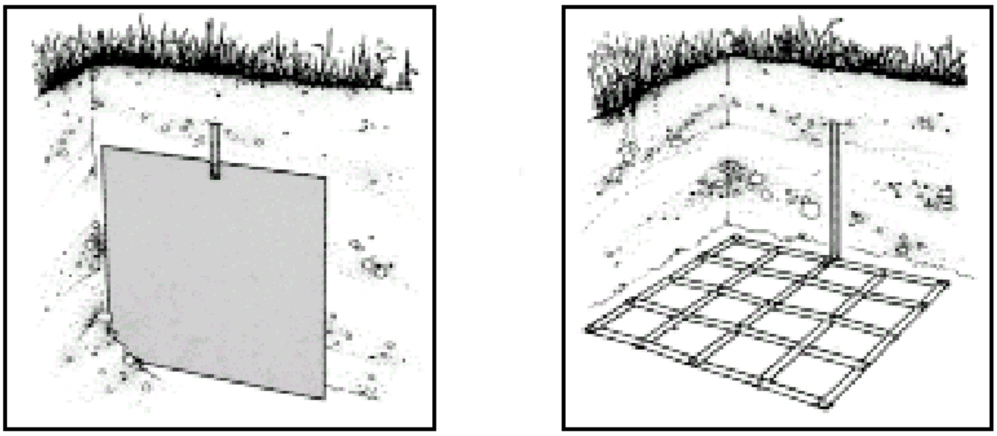


Plate electrodes are of copper or ribbed cast iron. The cast iron plates normally are a minimum of 12 mm thick and either 915 mm or 1,220 mm square. Copper plates are typically 600 mm to 900 mm square and between 1.6 mm and 3 mm thick.

Where multiple plates are used, they must be some distance apart to prevent any interaction. Normally this is a minimum of 2 m, possibly extending to 9 m.

4.3.3 Horizontal electrodes

These are made from high conductivity copper strip or stranded conductor. Strip is normally the preferred material as it has a larger surface for a given cross section area and is considered to have a superior performance at higher frequencies, due to a slightly higher capacitance when installed in the soil. It can be more difficult to connect (for example to vertical earth rods), so may involve a slightly higher installation cost.

To reduce overall costs, strip is often used for the electrodes which will be required to carry most current (i.e. the perimeter electrode and main plant connections) whilst smaller, stranded conductor would be used elsewhere (see chapter 7). Strip which is installed underground is normally fully annealed (ref. BS 1432, 'Specifications for copper for electrical purposes: high conductivity copper rectangular conductors with drawn or rolled edges' - C101) so that it can be bent easily.

For above ground purposes PVC sheathed strip, solid or stranded conductors are available. Tinned or lead covered copper tape is also available for special applications.

4.3.4 Electrode Derivatives

There are some interesting derivatives available which include a number of ideas which it is claimed improve the performance of an earth electrode. They include earth pits and ground reservoirs.

An earth pit may comprise of several large pipes inserted vertically into the soil. They are bonded together and surrounded by low resistivity material.

A ground reservoir is typically a cavity at a position where moisture collects, which is filled with scrap metal and other conductive material. Perhaps the most expensive electrode of this type is situated underneath the English Channel. One of the boring machines used for the channel tunnel has been used for this purpose. Because of the anticipated cost of removing it, it was directed downwards and is now used for earthing.

An example of a derivative is the XIT Grounding System. The electrode consists of a 50 mm diameter copper tube, available in lengths up to 6 metres.

The hollow shaft is partly filled with coarse metallic salts, called Calsolyte, and the top and bottom of the tube sealed with caps. Breather holes are drilled into the top, and drainage holes into the bottom. The backfill material recommended is Bentonite (see section 14.2 for a description of this material).

The device functions as follows: -

Changes in atmospheric pressure and natural air movement 'pump' air through the breather holes at the top of the tube. The moisture in the absorbed air comes into contact with the Calsolyte and, via a hygroscope process, droplets of water are formed. As the moisture accumulates, an electrolyte solution is formed which travels to the bottom of the tube.

In time, sufficient electrolyte is formed such that it flows through the drainage holes into the surrounding soil by osmosis. The electrolyte thus forms "roots" into the surrounding soil which help to maintain its resistivity at a low level.

5 Installation Methods

5.1 Introduction

When installing electrodes, there are three conditions which must be satisfied:-

- the work must be carried out efficiently to minimise installation costs,
- the backfill used must not have a pH value which will cause corrosion to the electrode; and
- any joints or connectors used below ground level must be so constructed that corrosion of the joint/connector will not take place.

The method of installation, backfill and connection detailed in the following paragraphs will depend upon the type of electrode system to be used and on the site conditions. Where practicable, use should be made of existing excavation work e.g. by laying electrode strip in a cable trench. Mechanical aids or hand tools are invariably required to assist in the installation.

5.2 Rods

These generally offer the cheapest and most convenient means of installing an electrode. Often, little surface disturbance is required (such as breaking of concrete or tarmac surfaces) - but checks are of course necessary to ensure that there is no equipment buried there that can be damaged when driving in the rods - such as water or gas pipes. The installation methods include manual driving, mechanical driving and drilling.

Short rods (typically up to 3 metres in length) are often installed just by using a manually operated heavy hammer. Relatively short, frequent blows are normally the most effective. The rods are normally fitted with a hardened driving head and a steel tip to assist in ensuring that the rod itself is not damaged during the process.

Longer rods are often driven in a similar way, but using a pneumatic hammer which requires much less physical effort and provides a more certain, directed inertia. Electric, petrol, hydraulic oil, or air driven tools have all been used successfully for this. Due to their weight, these tools sometimes require a rig to support them.. A typical electric hammer would have a consumption of 500 watts and deliver about 1500 blows per minute and some designs do not require a rig. It is possible to drive rods down to a depth of 10 metres or more using this method, depending, of course, on the actual soil conditions. It has also been recorded that rods of 30 m length have been installed in this way - but it is not known how straight they are! They have sometimes been known to bend and break back through the surface of the soil some distance away. The time taken to install the rod will vary according to the soil type. For example, in loose sand/gravel, the installation rate for an 11 mm diameter rod may be 3.5 metres per minute, but this can fall to 0.5 metres per minute in stiff clay.

The diameter of the rod is a major factor in the effort needed to install it. Smaller (9 mm diameter) rods are relatively easy to install, but as the required rod length increases, so the diameter must be increased to ensure that the rod has sufficient mechanical strength - particularly at joint positions. Doubling the rod diameter from 12 mm to 24 mm increases the mechanical resistance to driving by more than three times. Where the rods are to be deep driven, they are normally either welded or mechanically coupled together. The coupling arrangement must be such that the diameter of the rod is not increased significantly, or this will make installation more difficult and produce a hole with a wider diameter than the rod. The coupling should also shield the threaded section, to help prevent corrosion.

Copper plated steel rods are significantly stronger than solid copper rods, which bend quite easily and may break when attempts are made to drive them into rocky soil.

When deeper rods are required or in difficult soil conditions where there is underlying rock, the most effective means is to drill a narrow hole into which the rod electrode and a suitable backfill material are installed. This method is often surprisingly economic, since a significant number of deep holes can be drilled in a day using modestly priced equipment. Rods can be installed routinely to depths of 20 metres and, with more specialist equipment, to significantly greater depth. Besides the advantages of obtaining a greater depth and a more controlled route for the electrode, another benefit is that relatively thin, solid copper electrodes can be installed in this way.

Because the solid copper rod has a better conductivity than the plated type, this further improves the benefit obtained from use of long rods. If driven mechanically into the ground at such depth, rods would normally need to be much thicker and a copper coated steel rod may be necessary to provide sufficient strength. In the past a number of different shapes, such as star shaped cross section, have been used to increase the strength of the rod and make it less likely to bend in rocky conditions. However, they are not generally available now. The shape difference only has a marginal effect on the electrical resistivity obtained, but would require less material for the same surface area.

In many situations, long vertical rods can provide an economic solution and there are a number of specialist small companies with the drilling facilities to achieve this.

There is also equipment available which, to avoid using mechanical joints, uses stranded copper conductor deep driven to provide a similar effect to that of a conventional rod. A steel rod is driven into the ground, pulling the stranded copper conductor in behind it. In time the steel is likely to corrode away leaving the copper conductor to provide the permanent electrode.

5.3 Plates

Originally, in the early 1900’s, plates were so commonplace that all earth electrodes were called earth plates. As the use of electricity increased there was a need for the plates to deal with ever greater currents, which was accomplished by increasing the plate dimensions. Their use continued for some considerable time, mainly due to custom and practice, despite the fact that they have some disadvantages. For example, they generally require manual or mechanical excavation and so the installation cost can be quite high. To reduce the amount of excavation required, plates are normally installed in the vertical plane about 0.5 metres below the surface. It is easier to pack the soil thoroughly against the plate when backfilling, if they are installed vertically. Another disadvantage was due to the locations chosen for earth plates. Often they were positioned too close together and their zones of influence overlapped one another. This increases their combined resistance to a higher value than expected. If plates are required to carry a significant amount of current, then this resistance needs to be low. In practice, the combined resistance was not sufficiently low enough and the fault current would generally seek other routes. So, in this situation, the improved current density stated as an advantage for plates is not achieved. A better arrangement can usually be provided using rods and horizontal electrodes.

Because of the relatively high installation cost, there is little justification to use plates now and they are normally replaced by a cluster of rods when deterioration is detected.

5.4 Horizontal Electrodes

These can be mechanically ploughed directly into the ground or are more usually installed in ready opened trenches about half a metre deep. Use of narrow mechanical excavation equipment can result in modest installation costs in locations where this is possible. The installation depth is normally a minimum of 0.5 metres and more if necessary to be below the frost or cultivation level.

On many large projects the whole area may be excavated to allow civil works. This often presents a good opportunity to minimise costs by laying the electrode conductor at that time. Great care must be exercised to prevent damage to, or theft of, conductor once laid.

5.5 Backfill

In all cases the backfill medium must be non-corrosive, be of a relatively small particle size and should, if possible, help to retain moisture. More often than not, the previously excavated soil is suitable as a backfill, but should be sieved to remove any large stones and placed around the electrode, taking care to ensure that it is well compacted. The soil should have a pH value between 6.0 (acidic) and 10.0 (alkaline) - see chapters 11 and 14. Normal, stiff clay is not a suitable backfill material as, if heavily compacted, it may become almost impervious to water and could remain relatively dry. It may also form large lumps which do not consolidate around the rod.

Materials which should not be used as backfill include sand, coke-breeze, cinders and power-station ash, many of which are acidic and corrosive.

In some circumstances, special backfill materials are required. The materials available, together with advice on when to use them are listed in chapter 14.

5.6 Connections

The earth electrodes have to be connected together in some way and it is normal for this to be via bare copper if possible, since this will help in further reducing the overall impedance value. Connections between the various components must be mechanically robust, have good corrosion resistance and low electrical resistivity. It is prudent to avoid unnecessary joints and connections. Consideration must also be given to the fault currents and fault duration that the earthing system may be expected to withstand.

The British and other standards quote material specifications that are deemed acceptable, for example stating that couplings for copper rods need to have a minimum copper content of 80%. The jointing methods used include mechanical, brazed, exothermic, and welded and are explained in more detail below:-

5.6.1 Mechanical connections

These are commonly used and can be mechanical (bolted connection) or hydraulic (compression). The connectors must meet the requirements of the applicable standards. The process of proving compliance with standards normally involves a series of life tests during which the connector is subjected to mechanical, electrical and thermal shocks. It follows that the design, size and material used are important factors - particularly since such connectors may be buried unseen in the ground for a number of years before being required to perform. A good, low resistance electrical connection is essential, particularly on radial types of electrode system. It does not take much contact resistance for this to exceed the impedance of the electrode system. During maintenance, connections have been uncovered with a resistance of more than 20 Ω. Clearly this would prejudice the performance of the electrode system.

Where copper strips are bolted together, care should be taken with the hole size drilled to accommodate the bolt. If this is too large, the current carrying capability of the strip will be prejudiced. For this reason, the standards and codes of practice normally limit the hole diameter to one third of the strip width or less.

Where dissimilar metals (e.g. copper and aluminium tape) are bolted together the surfaces should be thoroughly cleaned and protected by an oxide inhibitor. Once the connection has been made, the exterior should be protected by bitumastic paint or other means (such as Densotape) to protect against moisture ingress. When jointing copper and aluminium, the copper should first be tinned. For outdoor locations and in electricity substations, a bolted joint of this type is presently the preferred method described in the standards for connecting dissimilar metals. These connections must be a minimum distance above ground and cannot be buried.

For jointing certain type of conductor e.g. earth rods to cable or tape, proprietary clamps are available. These should have a high copper content - brass should not be used.

At one time, tin and rivet type joints were used. The copper tape was drilled, then tinned, and riveted together. However, the rivets sometimes work loose due to vibration etc. This method of jointing is clearly not suited to deal with the higher values of fault current encountered now.

5.6.2 Brazed connections

Brazing is widely applied to copper and copper alloys. This method has the advantage of providing a low resistance joint which will not corrode. It is presently the preferred method described by the standards for connecting copper tapes within a substation. However, it is essential that the brazing is effectively carried out. A good joint can be difficult to make on site particularly where large cross sectional areas are involved. Clean flat surfaces are essential as brazing materials are generally not free flowing like solder. There is thus the possibility of adequate connection only at points of contact, but with significant voids left unfilled. For this work, a good source of heat is essential, particularly for large connectors.

5.6.3 Exothermic joints

These are made via a graphite mould which is designed to fit the specific type of joint and conductor sizes. A powder mix of copper oxide and aluminium is ignited using a flint gun and the subsequent reaction forms a virtually pure copper joint around the conductors. The high temperature reaction takes place within the confines of the graphite mould. Each mould, if properly maintained, can be used for between 50 and 70 joints. Benefits claimed for this type of joint are that it:-

- Provides a corrosion resistant, low resistance, permanent joint.
- Uses relatively unskilled jointing techniques.
- Can operate at high temperatures, possibly enabling the conductor size to be decreased.

This type of joint is not presently permitted for connecting copper and aluminium within substations. Metals which can be connected include stainless steel, brass, copper, copper plated steel, galvanised steel, bronze and steel rail. There are some safety aspects involved with this type of joint, but the technique is rapidly developing to address these - for example by reducing the gas given off.

5.6.4 Welded connections

Copper can be joined by bronze welding or gas shielded arc welding.

Bronze welding is an effective, low cost jointing technique, used primarily to make on-site joints (for example in copper pipework). In this classical technique, brass is used as a filler metal to form a surface bond between the copper parts. The technique uses a higher temperature and a filler material which is more closely matched to copper, than in brazing.

Whilst bronze welding can be used to connect copper to ferrous metals, this is not normally carried out for earthing.

When heavier gauge copper components need to be jointed, then gas shielded arc welding is used. An electric arc provides the heat, whilst the area around the electrode and weld is shielded by a gas such as argon, helium or nitrogen. This reduces the amount of oxidation which takes place during the welding process. Nitrogen is widely used as the "inert gas" when welding copper. Specially developed filler materials are required and are known to perform well when welding copper.

Aluminium can be welded via inert gas tungsten arc (to BS 3019 part 1) or inert gas metal arc (to BS 3571 part 1). Cold pressure welding is also sometimes used for joints between aluminium.

5.7 Fault Current Carrying Capacity

The type of joint can influence the size of conductor used due to the different maximum permissible temperature for the various joints. For example, BS 7430 1991 Code of Practice for Earthing recommends a maximum permissible temperature of 250°C for bolted joints, 450°C for brazed joints and 700°C for welded joints. Hence if we were to consider a fault current of 25 kA and a duration of 1 second, the following conductor sizes would be required for each type of joint:

Connection	**Bolted**	**Brazed**	**Welded**
Maximum temp.	250°C	450°C	700°C
Conductor Size	152 mm^2	117 mm^2	101 mm^2

Clearly the method of jointing used may permit cost savings via use of smaller conductor sizes. Note however, that the relevant standard being used should be checked, as different values of the maximum permissible temperature may be quoted.

5.8 Testing and Inspection Facilities

Where access to connections may be required, then this is normally facilitated by means of an inspection housing. Sometimes it is prudent to leave one or two inspection housings in place above a horizontal electrode to enable vertical rods to be added later, if required.

It is now suggested that connections to substantial individual sections of the earthing system have a test link accessible via such test housing. The link would have a circular cross section around which a clip on impedance tester could be fitted. It is not generally considered safe practice to remove test links whilst the earthing system is connected to live equipment.

6 Performance of Earth Electrodes

The earthing system designer is normally faced with two tasks:-

- to achieve a required impedance value, and
- to ensure that touch and step potentials are satisfactory.

In the majority of cases there will be a need to reduce these values. Initially the designer should concentrate on achieving a certain impedance value. This value may have been decided from considerations of protection. The factors which influence the impedance are:-

- The physical dimensions and attributes of the earth electrode system.
- Soil conditions (composition, water content etc.).

The earthing system consists of conductive material above ground (bonding conductors etc.), metal electrodes within the soil and the surrounding soil itself. Each of these will contribute towards the overall impedance value. The earthing system components will be covered first and soil discussed at the end of the chapter. However, it is important to recognise that the characteristics of the soil strongly influence the earthing system performance. The most important characteristic of the soil is its resistivity, which is measured in Ohm-metres.

The previous chapter dealt with connections. Contact resistances at connections and material interfaces must clearly be kept to a practical minimum. In addition, the metal used for the above ground connections should have good electrical conductivity and the superior property of copper resulted in its use in the majority of installations. The system of metal electrodes will present an impedance to current flow consisting of three main parts. These are the resistance of the electrode material, the contact resistance between the electrode and the surrounding soil and finally a resistance dependent on the characteristics of the surrounding soil.

The impedance of the metal electrode material is usually relatively small, consisting of the linear impedance of the rod and/or horizontal conductors. The properties of the metal used and the cross sectional area will clearly influence this. In electrical terms, copper is superior to steel, so has traditionally been the preferred material.

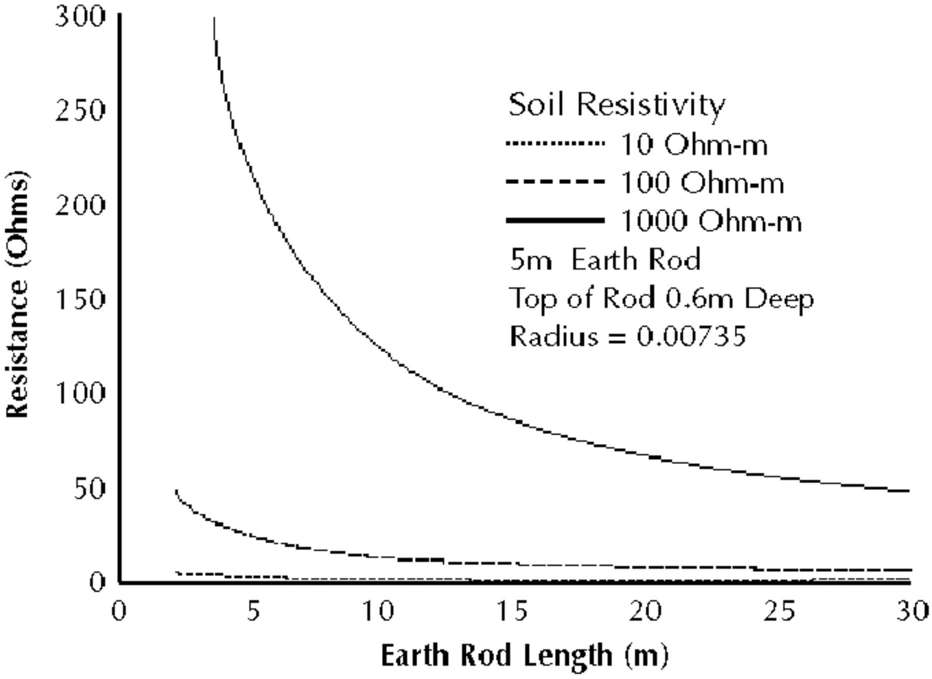
6.1 Effect of Electrode Shape, Size and Position

A dominant part of the impedance is that due to the physical orientation of the earth electrodes. The graphs in Figure 6-1 to Figure 6-6 illustrate the effect that changes in these dimensions can have on the impedance and enable the designer to assess the relative merit of each option. These are further discussed below:

6.1.1 Increasing the buried depth of a vertical rod in uniform soil.

Figure 6-1 shows the benefit that can be achieved in soils of different resistivity by increasing the buried length of the rod. It also shows that the improvement per unit length decreases as the rod length increases. However the graph illustrating the performance in uniform soil does not tell the complete story. The decrease in resistance obtained via a long rod may be particularly desirable in non uniform soil conditions. Figure 6-2 demonstrates the improvement in electrode resistance possible when increasing the length of a rod in a soil which consists of three layers. The top two layers are of relatively high resistivity down to a depth of six metres. The resistance of the rod is high until it extends beyond these layers, due to the high resistivity of the soil surrounding it.

Figure 6-1 Resistance v Rod Length



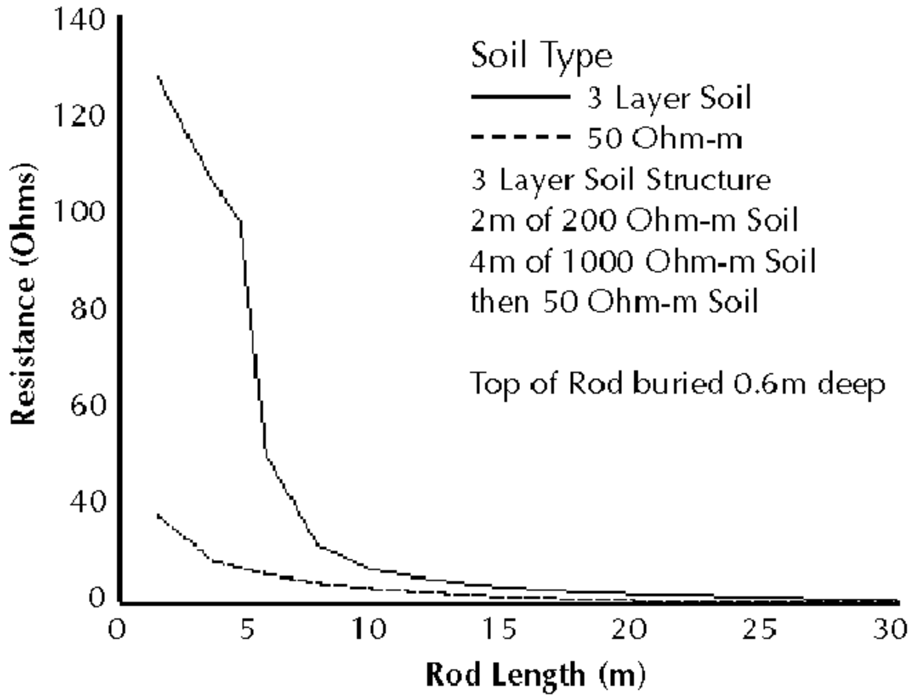
As the rod length increases the overall resistance falls progressively more quickly. This is due to deeper soil with better electrical properties being reached. In this case there is a clear improvement in performance with each additional metre of rod installed, far greater at this depth than for the rod in uniform soil. Once the rod reaches about 15 metres length, there is little difference in the resistance of a rod in this soil structure compared to one in uniform soil of 50 Ohm-metres resistivity. However, the per unit improvement with each additional metre installed starts to reduce rapidly as in the case of uniform soil.

In soil conditions as illustrated in Figure 6-2, it is important that the top section of the rod has a low longitudinal resistance as this section provides the connection to the beneficial electrode beneath. This could be achieved by using either a solid copper top section or a plated section with an increased cross section.

In some soil conditions, particularly where there is a limited area available, use of vertical rods may prove to be the most effective option, but it does depend on the soil structure.

Finally, it is important to note that vertical rods give a degree of stability to the impedance of an earthing system. Normally they should be of sufficient length that they are in or near the water table (if it exists at reasonable depth at the location) and below the freezing line. This means that the impedance should be less influenced by seasonal variations in water content or temperature.

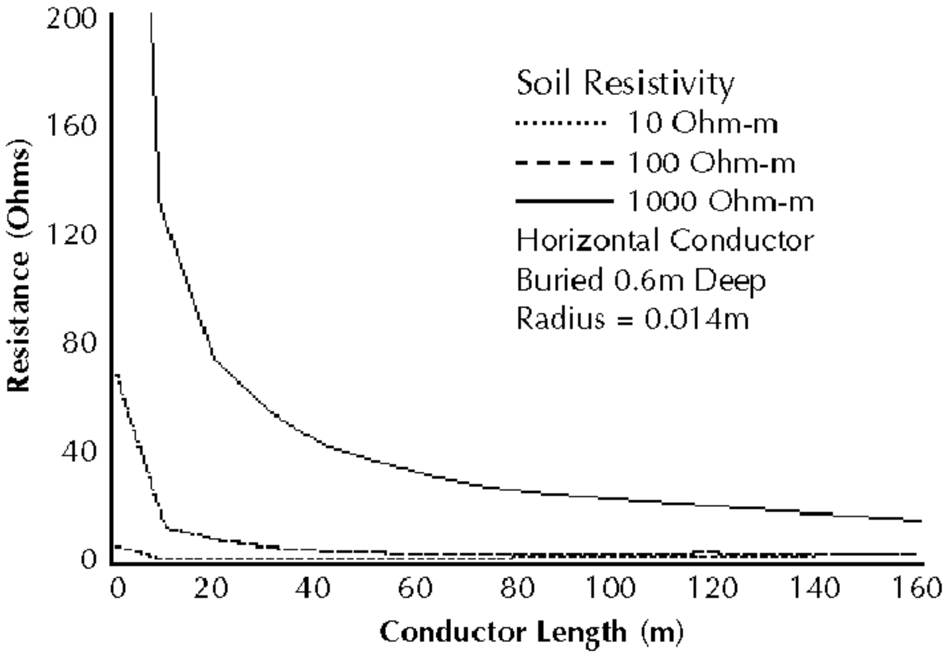
Figure 6-2 Resistance v Rod Length in Multilayer Soil



6.1.2 Increasing the length of a horizontal conductor.

Figure 6-3 shows the benefit that can be achieved in soils of different resistivity by increasing the length of a horizontally laid earth electrode.

Figure 6-3 Resistance v Horizontal Conductor Length

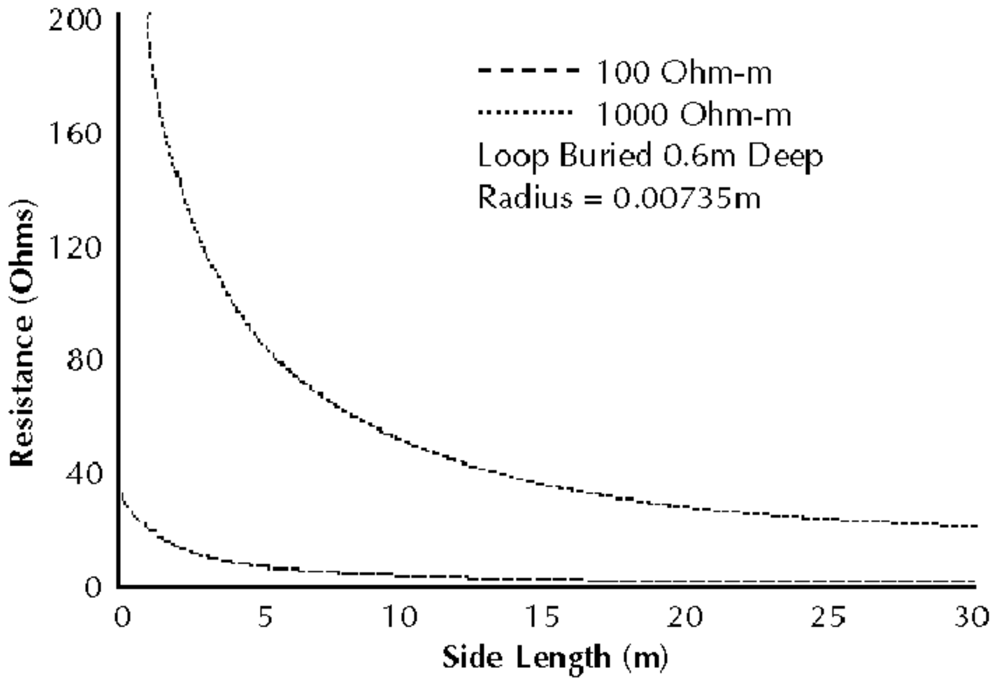


It should be noted that the calculations in this example do not take account of the linear impedance of the conductor, so the values are optimistic for long lengths. Again, the improvement per unit length decreases as the electrode length increases. Horizontally laid strip is generally considered to be a good option, particularly when it is possible to route this in several different directions. This further increases the reduction possible, although not by 50%. For high frequency applications, increasing the number of available routes in this way does significantly reduce the surge impedance.

6.1.3 Increasing the side length of a square earth grid/plate.

Figure 6-4 shows the benefit that can be achieved in soils of different resistivity by increasing the area encompassed by the earth electrode. Whilst it shows that the improvement per unit area decreases, the reduction in resistance is still significant. In fact this is, more often than not, the most effective way of reducing the resistance of the earthing electrode.

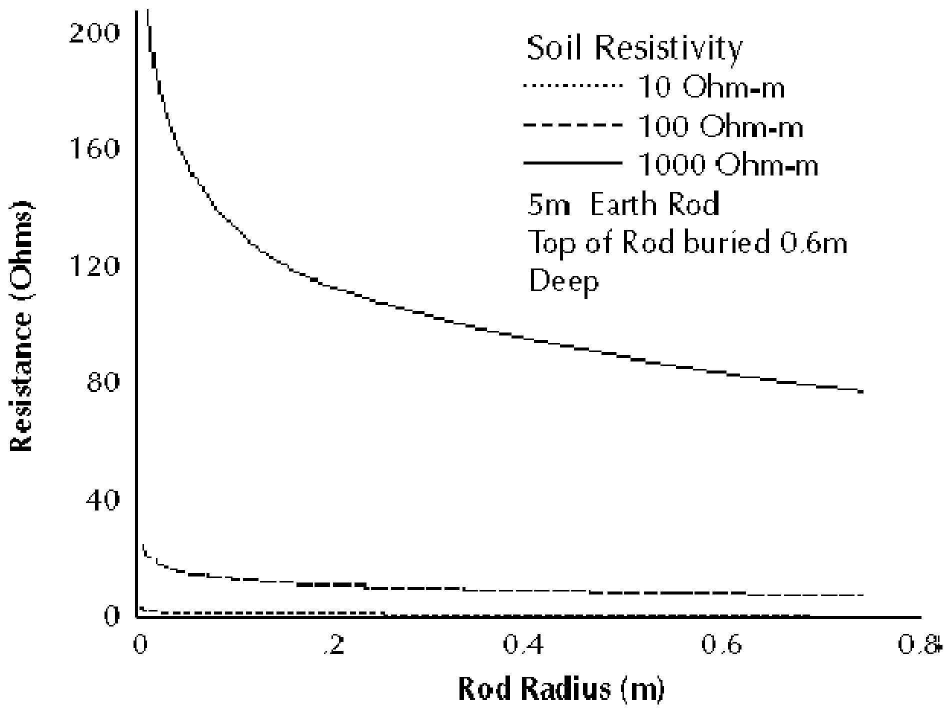
Figure 6-4 Resistance v Square Loop Side Length



6.1.4 Increasing the radius of an earth rod.

Figure 6-5 shows the benefit that can be achieved in soils of different resistivity by increasing the radius of the rod. There is a rapid reduction in the benefit per unit increase in diameter once this exceeds 0.05 metres, except in soil of high resistivity where the same effect is noticed at about 0.2 metres diameter. Normally there is little to be gained by extending the radius of earth electrodes beyond that necessary to deal with the mechanical and corrosion requirements. Tubes can be used instead of solid conductors to increase the external surface area, whilst moderating the increase in volume of the metal used. However, the increased installation cost may outweigh the value of the performance increase. In rocky conditions it may be advantageous to increase the effective diameter of the electrode by surrounding it with material which has a lower resistivity than the surrounding rock, as described in chapter 14.

Figure 6-5 Resistance v Rod Radius



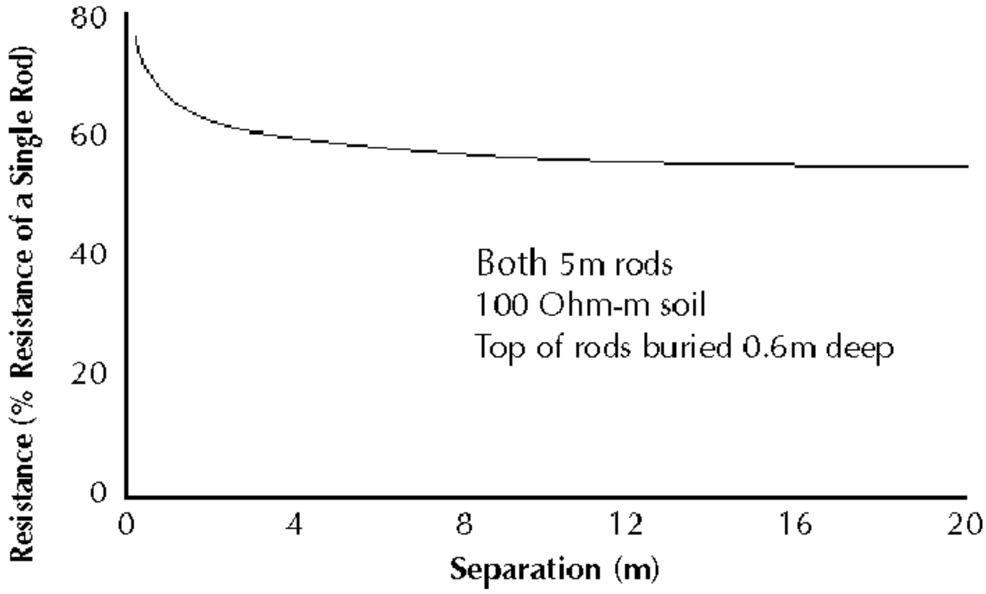
6.1.5 Buried depth

This only provides a marginal reduction in impedance, but at a relatively high cost, so is not normally considered. It should however be remembered that the greater the burial depth, the smaller the voltage gradients on the surface of the soil. Within a substation a high voltage is required above the electrode, to minimise touch voltages. However, if an earth electrode extends into a field, then a low surface voltage is required to reduce step potentials. In some cases it is advantageous to increase the depth of electrodes to reduce the risk of electrocution to horses, cattle and other animals. They are more susceptible to step voltages than humans because of the distance between their front and rear legs. For rods, this can be achieved by installing a plastic pipe around the top metre or two of each rod.

6.1.6 Proximity effect.

If two earth electrodes are installed close together, then their zones of influence will overlap and the full benefit possible will not be achieved. In fact, if two rods or horizontal electrodes are close together, the combined earth impedance of the two can be virtually the same as for one, meaning the second is redundant. Spacing, position and soil characteristics are the dominant factors in this. Figure 6-6 shows how the overall resistance of two five metre vertical rods changes as the distance between them is increased. From this it can be seen that the rods should be more than 4m apart in uniform soil. Calculations of this type are the basis for the established practice of installing electrodes at least the same distance apart as their length.

Figure 6-6 Combined Resistance of Two Vertical Rods as Separation Between them is Increased



6.2 Complex Electrode Arrangements

For more complex arrangements of electrodes, more detailed analysis to take all of the above factors into account, is required.

The figures (except Figure 6-2) illustrate performance in uniform soil conditions. Unfortunately, in practice, it is unusual to find uniform soil conditions. A multi-layer soil is more usual. For example, there may be a surface layer of loam or peat above sand, gravel or clay. Further underneath the material may change to rock. This may be represented as a three layer soil structure, the resistivity of the layers increasing with depth.

At another site there may be silt or sand/gravel and then a water table a few metres below the surface. This may form a two layer structure, with the resistivity beneath the water table being significantly lower than that of the surface layer. The actual soil structure and the electrical properties of each layer will affect the electrode resistance value and it may be important to assess this at an early stage.

The values shown in the graphs were obtained using computer software which takes into account soil structure and electrode geometry. In addition to calculating the value for straightforward electrodes, this type of software can deal with complex arrangements such as those that will be described in chapter 7. However, some relatively straightforward formulae are available to enable a reasonably accurate prediction of the resistance of electrodes in soil which is of uniform resistivity. It should be noted that different formulae are used by different standards and whilst these often provide similar values, this does mean that particular care is needed to ensure that the correct formulae and approach is used, depending on the design specification and the standard on which this is based.

In the case of a rod, the formula (taken from BS 7430 and EA S34) is:

$$R = \frac{\rho}{2\pi\ell}\left(\ln\left(\frac{8\ell}{d}\right) - 1\right)$$

where : R = resistance of rod (Ω)
ρ = soil resistivity (Ωm)
l = length of rod (m)
d = diameter of rod (m)

For a short, buried horizontal conductor, the formula (taken from BS 7430) is:

$$R = \frac{\rho}{2\pi\ell}\left[\ln\left(\frac{4\ell^2}{dh}\right) - Q\right]$$

where : R = resistance of horizontal buried conductor (Ω)
l = length of conductor (m)
d = diameter of conductor (m)
h = height below ground (m)
Q = 1.3 for circular conductors
Q = 1.0 for strip conductors

In DIN VDE 0141 and CLC TC 112, the above formula has been simplified to:

$$R = \frac{\rho}{\pi\ell}\ln\left(\frac{2\ell}{d}\right)$$

6.3 Contact Resistance

In the formulae and computer simulations it is assumed that the earth electrodes are in perfect contact with the surrounding soil. It is to reduce this contact resistance to a minimum value that it is important to ensure that the backfill material is of the appropriate type, as described in section 14. Clearly, large, dry stones surrounding the electrode would have a detrimental effect on its performance. In fact, in a new installation, the most significant resistance is likely to be at the interface between electrodes and soil. This arises mainly because the soil has not yet consolidated.

6.4 Soil Resistivity

The most important remaining factor influencing the impedance of the earthing system is the impedance of the medium in which the earth electrodes are situated, i.e. the soil.

Because soil resistivity is such an important factor governing the performance of earth electrodes, it needs to be discussed in some detail. Soil resistivity is expressed in Ohm-metres. This unit is the resistance between the two opposite faces of a one metre cube of uniform soil. The value obtained is thus in Ohm-metre^2 per metre, which is traditionally shortened to Ohm-metres. Some typical resistivity values are given in Table 6-1

.

Table 6-1 Typical values of resistivity for different soils

Type	Resistivity (Ohm-metre)
Sea water	0.1 - 1
Garden soil/alluvial clay	5 - 50
London clay	5 - 100
Clay, sand and gravel	40 - 250
Porous chalk	30 - 100
Quartzite/crystalline limestone	300+
Rock	1,000 - 10,000
Gneiss/igneous rock	2,000+
Dry concrete	2,000 - 10,000
Wet concrete	30 - 100
Ice	10,000 - 100,000

The two main factors which influence the soil resistivity value are the porosity of the material and the water content. Porosity is a term which describes the size and number of voids within the material, which is related to its particle size and the pore diameter. It varies between 80/90% in the silt of lakes, through 30/40% in sands and unconsolidated clay to a few percent in consolidated limestone.

As mentioned previously, it is most unusual to find soil which can be described as uniform for earthing purposes. We are interested in soil to a significant depth as the earth fault currents flow deeply into the ground. There may be thin layer of soil on the surface, with layers of rock underneath. Each successive layer of rock would have fewer cracks, be more solid and would be expected to have a higher resistivity.

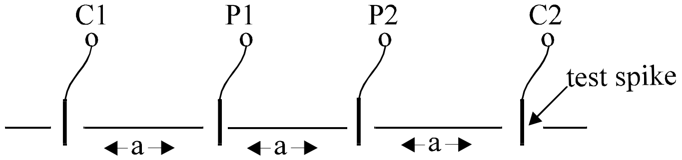
If an electrode was installed at the surface, then the distance, thickness and actual resistivity of each of the layers would be important factors influencing its eventual resistance value.

Temperature and water content have an important influence on the soil resistivity and hence the performance of the earthing system. An increase in water content causes a steep reduction in resistivity until the 20% level is reached when the effect begins to level out. Dissolved minerals and salts in the water may help further to reduce the resistivity, particularly where these are naturally occurring and do not become diluted over time. The water content will vary seasonally and is likely to cause variations in the impedance of the earthing system. Whilst there is data on the effect this has on individual rods, we are not yet aware of the effect on larger substations which encompass a larger area. The very high resistivity of ice (table 6.1) compared to water, shows why it is necessary to install the electrodes beneath the freezing line. This is about 0.6 metres depth in the UK, but may be deeper in exposed, mountainous locations.

6.5 Measurement of Soil Resistivity

It is important that the resistivity is assessed as accurately as possible, since the value of the resistance of the electrode is directly proportional to the soil resistivity. If the incorrect value of soil resistivity is used at the design stage, the measured impedance of the earthing system may prove to be significantly different to that planned. This could, in turn, have serious financial consequences.

The test is traditionally carried out using a four-terminal earth tester. Four spikes are driven into the ground as shown in the diagram, spaced a distance of “a” metres apart. The depth to which each spike is driven should not exceed “a” divided by 20 and is not normally greater than 0.3 metres. The outer two spikes should be connected to the current terminals C1 and C2 of the instrument, the inner spikes to the potential terminals P1 and P2.



It is important to ensure that the test spikes are not inserted in line with buried metal pipes or cables, as these will introduce measurement errors.

If "R" is the instrument resistance reading in Ohms, for a separation "a" metres, then the apparent resistivity is given by the following formula:

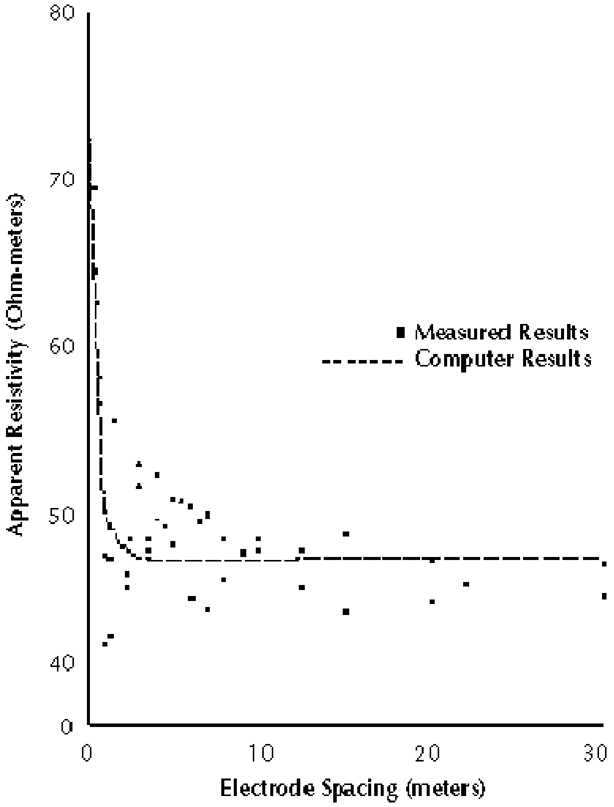
Resistivity = 2 x ã x R x a Ohm-metres.

The term "apparent resistivity" is used since the above formula assumes that the soil is uniform to a depth "a" metres below the centre point of the measurement traverse. We are able to obtain information about the actual soil layering by taking a series of readings, with "a" being increased by 1 m steps up to 6 m separation, then by 6 m steps up to typically 30 m separation. For very large area sites, especially where there is rock beneath, readings may be advisable at 50 m, 80 m and even 100 m spike separation. The test instrument used should be sufficiently accurate to measure quite small resistance values at these large spacings - in the order of 0.01Ω to 0.002Ω. The measurements should preferably be made in an area of reasonably undisturbed soil. Typically the lower values of "a" will give high values of soil resistivity because they are heavily influenced by the surface soil which normally drains or has its water content reduced by sun and/or wind. As the distance "a" increases, the apparent resistivity would normally decrease, unless there is underlying rock.

A curve of resistivity against separation should be drawn during the measurement exercise. This will provide information on the general structure of the soil in the locality, identify rogue readings and help in deciding how many measurements are required. If there are large fluctuations in measured values, then it is likely that the soil conditions are variable, the ground has been made up, or there are buried pipes in the area. In all cases, measurements should be taken on a number of traverses across the site. Some of these traverses should be at right angles to one another to enable any interference from nearby electricity cables to be identified.

Some examples of soil resistivity curves are shown in Figure 6-7 and Figure 6-8. In Figure 6-7, a number of measurements have been taken at the site and there are variations between them. The apparent resistivity value is higher at short spacings and then falls into a reasonably narrow, uniform band. Computer analysis produces a two layer model where the surface layer is 0.2 m thick and has a resistivity of 126 Ohm-metres. The underlying material has a value (biased towards the higher readings) of 47 Ohm-metres.

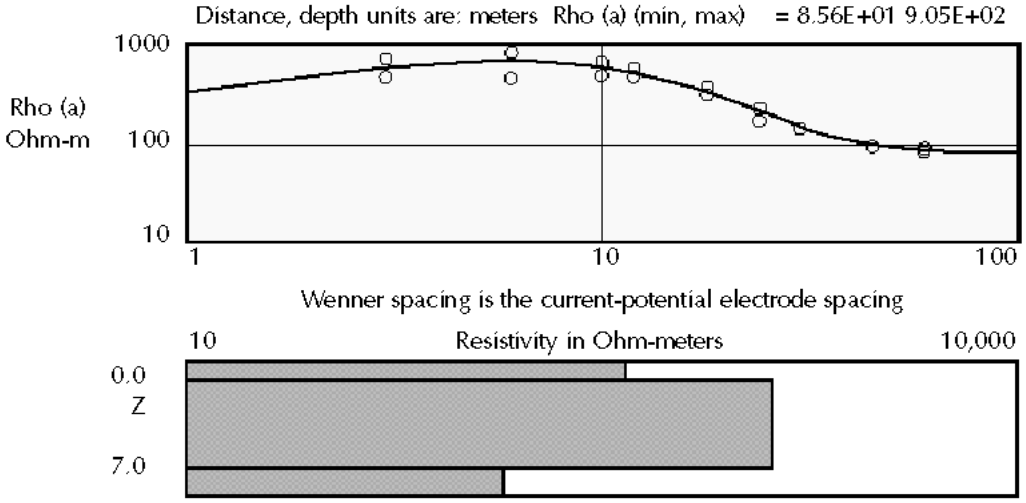
Figure 6-7 Apparent soil resistivity plotted against test spike separation - relatively uniform soil



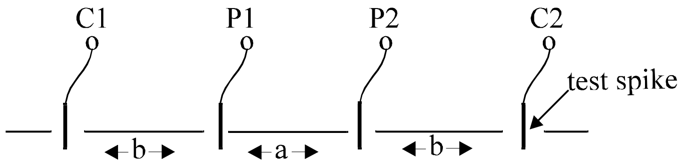
For practical purposes one would assume a uniform soil of 47 Ohm-metres, since the value of the surface layer will change throughout the year. In the second example (Figure 6-8), the readings are much more difficult to interpret and analysis via computer software produces a three layer model. The middle layer has a low resistivity, so vertical rods or horizontal electrodes installed at greater depth than normal would be used. The actual readings are shown to be either side of an average computer model and typifies the variation expected on different traverses across the same site. The average three layer model would normally be used for earthing calculations.

Test spikes should not normally be installed within 5 metres or so of an electricity substation, unless suitable precautions are taken. The buried cables there will influence the readings and should an earth fault occur whilst testing is taking place, the potential gradient near the substation may be sufficient to introduce a risk of electric shock to those carrying out the test.

Figure 6-8 Apparent soil resistivity plotted against test spike separation - three layer soil



The method of soil resistivity measurement described above is the Wenner method, using spikes which are equidistantly spaced. There are other methods available for use in more difficult locations. These include the Schlumberger technique where the distance between the instrument and each current spike and each voltage spike is the same, but that between the voltage and current spikes is different. This is illustrated below:



Software is also available which can enable the soil resistivity to be calculated when the spacing along the traverse is arbitrary. This may enable soil resistivity readings to be taken when there are physical obstructions (roads, pavements, concreted areas etc.) preventing use of the Wenner method. Finally, another method of determining the soil resistivity involves measuring the resistance obtained at different depths as an earth electrode is driven into the ground (the method of taking the measurement, but not how to interpret the readings is covered in chapter 13). The measurements are repeated at a number of locations around the substation and the average values used to determine the soil resistivity and layering. Because of localised effects, this method is not generally as accurate as the Wenner and other techniques, but may be the only one method available is some built up areas.

7 Design of Earth Electrode Systems

7.1 Introduction

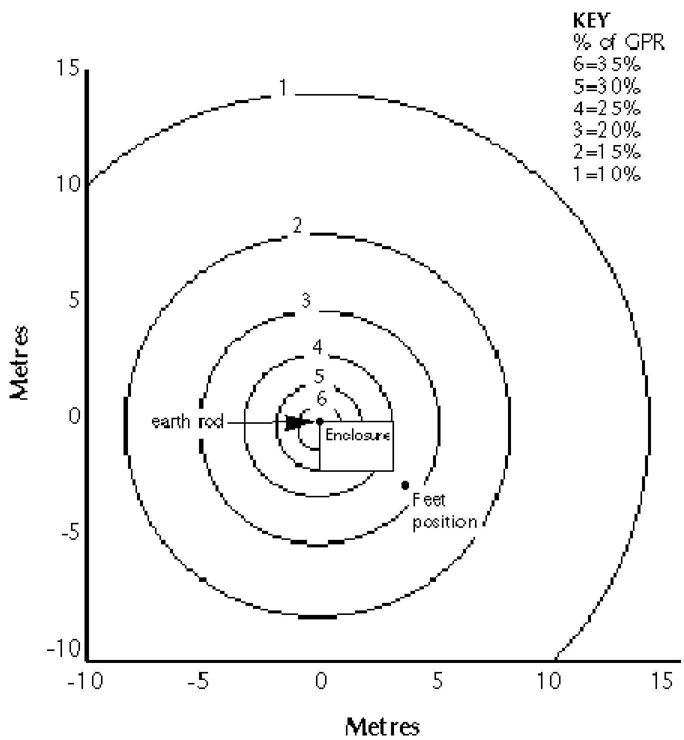
Chapter 6 covered ways in which the designer could seek to reduce the impedance of the earthing system, since in general this is likely to improve its performance. This chapter will concentrate on the more detailed design necessary to ensure that the step and touch criteria, on which the newer standards are based, are satisfied. Note that the fault currents used are higher than would normally be anticipated in a domestic or commercial installation, but the electrode performance would be similar.

To illustrate the different design concept required, imagine that the designer has been asked to ensure that the earth electrode has an impedance of 5.0 Ohms, in order that the protective equipment will operate. If we also assume that the soil in the location is of uniform, 50 Ohm-metre resistivity, and the mechanical properties of the soil are suitable, then the most economic method of achieving this value may be to use a single vertical rod.

From computer simulation, use of the formula in paragraph 6.1 or use of the graph in Figure 6-1, it can be calculated that a rod of approximately 12.5 m length will provide this value. Assume that the equipment to be protected by this earthing system is housed within a metal enclosure of 3 m length and 2 m width. If the fault current anticipated is 200 A, then clearly the potential on the electrode and enclosure will rise to 1,000 V during the time that it takes the protection to operate. There will be a voltage on the surface of the soil above the electrode, which will reduce with increasing distance from it.

Assuming the earth rod has been installed at one corner of the enclosure, then the voltage profiles on the surface of the soil surrounding it will be as shown in Figure 7-1 (note that Figure 2-1 is based on the same example and shows the situation in three dimensions).

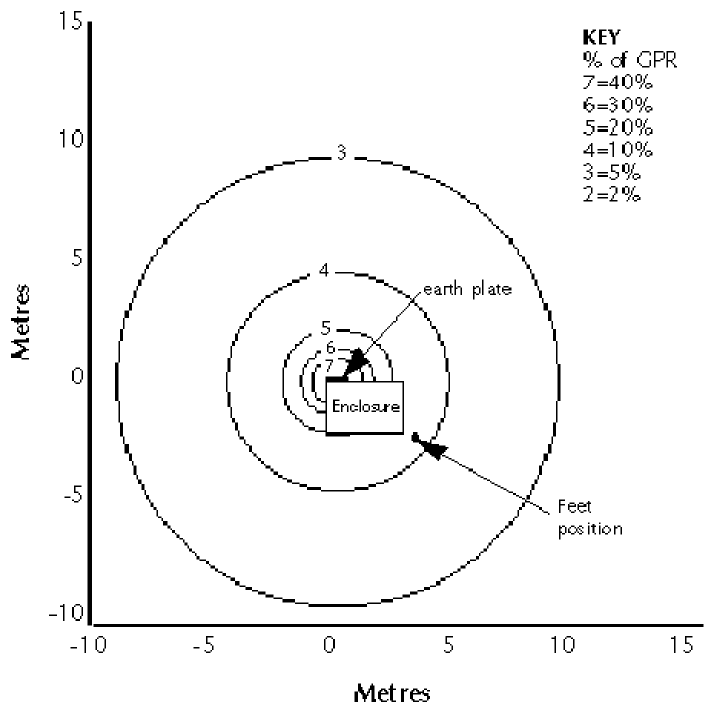
Figure 7-1 Potential on surface of soil around enclosure with single rod earthing



These are formed because the fault current is assumed to flow uniformly into the surrounding soil and the potential contours result from marking the position of equal voltages along each current path. (The equipotential lines in all the figures have been shown as percentages of the actual GPR (voltage rise)). A person touching the opposite corner of the enclosure, with their feet one metre away (i.e. at the position shown in Figure 7-1), would experience a potential difference between hands and feet of 784 V.

As mentioned in chapter 2, the permitted touch voltage depends on the relevant standard and the time taken for the protection system to disconnect the faulty circuit. Clearly a single rod does not provide a well designed earthing system, but is precisely the type which would traditionally have been used in the past. Another traditional method was to use a plate and for comparison purposes, Figure 7-2 illustrates the voltage profiles which would result if a buried plate, 900 mm square, at 0.6 metres depth was used instead of the vertical rod. This would have an impedance of 17 Ohm. The equipotential lines are elliptically shaped near the electrode and become circular as the distance from it increases. For a 200 A current flow, the touch potential at the corner of the enclosure is now 3,060 V. This higher figure is due to the higher impedance of the plate compared to the rod.

Figure 7-2 Potential on surface of soil around enclosure with single plate earthing

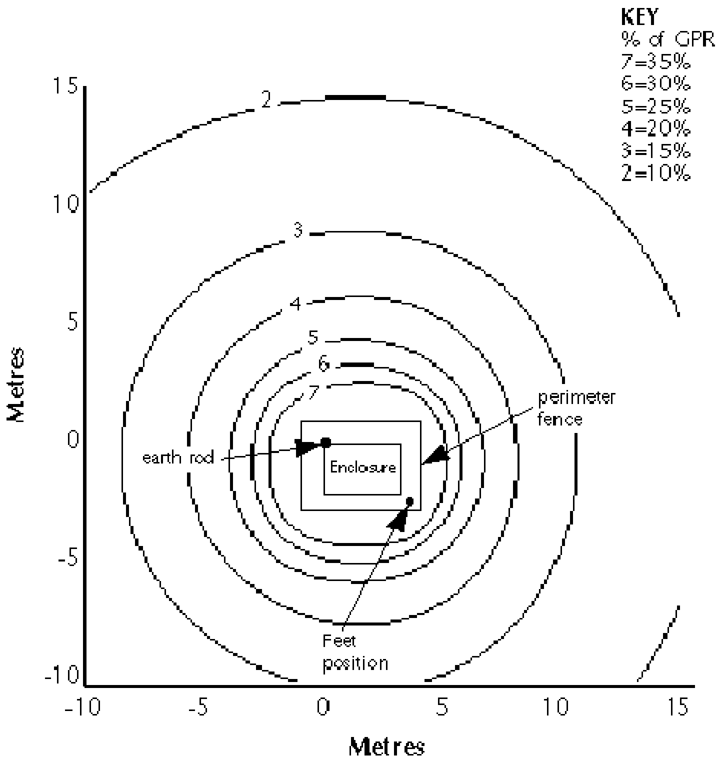


7.2 Small Area Electrode Systems

If the above electrode arrangements are used as the main earth for a domestic property, they may suffice. The anticipated fault current would be lower than 200 A, so the voltage rise would be significantly reduced and so would the touch voltage. In addition, the wall of the house would normally be non-conducting and the connection to the earth electrode insulated. It is thus unlikely that a person could experience a touch voltage of the type illustrated. It should be noted that the fault clearance time could be quite long, so the permitted touch voltage would be low

Within an industrial or commercial premise, the anticipated fault current will be higher and the touch voltage limit may be exceeded for arrangements such as those in Figure 7-1 and Figure 7-2. In a substation owned by an electricity company the fault current would almost certainly exceed 200 A - sometimes by a factor of ten to one hundred. Even if the protection operates in an electricity substation in less than 0.2 seconds, there may still be touch voltage (and other) problems if the arrangement in Figure 7-1 or Figure 7-2 were used.

Figure 7-3 Potential on surface of soil around enclosure with single rod and perimeter (potential grading) electrode



To improve matters a perimeter (or potential grading) electrode can be installed in the soil, situated approximately one metre away from the enclosure, buried at 0.5 metres. This conductor is sometimes called a guard ring. The voltage profile around the enclosure for the same fault current of 200 A is shown in Figure 7-3. In this case the single rod and perimeter conductor reduce the impedance to 3.17 Ohm. The touch voltage has now been reduced to 182 V. If the same arrangement is applied to the plate example, the impedance is reduced to 4.9 Ohm and the touch voltage becomes 307 V. Clearly the perimeter electrode has improved the safety of the installation.

This is the basic way in which earthing systems should be designed to comply with the new standards. The perimeter electrode is limiting the touch potential which can be experienced by smoothing the potential gradient in the vicinity of the enclosure. In addition, it reduces the electrode impedance and, in the above examples, the potential rise. Either of these arrangements may be acceptable within an industrial or commercial premise. In this case the perimeter conductor of the electrode system also provides the potential grading required to reduce the touch voltage. It is possible to have separate electrodes to achieve this, as discussed in section 7.3 below.

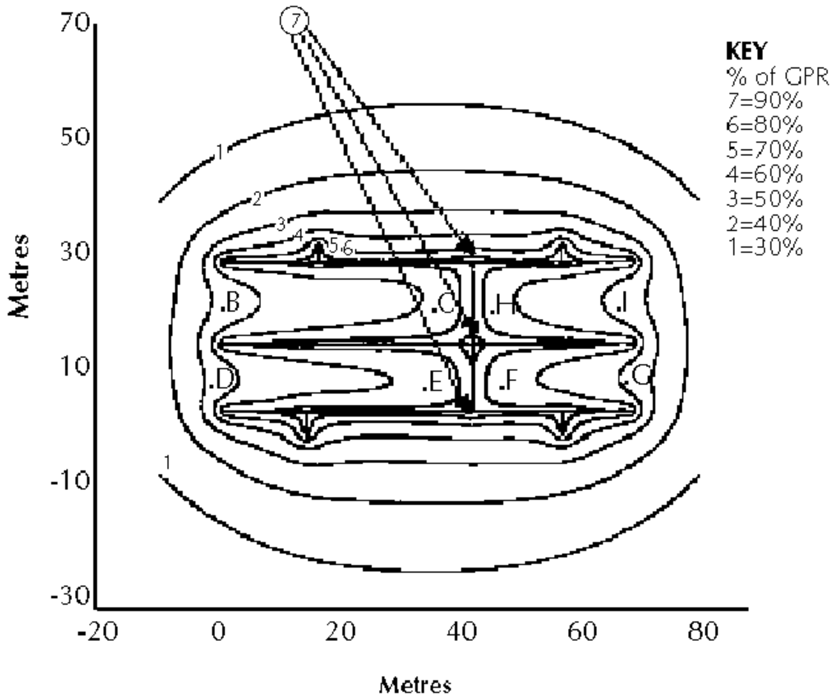
For small electricity substations, a better design is to use a loop of horizontal conductor as the perimeter electrode and position vertical rods at each of the four corners. These would be shorter than the previous example, typically 3 metres in length. This would provide a more efficient earthing system in 50 Ohm-metre uniform soil and provide an impedance of 3.7 Ohm. The touch voltage would be 175 V.

7.3 Medium Area Electrode Systems

Medium area systems would typically be found at an electricity substation. It should be noted that there are other components of the earthing system associated with substations which also need to be considered. For example, it is usual for steel reinforcing bars within building foundations or piles, the cable sheaths of underground cables and the earth wire of overhead lines (the type supported on steel towers), to be connected to the earthing system. Individual consideration of these is beyond the scope of this book, which will concentrate just on the earth electrode installed at the substation.

In older designs, it is not uncommon to find electrode arrangements such as that in Figure 7-4. As previously, the main objective with this design was to obtain a specific earth impedance value. The design is based on vertical earth rods and arose from the knowledge that placing earth rods approximately the same distance apart as their length, made effective use of the land area. Horizontal electrodes interconnect these rods and further decrease the impedance value. This concept was the start of the modern mesh designs, but at this early stage, it was not recognised that the rods within the site have little effect. Because of the radial type design, the performance of the system could be seriously compromised if corrosion occurs at any one of a number of positions.

Figure 7-4 Potential on surface of soil around and within a substation with older design incorporating rods and horizontal electrodes



Finally, there are areas, indicated on the figure, where touch voltages could be excessive. These are on the lines between B-C, D-E, F-G and H-I. If exposed metalwork, connected to the earthing system, were present here, touch potentials might exceed the allowable values.

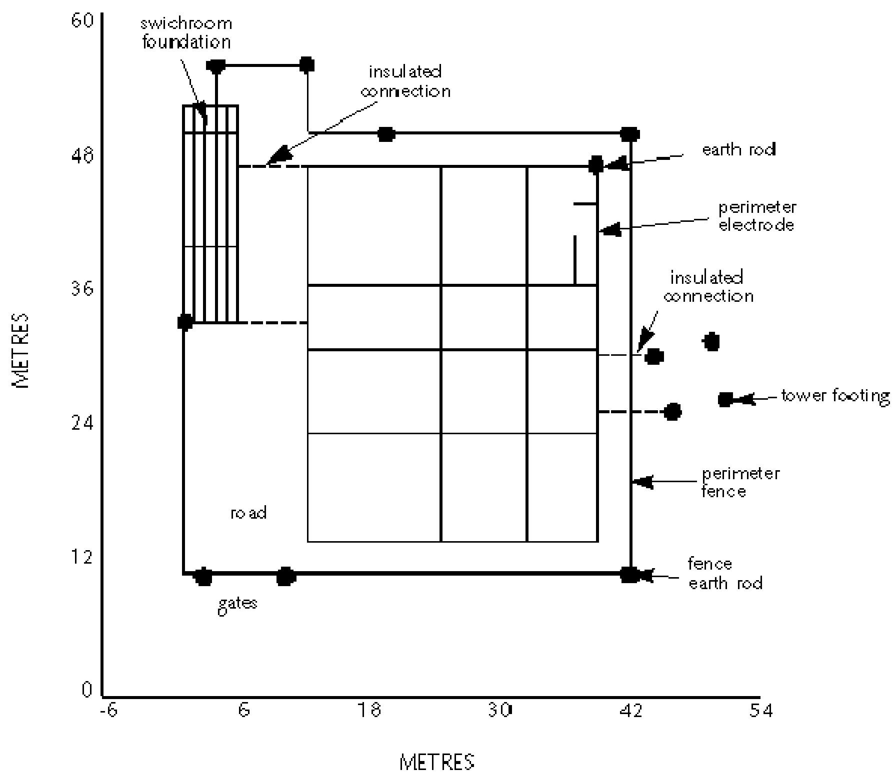
The voltage profiles on the surface of the soil are shown in the figure to illustrate this, again as a percentage of the GPR.

A modern design is shown in Figure 7-5. It is based on the following principles:

- An effective perimeter conductor loop.
- Good interconnection between electrodes and important items of plant.
- Economic use of good quality material.
- Potential grading across the site.

The perimeter electrode is positioned either 2 m inside the fence or about 1m outside. Vertical earth rods are connected to this. The perimeter electrode distributes or collects most current at power frequency and is a key component. It may be of larger cross sectional area than that used underground within the substation. It will often be of copper tape to take advantage of its greater surface area compared to stranded conductor of a similar cross sectional area. The vertical rods are connected to this electrode to improve its performance and allow a degree of security against seasonal variations, such as changes in the level of the water table. Where theft of third party damage is a possibility, then the perimeter conductor may be covered in concrete at regular intervals. A number of horizontal cross members are installed across the site area, often ten metres or so apart. The actual separation will depend on soil conditions, the fault current and predicted rise of earth potential.

Figure 7-5 Modern substation mesh type earthing arrangement



The cross connections perform two functions. The first is to allow all exposed metalwork to be connected together and prevent potential differences between them (i.e. bonding). The second is to provide potential grading on the surface within the site area, to reduce step and touch voltages. The cross members are normally connected at each intersection and at each end to the perimeter electrode. If the perimeter conductor is situated 2m within the fence, but there is a reason to believe that the touch voltage on the fence could be excessive, then a potential grading conductor could be installed 1m outside the fence. This would be connected to the fence, but not to the main earth grid. Because it would not be required to carry significant current, it can have a small cross sectional area. This option is costly, mainly due to the additional excavation involved and it is more usual to combine the role of perimeter conductor and fence potential grading conductor and extend the electrode outside the fence.

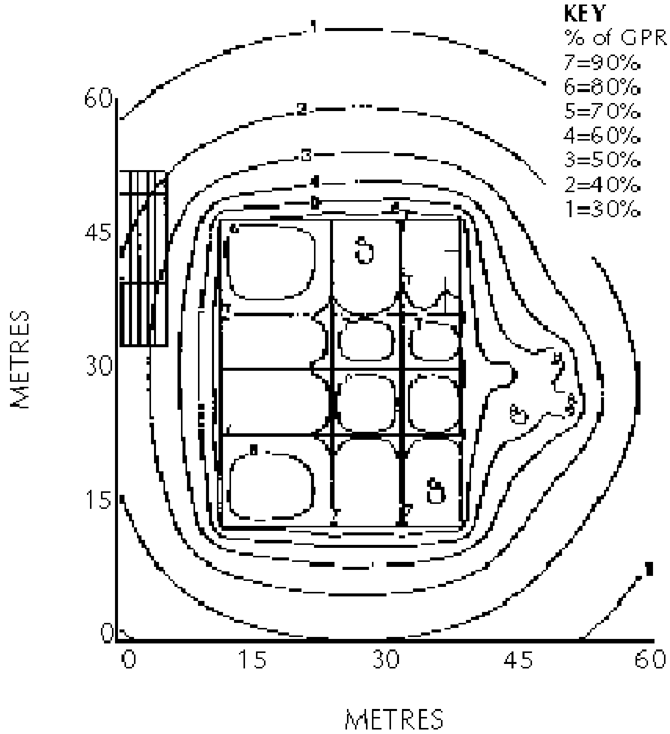
All electrodes are interconnected, ensuring a high degree of security. Mechanical failure or corrosion of one or more connectors should not seriously effect the performance of the earthing system. This is an important feature since the electrode system is unseen, possibly in a corrosive environment and must perform adequately over a long period of time.

This newer type of design uses more copper, but uses it effectively. Care needs to be taken in the choice of material used, since it is possible to experience chemical or electro-chemical corrosion. Use of dissimilar metals can increase the risk of this, so copper is often used throughout.

The fence in this example is earthed via rods at each corner and near the overhead line crossing. The fence earths are independent of the earth grid. However, if the earth grid perimeter electrode is taken outside the fence, it is usual to bond the fence to the main earthing system.

The above features of the design will ensure that touch and step criteria are met. The voltage contours on the surface of the soil are shown in Figure 7-6. An inspection of these shows that the potential on the surface area above the main electrode system is between 70 and 90% of the GPR. This means that the touch voltages will be within approximately 30 and 10% of the GPR. There may still be a need to reduce the impedance of the electrode system. For example, additional precautions are presently required if the GPR is above 430 V (low reliability circuits) or 650 V (high reliability circuits). It is sometimes advantageous to extend the earthing system so that the rise of earth potential is reduced sufficiently that these limits are not exceeded. The two main choices are to use longer vertical rods on the perimeter conductor or to extend the earthing system outwards to enclose a larger area. The type of improvement possible by these methods can be assessed by reference to chapter 6.

Figure 7-6 Potential on surface of soil above and around a modern 'mesh' type earthing arrangement



7.4 Sites Requiring More Specific Attention

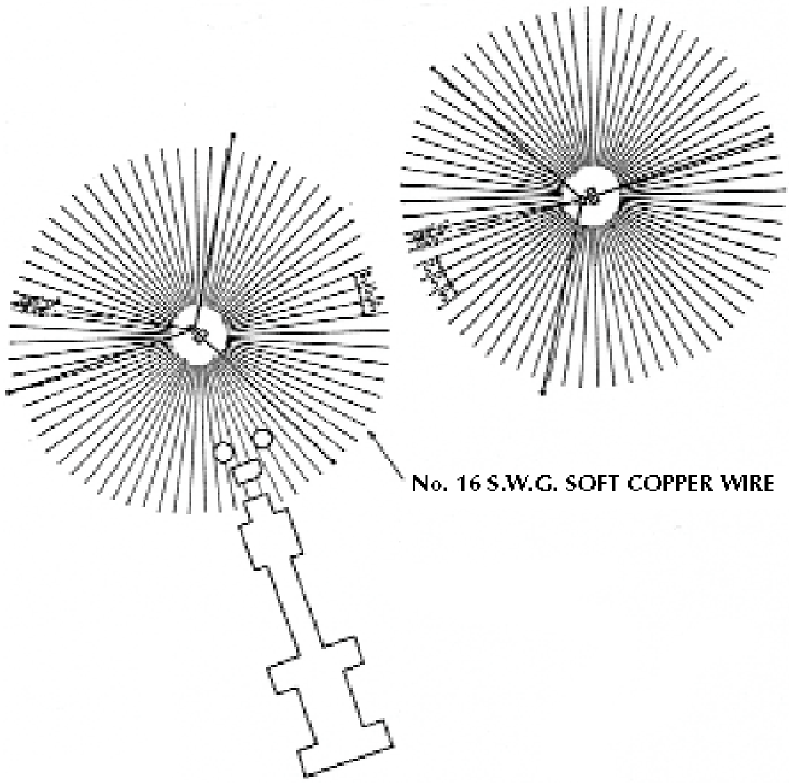
The previous designs have been concerned with power frequency (50 Hz) performance and the most common electrode arrangements. However, it is recognised that there are many circumstances when further consideration is necessary. Some of these are described in the following section.

7.4.1 Communication facilities

Because of the high frequencies involved, a different earthing grid design is required. This attempts to maximise the amount of conductor in the immediate vicinity of the structure. This is achieved by a design similar to that shown in Figure 7-7, which was used at a medium wave radio station. Long lengths of thin copper wire have been installed radially out from the communication mast. They were installed to a shallow depth using a plough.

At high frequency radio stations a local earth is required, but is not generally as large as that required for medium wave.

Figure 7-7 Earthing system for a medium-wave radio station



7.4.2 Surge diverters.

These devices are used to protect the electricity system within a building (typically being situated where the electricity supply enters the building), to protect an individual item of equipment in a building and to protect equipment within electricity substations. When the device operates, it diverts some current to ground to reduce the voltage "spike" which could otherwise damage the equipment which it is required to protect. The current flowing through the surge diverter is not sinusoidal and when transformed into Fourier components, it has a waveform which is made up of high frequency components.

The connection from the surge diverter to earth and the electrode system itself have an impedance which is predominantly resistive but also has an inductive component. This inductance is especially important at higher frequencies where the inductive component of the subsequent voltage rise may be considerably higher than the resistive component. This effect can seriously reduce the efficiency of the surge diverter. To counteract this, special earthing arrangements are necessary. For example, the conductor which connects the earth of the device to the earthing system must be as short and straight as possible. In most cases a separate earth electrode is installed immediately adjacent to the device and connected direct to the surge diverter. This is in addition to the normal connection to the main earthing system.

7.4.3 Reactors and AC to DC converters

Normally there are high electro-magnetic fields associated with such devices. These can, in turn, induce high currents in any nearby metal structures or earth conductors. Additional precautions are required to prevent induced circulating currents. One method is to ensure that such equipment is only earthed at one point. Another solution is to use non-metallic fencing or supports in close proximity to these devices. Where thyristors are used, again high frequency harmonic currents may be present and the earth electrode may need to be positioned close to their source to prevent significant potential differences arising.

7.4.4 Co-generation plants

Special arrangements are normally required, particularly to enable generation to continue when the main electricity supply is not available. The method of earthing must be compatible with that of the electricity network, which may be earthed at a single point or be multiply earthed.

In larger installations supplied via high voltage networks, a separate earthing system will normally be required. When the main supply fails, the generator will be disconnected from it and the separate earthing system switched in. Generation will then be possible in "islanded" mode, with the installation being earthed as required by the regulations. In some situations, for example near a large substation, it may be possible to share the main electricity earthing system.

When connected on the low voltage network, it is sometimes possible to use the electricity system earth in parallel with that of the generator.

In most cases an earthing system will be required and the guidance given in this book would be applicable in designing the electrode arrangement. However, the need to switch the earth connection and precautions which are sometimes necessary when several generators operate in parallel, make this a specialist topic. For example a special earthing transformer may be used. There is a considerable amount of advice available and some of the main sources are listed in chapter 16.

In large generating stations, use has traditionally been made of the deep pile foundations which are required to support the plant. These can form effective electrodes, but continuity strips are required across any joints in the pile, to ensure a low electrical resistance. These sites typically occupy a large area and it is necessary to consider the voltage drops which occur across the site and take steps to reduce these.

7.4.5 Capacitor banks/capacitor voltage transformers

Switching transients from the high voltage system will see these devices as virtually a short circuit to earth and will be dispersed through them with little attenuation. The bonding connection and the in-ground electrodes need to be designed to cater for this. Normally an independent high frequency electrode (rod) is installed immediately adjacent to the equipment. A connection is also made to the main earth grid.

7.4.6 Gas insulated switchgear (GIS)

This type of equipment is very compact and occupies a small area of land, typically only 10% to 15% of that required by conventional outdoor air insulated equipment. The reduced area available usually places an immediate limit on the impedance value which can be achieved practically. However, there are additional factors associated with GIS which considerably complicate the design task. These are as follows:

- High fault current. Because of the expense of GIS equipment, it is normally used at higher voltages. The earth fault current at these voltages is high - typically 20kA or more, and this places an onerous demand on the earthing system.
- Residual AC current. GIS equipment uses earthed metal screens around individual phase conductors. Current is continuously induced in these screens and a residual AC current

is likely to flow continuously via the earthing system. There is presently concern that these AC currents may cause accelerated corrosion, particularly in steel electrodes.

- High frequency currents. The nature of the equipment means that switching transients can occur whilst electrical currents are being interrupted. These transients include components at very high frequencies. As has been previously mentioned, the electrode system to deal with high frequency currents is different to that for 50 Hz operation. The most often quoted solution is to increase the density of the earth electrodes in the immediate vicinity. However this needs to be accompanied by specific screen terminating arrangements and secondary control wiring needs to be routed to minimise inductive interference. The design seeks to ensure that high frequencies are confined to the inside of screened enclosures, but the presence of interfaces (such as at air terminations, insulated CT flanges and transformer bushings) allow some opportunity for these to escape.

It is also important to ensure that the earthing design does not permit circulating currents to flow, which would cause interference. Design of the earthing system for GIS equipment is thus a particularly challenging task and present research should result in improved earthing arrangements. At present, the advice generally given is to earth GIS equipment at the following positions: -

close to the circuit breaker,

close to cable sealing ends,

close to the SF_6/air bushing,

close to instrument transformers,

and at each end of the busbars (intermediate points also, depending on length).

7.4.7 Fence earthing

General

Generally, for reasons of security and economics, a metal fence is used to enclose the substation. Where a bare metal fence is used, then it must be earthed. This is to cater for the situation where a live conductor (say an overhead line) has come into contact with the fence or to prevent the fence voltage rising due to coupling with nearby live conductors. If it was not earthed, it might be possible for it to be energised at a considerable voltage, with obvious safety implications. The fact that members of the public are likely to have direct access to these fences means that certain precautions are necessary to avoid danger. Use of a non-metallic fence (or brick walls), whilst generally more expensive, avoids many of the difficulties which the following practices are designed to overcome. Plastic covered fences are treated the same as bare metal fences, because of the possibility of wear to the plastic covering. Metal gates should be bonded at both top and bottom by flexible connections to the gate post. The following practice is based on Electricity Association Technical Specification .

7.4.7.1 Independent fence earthing

This is the most common arrangement, however it does not permit full use of the area available for installing electrodes. A 2 m corridor is required between the fence and the edge of the earthing system (i.e. the perimeter conductor). Exposed equipment is then normally situated 1 m inside the perimeter electrode. The fence is earthed by installing 3m rods at each corner, either side of where overhead HV conductors cross, and at approximately 50 m intervals along the sides. Any buried electrodes which pass under the fence must be insulated for a distance of 2m either side of it. Gate posts must be bonded below ground to prevent touch voltages occurring between the two posts or the open gates.

The main advantage of this arrangement is that lower touch voltages arise on the fence and all earth electrodes are enclosed in an area where they are under the control of the occupier of the site.

7.4.7.2 Fence connected to the substation earthing

If the fence comes within 2 metres of the perimeter earth conductor or any exposed metalwork, or if the fence is situated wholly within the earthing system, then the fence is normally bonded to the earthing system. Bonds are required at 50 metre intervals, the fence corners and where overhead HV conductors cross the fence. Wherever possible, it is best to extend the earthing system such that the perimeter conductor is 1 m outside the fence. This ensures that touch voltages on the fence remain at a low level and considerably simplifies the design. The increased land area used results in a lower earth impedance, but there is an increased risk of third party damage to the perimeter electrode. Where such a fence is close to an independently earthed fence, they should be electrically separated, e.g. by a non-metallic fence or by insulating fixings.

In some situations, it may not be desirable to bond the fence (for example if this will result in high surface voltages during faults, or if the fence is near third party equipment). Another option is to separately earth the fence and then install a small potential grading conductor 1m outside the fence and connect this to the fence at regular intervals. The fence potential rise will be lower than that of the main earthing system and the potential grading conductor will ensure that touch voltages are low.

8 Earthing Design Within Buildings

8.1 Introduction

There are presently more publications on this aspect of earthing than on any other and it is the purpose of this chapter to provide just an overview of the more important aspects of earthing within buildings. Those requiring a more detailed coverage are referred to the standards and books listed in chapter 16. Additional material can also be found in books which deal with Building Services. The Institution of Electrical Engineers run a series of courses covering design, installation, maintenance and testing of fixed and portable appliances.

BS 7671, Requirements for Electrical Installations, 1992 is the prime reference document. The main objectives of this and other regulations is to protect persons, property and livestock against hazards arising from an electrical installation. Earthing is fundamental to most of the practices for achieving safety. The earthing system must provide a direct route to the soil for fault current whilst minimising touch and step potentials. The secondary function, is to help mitigate disturbances and serve as a common voltage reference for sensitive electronic equipment. However, with greater use of sensitive electronic equipment, particularly computers, there is a growing awareness of the importance of the secondary function of the earthing system. This is leading to a consensus of opinion that the earthing system must be designed as an overall system such that it fulfills the safety and performance requirements.

8.2 Typical TN-S Arrangements

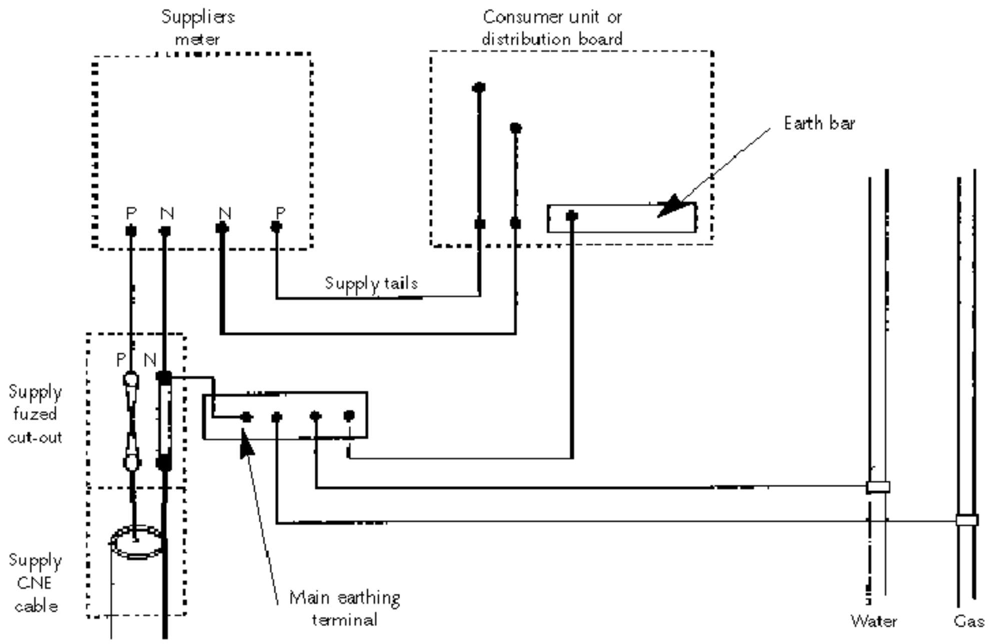
The most common protective measure is earthed equipotential bonding and automatic disconnection of supply. The standards set maximum disconnection times for different types of equipment. In deciding which times are appropriate, the earthing arrangement outside the property, i.e. the supply network, also has to be considered. This is because any earth fault current normally has to return to the source transformer. The earth loop impedance is made up of the impedance of the earthing system at the source transformer, the earth conductors between the transformer and the property and the impedance from the point of fault back to the supply point in the property.

Figure 3-3 illustrated a typical TN-C-S supply and this is the most common arrangement for new and recent supplies to domestic premises in the UK. In this arrangement the neutral and earth conductors are combined in the supply network. However they must be separated within premises.

Figure 8-1 shows a typical arrangement.

The main earth terminal is installed at the supply position. This is connected to the supply neutral and the earth bar in the consumer unit or distribution board. In addition, the gas, water and other services entering the property are bonded to the main earth terminal. A circuit protective (earth) conductor is run with each electrical circuit which leaves the consumer unit. In a normal wiring arrangement, this would be the uninsulated copper earth wire which is enclosed with the insulated phase and neutral conductors in a PVC sheathed cable. All items of exposed conductive metalwork are bonded together to ensure that there are no potential differences between them during fault conditions.

Figure 8-1 TN-C-S earthing arrangement in a domestic property

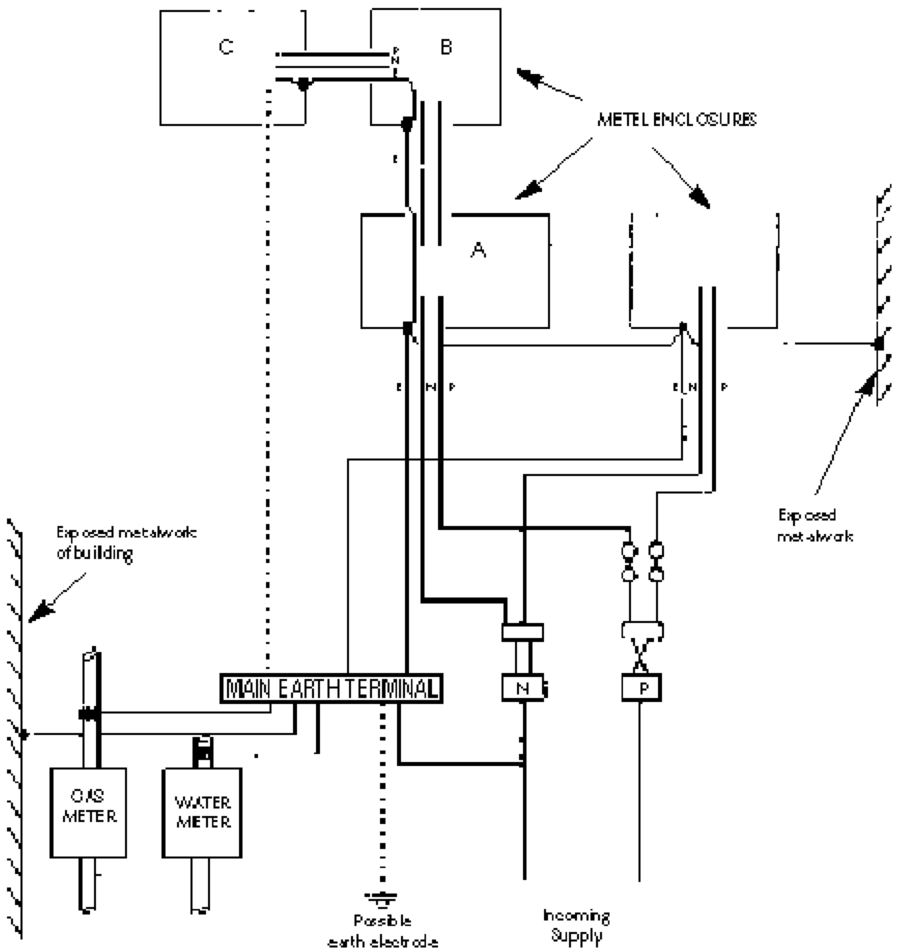


Now consider a more complex installation, for example part of that within an office or small factory. An arrangement, with emphasis on the earthing arrangement, is illustrated in Figure 8-2. The different types of earth conductor were described in chapter 2 and there is now an opportunity to explain them in more detail.

The supply is TN-C, whilst the installation is TN-S. There is one main earthing terminal which is connected to the supply neutral. The protective conductors and main equipotential bonds are routed back to the main earth terminal. The main earthing terminal acts as the single reference point and can comprise of a bar, a plate or even a copper internal "ring" conductor. This would often be connected directly to an effective earth electrode and this connection must be of copper, as the regulations will not allow use of aluminium or copper clad aluminium because of the corrosion risk involved. The earth electrode should be positioned as close as possible to the main earthing terminal.

A circuit protective conductor accompanies all current carrying conductors. If this conductor has a cross sectional area of 10 mm^2 or less, then it must be of copper. The main equipotential bonds are used to connect incoming services (such as metal gas or water pipes within the property). Supplementary bonding conductors give a visible indication that exposed metal equipment is interconnected and are mainly used when the required disconnection times cannot be met. The circuit protective conductors should already have ensured this, but the supplementary bond is normally shorter and thus more direct. It is not intended to carry fault current, but the minimum sizes are such that it is likely to carry some. Supplementary bonding conductors can (if necessary) also be used to connect external metalwork such as ladders, handrails etc. This would only be necessary if the external metalwork could introduce a potential (normally earth potential) and were within reach of conductive parts of equipment.

Figure 8-2 Typical TN-S installation within a commercial or light industrial property



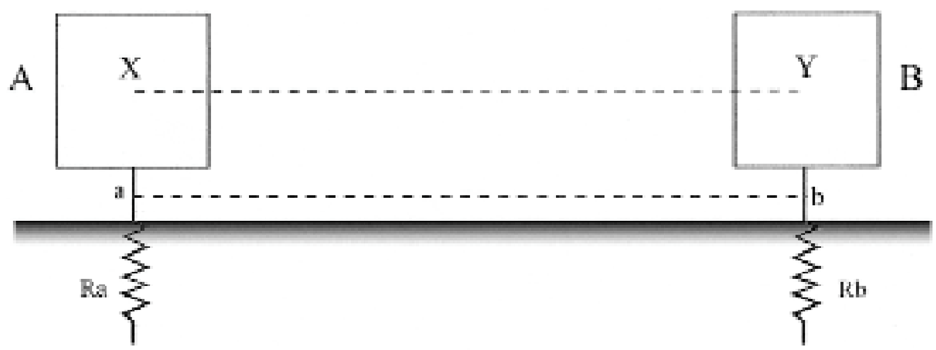
The designer must ensure that the protective conductor impedance is co-ordinated with the protective equipment characteristics such that during an earth fault, any voltages on exposed equipment which can be simultaneously touched are of magnitude and duration that they do not introduce danger. The voltage rise within an area during a fault has to be limited to a value stated in the regulations and this value is established by setting a minimum value of earth loop impedance. The maximum values are given in tables 41A1 and 41A2 of BS 7671. It is essential that copper protective conductors used have a sufficiently large cross sectional area and guidance on selecting the appropriate size is included in BS 7671 (tables 54B and 54C) Section 543.

Note that earth connections to metal enclosures should be grouped at one point, to avoid current having to flow through the metal of the enclosure itself. This could create interference. Where cables run between buildings, they should enter/leave at one point and if possible be routed through metal ducts which are electrically continuous. The duct/armouring should be connected back to the main earthing terminal. Surge protection may also be required at this point.

IT type equipment, such as computer power supplies, are now found to be causing particular problems with traditional types of earthing arrangements. This type of equipment has a permanent connection to earth and is a source of earth leakage current which has a high content of harmonics. Single phase rectified loads produce odd harmonics, some of which are additive in the neutral and earth conductors. If we assume that such equipment is situated at locations A, B and C in Figure 8-3, then the route along the protective conductor from C to the main earth terminal can be long, will have an impedance and there will be a voltage difference between the "earth" at C and that elsewhere. The inductance of the protective conductor will be especially important as the voltage difference will be greater for the harmonic currents than those at power frequency. This voltage difference is likely to create noise (or interference) and ultimately a shock risk. Heating and radiated electro-magnetic fields will be produced which could also cause interference. One way of reducing the voltage at C is to route an additional, separate protective conductor directly back to the main earth termination or as close as practical to it. This conductor should preferably be insulated and not run in parallel with cables or steelwork. A route which is as direct as possible will minimise its impedance.

In addition to the voltage reduction gained by this reduced impedance, there would be a further reduction because the leakage current associated with equipment at A and B would no longer follow the same route. This is called a "clean" earth and is shown in Figure 8-3. The "clean" earth could only be taken to a separate earth electrode if this in turn is bonded back to the main earthing terminal. If this bond did not exist, the arrangement would not conform to the regulations and could be dangerous. Other methods of producing a clean earth include use of isolation transformers and power line conditioners (typically an isolation transformer together with voltage regulation and some filtering of harmonics).

Figure 8-3 Earthing problems arising when equipment is interconnected



As mentioned previously, it is essential to select the appropriate cross sectional area and to reduce unwanted interference there is a growing tendency to increase the size of the protective conductors to help reduce interference in such installations. The cost to customers of data loss and equipment failure is often far greater than the initial capital cost of improving the earthing system.

8.3 Integrated Earthing Systems

It is not generally possible to have a system consisting of a number of different earthing systems, since these will inevitably interact and it is generally accepted that one integrated design with a low earth impedance is better than a number with medium impedance values. Figure 8-3 helps to illustrate why it is necessary to have one integrated design. It is first assumed that items of equipment at A and B each have their own earth electrode and that the metal enclosures of each are bonded to these. If an earth fault develops at A, possibly due to lightning, then fault current will flow to the ground via R_b and the potential on the exposed metalwork will rise. If there is no connection between A and B, equipment at B will be unaffected.

However, if there is a need to take a communication cable (X-Y) between the two sites, and assuming initially this has its sheath earthed only at A, there will be a potential difference between the sheath and the enclosure at B which may cause a flashover. If the cores of the cable are connected to a signal reference ground (the electronic equipment ground plane) at either end, then significant damage could result due to the potential difference and current flow. If the cable sheath is connected at each end, then some current will flow along it to earth via R_b. The potential difference between A and B will depend on the magnitude of the current, the impedance of the cable sheath and the individual impedances of R_a and R_b. Note that even when using fibre optic cables, care needs to be exercised as these often incorporate metal screens or draw wires.

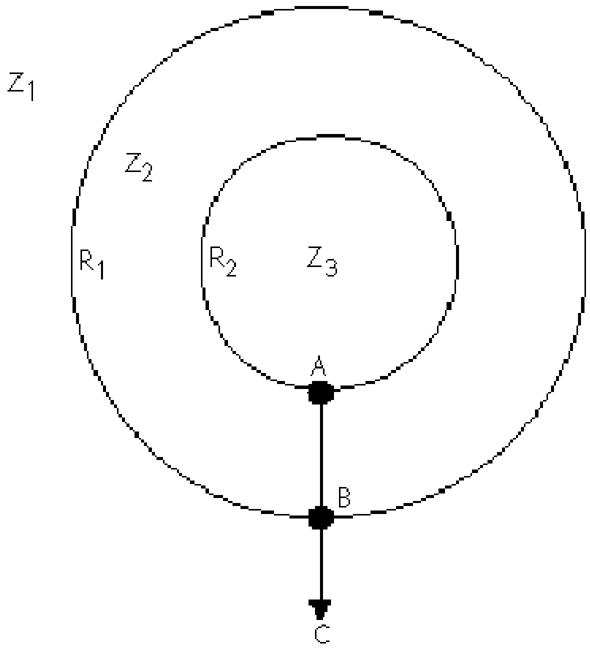
The accepted way to reduce the potential difference is to bond the two enclosures together as closely as possible, by using a number of parallel connections. This would include copper earth wire, the cable sheaths and conduits etc. If A and B were separate buildings, the preferred way to bond the earthing systems would be a horizontal loop electrode approximately 1m outside each building, with several large electrodes interconnecting these.

Consider now that A and B are within the same building and that B has been provided with a so called "clean" earth. During normal operation the equipment at B will not be affected by interference on the earthing system at A (assuming it is possible to separate them totally - which is unlikely). However, during fault conditions there will be a potential difference between the enclosures (and possibly the reference earths) in exactly the same way as described above. For this reason it is normal to bond the two earthing systems together, although sometimes this is arranged to happen only during fault conditions.

8.4 Arrangements to reduce interference

The basic method is to ensure that the supply and return paths for fault current are as close as possible, since this reduces the electromagnetic field produced. This is accomplished with armoured cables and a protective conductor routed with the phases. If single core cables are used with single point bonding, these requirements are normally achieved by running an earth wire with the cables. One source of interference arises when the earthing system forms loops through which leakage and fault currents can circulate. One arrangement which limits the number of such loops and also provides a progressively more protected environment within a building is termed a nested shield arrangement. Whilst this arrangement is mainly concerned with surge protection, it is relevant here as it also involves earthing zones. Figure 8-4 shows three zones. Equipment within zone 2 is connected to the outer earth conductor and shield. This has a single connection to the main earth electrode. Equipment within zone 3 is connected to the shield/earth conductor surrounding it and then via a single connection to the shield of zone 2.

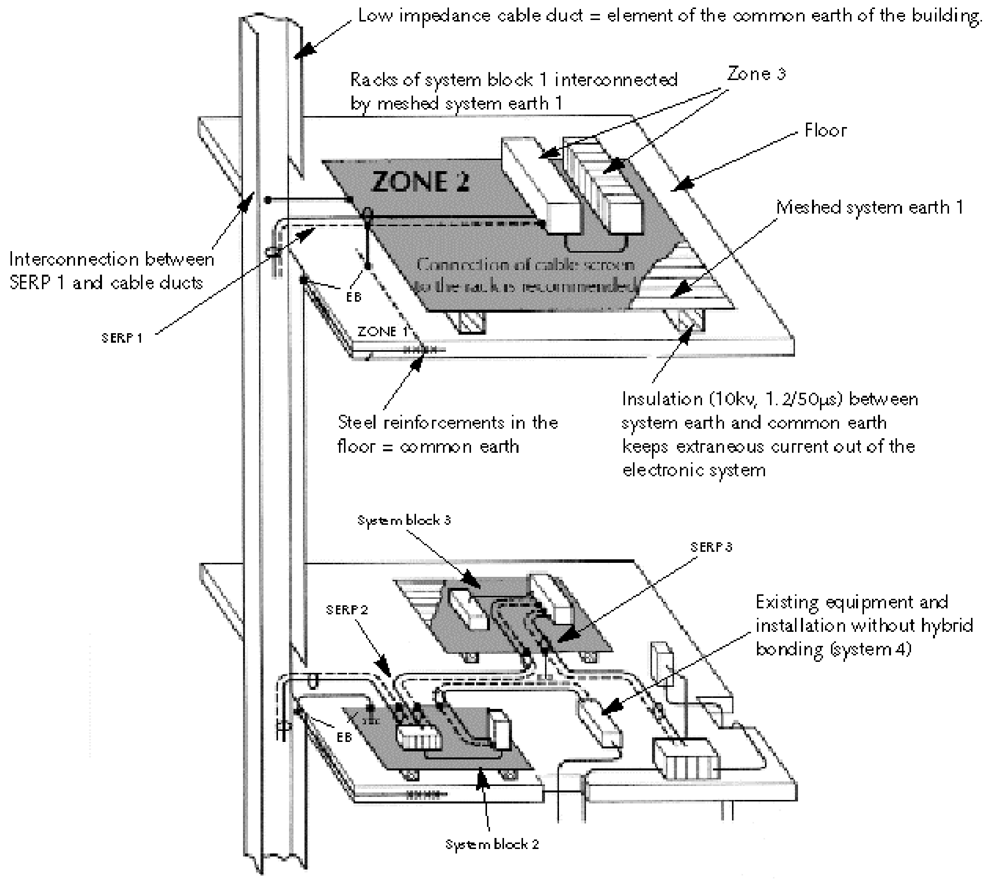
Figure 8-4 Nested shield type arrangement



This progressive shielding arrangement enables different amounts of protection to be afforded and, for example, zone 3 would normally be expected to have the least interference and would be the location for particularly sensitive or critical equipment. Cables passing between zones would require special connections such that the design is not compromised. Surge protection units would also be required at each position where a cable passes through a shield. Any fault current or induced interference current is transferred to the outer shield and eventually into the earth electrode. Faults which do arise should be diverted to ground at the outermost boundary to minimise the effect on equipment within.

Another arrangement designed to minimise interference, whilst ensuring that the earthing system is designed in a controlled manner without loops, is the hybrid design illustrated in Figure 8-5. It is intended to minimise earth loop areas, such as those that can arise when cabling between floors or adjacent areas. This arrangement is particularly applicable to buildings made from non-conducting materials.

Figure 8-5 Hybrid Earthing arrangement to reduce interference (courtesy W J Furse, based on work by Eric Montandon)



Note the new system blocks (1, 2 & 3) are hybrid-bonded and may be connected to the existing 4.

KEY

Zone 1	Not directly exposed to lightning
Zone 2	No partial lightning currents
Zone 3	Made up of equipment shielding
EB	Equipotential bonding
XXXX	Steel reinforcements in concrete
SERP	System earth reference point. This is the only metallic interface between the system and common earth. It must be directly connected to the structures steel reinforcement where cables leading to the system enter. All conductors that are bonded to the system earth within the system zone must be earthed at the SERP.

9 Lightning Protection

9.1 Introduction

The main purpose of a lightning protection scheme is to shield a building, its occupants and equipment from the adverse effects associated with a lightning strike. These effects could otherwise result in fire, structural damage and electrical interference - leading to equipment damage or electric shock. To perform correctly, the protection scheme must capture the lightning, lead it safely downwards and then disperse the energy within the ground. The components used to facilitate this are air terminations, down leads and bonding leads and the earth termination (or electrode). These are all discussed in more detail in this chapter. The final component, which has not been covered here, is surge protection equipment. There are a number of specialist books on this subject where detailed advice is available, some of which are listed in chapter 16.

9.2 The Formation of Lightning

It is generally accepted that lightning is created by a separation of electric charges due to air turbulence. The charge separation is thought to be due to the interaction of raindrops, snowflakes and ice crystals. Clouds containing moisture rise and cool as they do so. If the rate of rise is gradual, then mist and rainfall normally result. However, if the rate of rise is above a certain level, the cooling effect will be accelerated. This may cause larger raindrops or even freezing. The mechanics of the rainfall or freezing helps to cause charge separation, leading to a build up of negative charge on the cloud base and positive charge on the top of the cloud or on the ice particles. The subsequent potential differences created between clouds or between clouds and the ground can then be sufficiently high that a cloud to cloud or cloud to ground discharge (lightning strike) occurs.

Cloud to cloud lightning can cause electrical interference and sometimes significant damage, but it is the ground strikes which are generally the most destructive. As the potential difference between the cloud base and the underlying air/ground plane exceeds the breakdown value of the air in the immediate vicinity, the air becomes ionised and a downstroke begins - travelling at about 2 metres per micro-second. It follows a haphazard path, generally downwards, made up of small steps. There is some debate about the way in which the steps are produced and the point at which the actual arc commences, but eventually the negatively charged downwards leader will approach the ground. Positive charges will, in turn, be induced on the ground surface and, in particular on any high structures. If the potential is sufficiently high at the ground (or on a high structure), then ionisation of the air here commences and an upward charged leader, positively charged, will be created. Eventually the negative and positive charged leaders will meet, often via a seemingly haphazard route, and the lightning discharge will be experienced, which is normally negative. A high current of short duration, is accompanied by a bright flash and noise.

The amount of lightning activity is not the same throughout the country, it varies according to many factors, including geographical location, height etc. The energy associated with the discharge also varies. It is necessary to consider these factors and others, in deciding whether a lightning protection scheme is required and the form it should take.

9.3 Risk Assessment

:BS 6651:1992 'Protection of structures against lightning', is based on a probabilistic assessment which takes the following factors into account:

- Soil resistivity.
- The external dimensions of the structure and any electrically connected adjacent structures.
- The length of overhead cables emanating from the structure.
- The flash density in the locality - associated with the thunderstorm days per year.
- The construction type - mainly the height, type of roof, and protection scheme (if any) in place. In general, the larger it is, the more likely it is to be struck.
- Geographic factors - the vertical height above sea level and relation with other structures, for example how close is it to tall trees.
- Ground profile and terrain.

These factors take into account the collection area made up by the structure and cables connected to it and the methodology enables the risk of a strike to be calculated. If the risk is less than 1 in 100,000, then generally no protection is required. However, in order to carry out the formal risk assessment, this needs to be assessed in relation to the consequences of a direct strike. If the building is associated with an oil refinery or houses explosives, then a lightning protection scheme offering the highest possible degree of protection will be required, even if the risk of a strike is small.

9.4 Components of the Lightning Protection System

The overall design is based on the concept of a rolling sphere, which is applied to the structure to ensure that all exposed areas are protected by the scheme. The individual components are as described below. The materials used are generally high purity copper or aluminium (99%+ pure) of a similar grade to that used for electrical conductors. The lightning protection system must be designed to provide a sufficiently low impedance that the lightning energy will follow the required route. This requires an integrated design and use of materials with sufficiently low impedance. The various components of the system are each described in more detail below.

9.4.1 Air terminations

These consist of vertical rods and/or a lattice of conductors on the roof and top edges of a structure. The strips of the lattice typically form a mesh of 10 m by 20 m, smaller on high risk buildings. Metal projections, including rods, are connected to this. BS 6651 requires that all parts of the roof are within 5m of a conductor of the air termination. This distance is reduced to 2.5 m in high risk buildings. Copper is again the most widely used material. Rods were traditionally pointed, but modern designs now normally have a smoothed, but blunt tip. Rods, if used, are positioned near those locations where a strike is most likely - i.e. roof peaks, building corners etc.

9.4.2 Down leads and bonding conductors

These are required to provide a low impedance path down the structure, in a manner which minimises potential differences and induced current. The ideal arrangement would be a metal building where the current would flow through the skin of the building. The design for traditional buildings seeks to use the advantages of this, i.e. by providing a number of parallel paths to reduce the fault current in each. These would be symmetrically positioned around the building, ideally including the corners. Sensitive electronic equipment should not be positioned within the building, near to these down paths as there is a risk of inductive interference. Current would flow in all paths, but the largest would flow in the path nearest to the point of impact.

The down leads are required to be as short and straight as possible, any bends being gradual rather than right angled. They are typically 10 m to 20 m apart. They should be of robust construction and securely fixed in order to withstand the significant mechanical forces which accompany the flow of lightning current. In addition to formal down leads, metal girders, metal sheeting and reinforcing are also used.

Bonding conductors are used to connect these to any exposed metalwork on or near the structure. This is to ensure that a sideflash does not occur. As the current flows down the lead, a potential would be created. If metalwork (such as central heating ducts, pipes etc.) were not bonded, this could initially be at a potential nearer to that of earth and thus could offer a more desirable path to ground. If the potential difference exceeded the breakdown value of the air or medium in-between, then a sideflash could result, accompanied by severe damage.

BS 6651 contains a formula to determine whether a nearby structure needs to be bonded or not. Potential equalisation is thus provided on the top and sides of the structure.

Copper and aluminium are the most widely used materials. Stranded conductor is normally preferred to tape as it is easier to install and its skin effect at high frequencies results in better performance. Copper is considered to be more resistant to corrosion in areas with salt laden, moist air, near concrete, on tree bark and where there is air pollution. The copper is sometimes lead coated to increase its corrosion resistance when used on chimneys and near other sources of flue gases. PVC sleeving is also sometimes fitted for aesthetic reasons.

Each down lead should be taken to an earth termination and if these are not interconnected, then the down leads would often be interconnected via a horizontal ring conductor installed near ground level. A test clamp is often fitted to enable the continuity of pairs of downleads to be checked at ground level and provide a means of isolating the earth electrode.

9.4.3 Earth termination

This can consist of a ring of buried copper (referred to in the USA as a counterpoise) which encircles the structure, and/or vertical earth rods. The impedance of the termination (i.e. below a down lead) is required to be a maximum of 10 Ohm. Aluminium is not permitted for use underground. Each down lead must have its own earth electrode termination and these are normally looped together to form a ring, with horizontal electrodes being used to interconnect them and help to reduce the overall impedance. The most common terminations are driven rods and these are required to be at least 1.5 m long with a minimum of 9m being used for each system.

The ring helps to provide potential equalisation at ground level, in addition to potential grading. The latter helps reduce the touch voltage which could be experienced by a person in contact with the down lead during a lightning discharge.

Although the other parts of the protection system may be designed in isolation, the electrode arrangement should not be. The complete installation should rise in potential together, to avoid excessive voltage differences, and this means that the earth termination should both be bonded to the rest of the earth electrodes and significantly, designed as an entity. Within buildings, it is necessary to contact the electricity company if the lightning protection system is to be connected to the earth terminal. Whilst this may cause potentials to arise on the earthing system outside, connection is generally necessary to ensure that all exposed metalwork is bonded.

Normally the lightning protection and main power system earths would be interconnected. Where this is not desirable, for technical reasons, an "earth potential equaliser" can be installed between them. This will interconnect the earthing systems if the voltage between them exceeds a certain value - typically several hundred Volts.

9.4.4 Surge protection devices

Having designed the lightning protection system, the main areas at risk should be readily identifiable and additional precautions taken, where necessary, to protect electronic equipment. Earthing, shielding and bonding cannot always guarantee immunity from interference, so surge protection devices supplement these where necessary and form the last part of the formal defence. There is a wide range of devices available for this purpose. Generally, they are designed to divert the energy associated with an over-voltage into the earthing system to avoid this causing insulation breakdown within equipment.

The operating voltage is below that at which damage to the protected equipment would occur. They are voltage limiting devices connected between phase and earth, normally metal oxide varistors. Voltage switching devices suddenly switch to a low resistance once a threshold voltage is exceeded. They include spark gaps and gas discharge tubes. Other devices used include surge reduction filters (to give added protection to sensitive electronic equipment) and surge barriers (where cables enter or leave a building).

Appendix C of BS 6651 contains useful additional information about the application of surge diverters.

9.5 Lightning Protection of Power Lines

The majority of high voltage transmission and distribution lines (132 kV, 275 kV, 400 kV) are installed on steel lattice towers. Due to the length of these lines, if in an area with significant lightning activity, they are susceptible to direct strikes and induced effects due to a nearby strike or cloud-to-cloud lightning. An over-running earthwire is provided to give the appropriate protection. This is earthed at the start and end of each line and at every support position. In general, the earth electrode at the support is formed by the steel legs installed in concrete in the soil. This normally provides an impedance at power frequency of 10 Ohm or less. However in high resistivity soil, the impedance may be too high and additional earth electrodes are installed.

The earth electrode arrangement may be a horizontal loop situated one metre or more outside the tower footing, possibly with some vertical earth rods attached to it. As the soil resistivity increases, long (say 20 m) horizontal electrodes may need to be installed, routed radially outwards from the tower footings. In worst cases, this is accompanied by a buried earth wire which runs underground alongside the line itself. In older line designs, sections of cast iron pipe were sometimes installed underground between the tower legs, but in this position the improvement to the earth impedance is not normally significant.

If lightning strikes a tower, then some of the associated current will be diverted through the footings to earth and some via the over-running earth wire to adjacent towers. The voltage arising on the tower can, in some cases, be sufficient that the breakdown voltage of the line insulators is exceeded and a back flashover will occur from the tower to the phase conductors. This will often be followed by a power frequency discharge.

Over-voltage protection devices are installed to protect equipment on overhead lines. This includes surge diverters and a variety of "spark gaps". The latter involve one or more steel rods connected to the phase conductors, the rod tips being positioned a set distance from an earthed rod or plate. When the voltage exceeds a certain value, the air gap between these breaks down and diverts the associated energy down into the earthing system.

10 Electrical Interference

Interference is an everyday occurrence in electrical circuits, but fortunately in the majority of cases it is un-noticed. This may be due to design of the installation or the immunity built into the equipment being used, so performance continues despite the interference. The consequences of interference can range from audible 'clicks' on hi-fi systems, flicker in lighting circuits, loss of data in IT systems, incorrect operation of equipment through to actual damage or destruction of equipment. The latter examples can be very costly in terms of lost production, in addition to that due to equipment damage.

Interference is particularly troublesome for data processing and communication circuits which require a high degree of quality. Part of the reason for this is that electronic equipment from which these cables emanate has a "ground reference plane" to which digital signals are referred. To avoid excessive voltages within equipment, the ground reference plane is normally connected to the metal equipment enclosure. This in turn is connected to the main earthing system. Communication cables normally have an earthed screen, but also contain a signal reference conductor which is connected to the ground reference. Problems arise when special arrangements are made to avoid connecting adjacent equipment via the cable screen or armour. However, they may unknowingly be interconnected via the ground reference conductor.

The mechanisms by which interference arises are:-

- resistive (also known as galvanic) coupling
- capacitive coupling
- inductive coupling.

These will all now be covered in a little more detail. Improvements to the earthing system are often required to reduce such interference and the shielding aspects can require a lower earth value than the safety and protection operation criteria.

10.1 Resistive Coupling

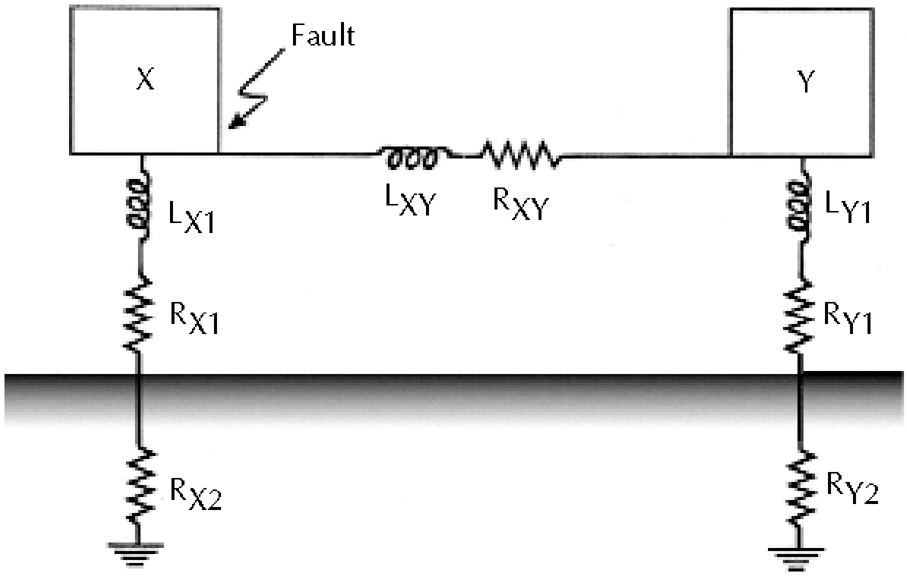
This coupling arises when there is either a direct electrical connection between the source of the disturbance and the affected circuit, or via a resistive medium (such as the soil). The conditions giving rise to resistive coupling via the soil have already been covered in chapters 1, 2 and 7. As described in these earlier chapters, an earth fault condition may have caused the potential on an earthing system to rise. A voltage created on the sheath of a cable which passes near to the earthing system is said to be due to resistive (or galvanic or conductive) coupling.

The implications arising from galvanic coupling can be seen by reference to Figure 10-1.

Assume that the equipment at X has been affected by a lightning surge and the excess voltage has been reduced by diverting the energy to earth via a shunt connected surge diverter (i.e. between phase and earth). As the current flows down into the soil, it must pass through the impedance of the above ground connections (L_{x1} and R_{x1}) and below ground electrode (R_{x2}) of the earthing system. A voltage will be present on the earthed equipment at X. If the equipment is connected to that at Y by a cable sheath having an impedance made up of resistance (R_{xy}) and inductance (L_{xy}), then there will be a difference in voltage between the earthed equipment at X and Y. The magnitude of the voltage difference will depend on the earth impedance values at X and Y, together with that of the connection between them (L_{xy} and R_{xy}). The potential difference in this example is called resistive (galvanic) interference and it can be reduced by either:-

- decreasing the earth impedances (R_{x2} and R_{y2})
- reducing the impedance of the connection between X and Y, i.e. L_{xy} and R_{xy}.
- reducing the above ground earthing connection impedance at X and Y.

Figure 10-1 Example illustrating resistive interference



Normally the most effective way is to closely bond the equipment via cable sheaths, conduit etc. and earth wire. If the connection is via a cable sheath, then a surge protection unit may be necessary to prevent an excessive voltage difference between the cable cores and sheath during fault conditions. Ideally, connected equipment would be situated upon an equipotential platform consisting of a continuous plate. As this is generally impractical, the common method is to provide a magnetic shield (say a metal conduit) and several conductive paths in parallel with this, being earthed at each end and at intermediate locations.

10.2 Capacitive Coupling

Any two conductive metallic components which are separated in a medium will have a capacitance between them. If one component is charged, then a charge will arise on the second one.

This mechanism is used beneficially in electronics and electrical engineering, but when it creates unwanted voltages, it is called capacitive interference. This is the type of interference which would be experienced if a metal conductor is routed near a high voltage overhead line and is due to the electric field.

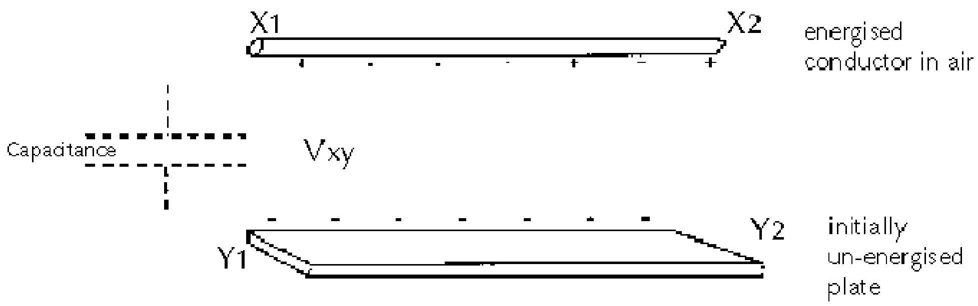
The overhead conductor is shown as X_1 X_2 in Figure 10-2. It is assumed that at one moment the conductor is positively charged, then (due to the capacitance between them) a negative charge will be created on the plate Y_1 Y_2. The capacitive current which flows is directly proportional to the frequency and voltage magnitude. For this reason, the interference current can be significant if the overhead line is struck by lightning, when the magnitude, harmonic content and rate of change will all be high.

The methods available to reduce this interference are:-

- reduce the overlap between the components (for example the distance in parallel).
- increase the separation between them.

Both methods are traditionally used for signal and communication cables, which are routed some distance from mains cables and if they need to cross them, would do so at right angles, wherever possible.

Figure 10-2 Example illustrating capacitive interference



Another method is to place a metal screen around the circuit requiring protection and connect it to earth at one point. The interference voltage arising in the sheath will be dispersed to earth and the effect on the cables inside will be significantly reduced. Normally an electrostatic screen would only be earthed at one end, the one having the lowest earthing system impedance. There will be potential differences along the length of the screen, as capacitive currents are distributed but must flow to one end to be discharged. This could cause interference at the remote end, so good conductive material such as copper is used to minimise this. An electrostatic shield would preferably be applied around each twisted pair in a large cable and another around the whole cable.

The following materials are typically used for capacitive screening:-

- tape or foil made from copper or aluminium
- single braid, made of tinned copper
- single spiral lap, made from tinned copper
- double braid, made from tinned copper.

Tape or foil provides the greatest screening protection, whilst braid has better mechanical and electrical properties.

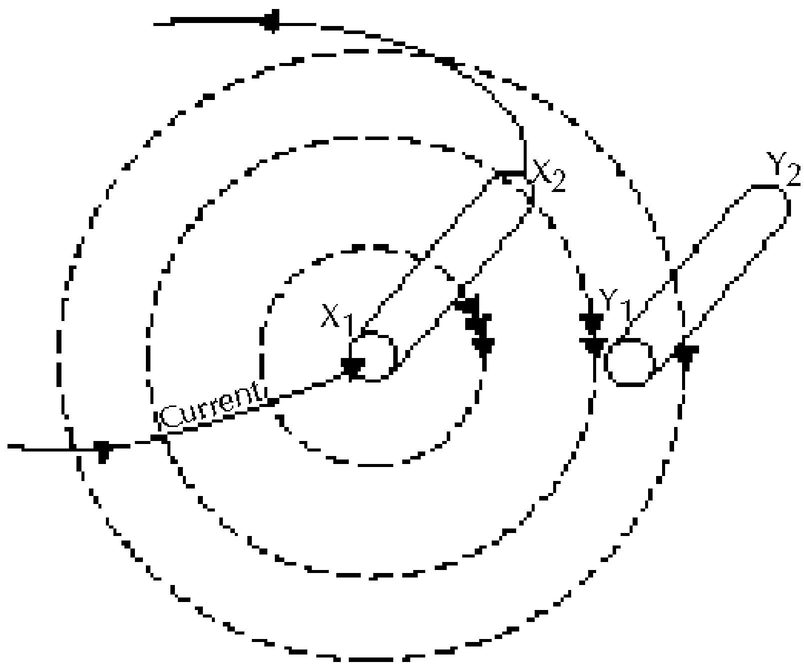
10.3 Inductive Coupling

This is the most common type of interference, caused by electro-magnetic coupling, particularly at power frequency (50Hz). It is due to magnetic fields.

Figure 10-3 helps to illustrate how inductive coupling arises. The current flowing in conductor X creates a magnetic field around it, as shown. The magnetic field is produced because the current in X is alternating. The magnetic field strength reduces as the distance from X is increased. Conductor Y may be some distance away, but some flux lines from X will encircle it as shown. As the current in conductor X changes, the magnetic field encircling conductor Y will change and this, in turn, will cause a voltage along its length.

The voltage arising in conductor Y is thus caused by inductive interference and increases with the rate of change of current in conductor X.

Figure 10-3 Inductive interference



If conductor Y is earthed at both ends, as shown in Figure 10-4, then the potential difference between the two ends will cause a current to flow along the conductor and through the earth/ground. The current in Y will be in a direction such that the magnetic field it produces will oppose that existing around conductor X.

Sources of this type of interference can be normal mains cables, mains or earth cables carrying unbalanced current (particularly earth fault current) or lightning protection conductors which are dispersing fault current.

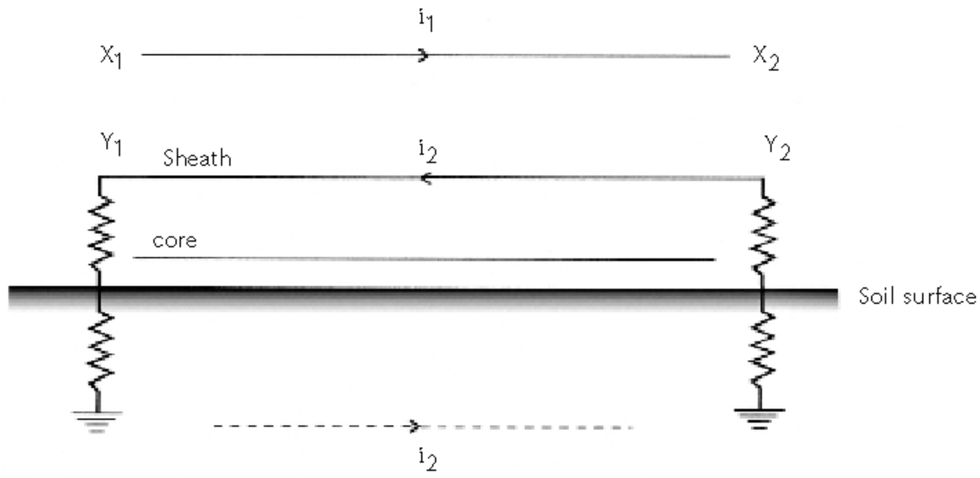
It is particularly difficult to protect against this type of interference and the general methods used include:-

- increasing the separation between cables (X to Y). Increasing the separation is not always practicable and may involve considerable expense if not implemented at the initial construction stage.
- reduce the effect of the magnetic field on circuit Y. One method of achieving this is to use twisted pair cables, but this only works for balanced differential types of signalling.
- reducing the magnetic field produced around the cables to be protected. If the cable sheath or screen is earthed at both ends, as shown in Figure 10-4, then whilst current is flowing in cable X, a current will also be induced in cable sheath Y. Its direction will be such that the magnetic field it produces will act in opposition to that from conductor X. The end result is that the magnetic field and interference on the cores of cable Y will be reduced. Individual power cables would be arranged in a triangular manner (trefoil) such as to reduce the magnetic field produced around them under normal load conditions. Power cables would also be run on earthed steel trays to reduce the magnetic field created. If plastic conduit is used, then a separate shield wire may be required, earthed at each end.

- diverting the magnetic field away. This is achieved by using a high permeability material (such as steel) as a screen. This will normally be earthed at each end. The magnetic field surrounding it will be distorted and the field density within the steel increases whilst that around the cores decreases

Note that capacitive coupling can still arise when twisted pairs are used, so it is best practice to position these as close to the ground conductor as possible.

Figure 10-4 Reducing inductive interference by using an earthed shield/screen



11 Corrosion

11.1 Introduction

Electricity supplies are required in all areas of the country, which include rural areas, city centres and industrial areas. Earthing system components are installed above and below ground and in both situations must cope with a wide range of environments. In air, there may be smoke from process plants, or rainwater which has dissolved airborne material. Underground, the moist environment may include naturally occurring minerals, chemicals (fertilisers etc.) or contaminated substances which have been buried. As mentioned previously, the earthing system is a critical part of the electricity supply system and needs to perform, normally unseen, over a considerable period of time. The security required can be assured by careful selection of material.

11.2 Types of Corrosion

11.2.1 In air

In air corrosion is normally caused by either chemical reaction with rainwater solutions which have dissolved airborne gases or dust particles from industrial processes. Corrosion can also occur due to inappropriate bimetallic connections or contact with other materials. This type of corrosion is the least troublesome and can generally be controlled by good construction practice, including material selection. The standards include the necessary guidance on this. For example, selection and fitting of bimetallic connections, to include the physical orientation, how to exclude water, contact materials required etc. The standards also include guidance on fitting earth conductors, for example BS 7430 stipulates that aluminium conductors should not be drilled and fixed direct to concrete structures, because of the risk of corrosion.

11.2.2 Underground

Corrosion underground generally takes place in a combination of two ways, uniform general corrosion leading to an overall loss in weight of the component and pitting corrosion in small, selective areas. The latter type of corrosion can be serious for tubes but less so for earthing strips or plates. It is also important to consider what other equipment is present in the area, as this may influence the corrosion risk. For example, a nearby pipeline may be fitted with an impressed current cathodic protection scheme which may interact with the new earthing system. There may also be a residual standing voltage at the electrical installation which may either affect the corrosion rate (AC influenced) or cause nearby electrolytic action (DC influenced).

There are two sources of general corrosion, which are bimetallic corrosion and chemical corrosion.

11.2.2.1 Bimetallic corrosion

When dissimilar metals are joined and in an electrically conductive aqueous liquid - such as most underground situations, the possibility of bimetallic corrosion exists. The most susceptible metal will be preferentially corroded. This sacrificial effect is exploited in many corrosion reduction techniques. The most susceptible metal will be the one which is least ‘noble’. Table 11-1 shows the ranking of the more common metals in descending order of nobility. In the presence of an electrolyte, the more noble metal becomes cathodic to the lower order metal which become anodic. The anodic metal corrodes. The design should allow for the smallest components to be more noble than large ones.

One method of assessing the risk of galvanic corrosion is provided by the "areas" rule. For this the anodic area (e.g. of steel) is divided by the cathodic area (e.g. of copper). As the ratio between the anodic and cathodic area decreases, the rate of corrosion increases sharply. For example, if a steel pipe is jointed to a large copper pipe, the ratio of the areas is small and rapid corrosion occurs in suitable conditions.

An additional problem which can be experienced is severe corrosion at a joint between different metals, say copper and aluminium or copper and steel. Where the joint is unprotected and accessible to moisture, a significant rise in electrical contact resistance can occur.

The implication of this type of corrosion is that care must be taken to ensure compatibility between dissimilar metals used, i.e. the electrical potential (as indicated on the galvanic series) between them should be kept to a minimum to prevent galvanic action. A particular case is the combination of galvanised earth rods and copper/copperbond earth rods. The zinc layer on the galvanised rods behaves as the anode to the more noble copper cathode. Corrosion of the zinc layer can then occur leaving the steel core of the galvanised rod exposed which in turn will offer relatively little corrosion resistance to the surrounding soil. Note also that sometimes the zinc layer may be removed due to 'general' soil corrosion (e.g. in soils with a high chloride content).

11.2.2.2 Chemical corrosion

The soil can either be neutral, acidic or alkaline and the relative state of a soil is represented on a pH scale as follows:-

pH number 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Chemical action will take place between the metal and any acid or alkali in solution in the soil. The rate of corrosion will be influenced by the nobility of the metal, i.e. the lower its nobility, the more rapidly it corrodes. Again guidance is given in the standards, where the material surrounding the electrode is required to be relatively neutral.

Additional aspects of corrosion which should be considered are:

- Corrosion Fatigue (Stress Corrosion). Fatigue failures can be found under conditions of less severe stress than would be expected when the effect is aggravated by the presence of a corrosive atmosphere or liquid. They can be accentuated in corrosive environments, especially in the presence of retained internal stress caused by cold working.
- Crevice Corrosion. Where a crevice is formed, as can happen in the small gaps between mating flanges or joints, a crevice can be set up where the water is static and likely to become anaerobic. This can accelerate corrosion in some metals, especially in the common stainless steels, where their surface condition becomes active rather than passive. As shown in Table 11-1, this will alter their position in the electrochemical series. In addition, this type of corrosion may affect copper coated rods. Should the copper coating be scratched and removed from the steel core, corrosion will be more probable.
- Biofouling. This involves the growth of moss, lichens and similar matter. Copper does not suffer from this and it is not hospitable to growth of organisms.

11.3 Resistance to Corrosion

Although corrosion resistance is not as easily quantified as many other mechanical properties, it does influence lifetime costings, for example good resistance to corrosion resulting in fewer expensive service failures. This is one of the many reasons why copper is so frequently selected as an engineering material.

11.3.1 Atmospheric oxidation

Copper forms two oxides, both of which are conductors. In humid air, cuprous oxide forms first and then gradually darkens through brown to the black of cupric oxide. When copper is heated, copper oxide forms more rapidly and may be loosened by quenching in water.

When copper is outdoors and exposed to rainwater containing dissolved carbon dioxide, the typical protective green patina forms.

The patina or oxides formed are relatively thin and form a layer which inhibits further corrosion.

11.3.2 Underground corrosion

Many of the applications of copper and its alloys rely on good corrosion resistance, particularly in many aqueous, chemical and underground environments. Objects dating back to 4,000 BC have been discovered in good condition after being buried by floods in early Mesopotamian times. The Egyptians used copper extensively in architecture, even making water pipes by rolling up copper strip. Sections of water pipe that had been buried in gypsum 5,000 years ago have been recovered in useable condition. Copper implements dating back to 2,500 BC have been found buried in various parts of the British Isles.

The use of copper for earthing is more recent and it has performed well in the majority of soil conditions. Experience gained with buried copper pipes is a useful means of illustrating this and allowing comparisons to be made.

Table 11-1 shows the galvanic behaviour of metals, measured in saline water. Common stainless steels are shown with values for normal exposed passive conditions, together with the active surface conditions often found in crevices. Copper is towards the more noble range of the series, but having a significantly lower price than the most noble metals, which again explains its use for underground purposes.

Interestingly, despite its good anti-corrosive properties, copper is an essential trace element in the diet of humans and animals and essential to the growth of most plants. It is not normally considered to be a harmful toxic metal.

Table 11-1 Corrosion Susceptibility of Metals

Most Susceptible (Least noble)	
↓	Magnesium and its alloys
↓	Zinc and its alloys
↓	Aluminium and its alloys
↓	Cadmium
↓	Stainless steel, 13% Cr (active)
↓	Lead-tin solder, 50/50
↓	Stainless steel, 18/8 type 304 (active)
↓	Stainless steel, 18/8/3Mo type 316 (active)
↓	Lead
↓	Tin
	Brasses
	Gunmetals
	Aluminium bronzes
	Copper
	Copper-nickel alloys
↑	Monel
↑	Titanium and its alloys
↑	Stainless steels (passive)
↑	Silver
↑	Gold
↑	Platinum
Least susceptible (More noble)	

11.4 Corrosion Test Field Trials

Although it is well accepted that copper resists corrosion well in service in normal conditions, it is useful to remember that only the precious metals such as gold and platinum resist corrosion under all circumstances. Occasional failures have occurred when soil conditions have been unusually aggressive and sufficient experience gained to give guidelines on soil conditions to be avoided in order to obtain full service life from copper.

Because of the very great number of variables encountered in service, accelerated tests carried out in laboratories have been of limited use. Field trials carried out in closely monitored service conditions have proved far more reliable. The results of some of these are summarised in Table 11-2.

Table 11-2 Effect of Soil Characteristics and climate on Corrosion

The table is condensed from 'Underground Corrosion', National Bureau of Standards (USA) 450pp., November 1945 and shows results obtained after field trials with exposure periods ranging from four to thirteen years. The effects of many variables on corrosion rates were studied for four metals commonly used for underground pipework. The range of results was wide and showed different influences on each metal. Generally, the durability of copper was very evident when compared with steel or cast iron. Further tests were carried out with galvanised steel ($3oz/ft^2$ - $915g/m^2$) which was shown to give some extension to life but to be largely ineffective after five years.

Test No	**Soil**	**Average corrosion rate, inches x 10^{-3}/y**					**Characteristics of soil and climate**				
		Copper	Brass	Lead	Steel	Cast Iron	Mean Temp. ^oF	Annual rainfall (inches)	Moisture %	pH	Resistivity Ω-cm
67	Cinders	1.58	3.51	3.22	9.67	>20	46	30	11	8.0	455
43	Tidal marsh	0.81	0.04	0.02	2.13	2.51	52	43	55	3.1	60
63	Tidal marsh	0.62	0.011	0.004	1.44	1.09	66	45	47	2.9	84
60	Peat	0.91	0.64	0.07	2.77	3.82	49	37	43	2.6	218
33	Peat	0.17	0.25	-	1.81	2.47	46	30	73	6.8	800
58	Muck*	0.29	0.49	0.64	2.61	3.59	69	57	58	4.0	712
29	Muck*	0.16	0.39	0.36	2.27	3.90	69	57	34	4.2	1,270
45	Alkali Soil	0.04	0.02	0.02	1.23	2.00	47	15	15	7.4	263
64	Clay	0.60	0.30	0.05	>20	>20	58	16	41	8.3	62
56	Clay	0.11	0.14	0.12	4.67	>20	69	49	29	7.1	406
61	Clay	0.05	0.18	0.58	0.93	1.26	69	57	31	5.9	943
27	Clay	0.016	0.06	0.05	0.82	0.68	67	56	43	6.6	570
28	Clay adobe	0.11	0.11	0.07	2.59	3.84	61	10	25	6.8	408
5	Clay adobe	0.04	0.08	0.45	0.70	1.06	56	23	29	7.0	1,346
3	Clay loam	0.04	0.10	0.06	0.60	0.57	61	48	29	5.2	30,000
8	Clay loam	0.03	0.03	0.06	0.97	3.06	49	21	37	7.6	350
25	Clay loam	0.016	0.07	0.03	2.4	0.51	46	30	26	7.2	2,980
36	Sandy loam	0.26	0.07	0.03	0.30	0.16	64	53	14	4.5	11,200
10	Sandy loam	0.12	0.33	0.09	0.60	0.79	50	41	13	6.6	7,460

12	Fine sandy loam	0.40	0.31	0.12	0.49	0.36	62	15	12	7.1	3,190
16	Fine sandy loam	0.08	0.24	-	0.97	1.36	67	61	22	4.4	8,290
37	Fine sand	0.23	0.21	-	1..00	2.14	69	47	7	3.8	11,200
Test No	**Soil**	**Average corrosion rate, inches x 10^{-3}/y**					**Characteristics of soil and climate**				
		Copper	Brass	Lead	Steel	Cast Iron	Mean Temp. ^oF	Annual rainfall (inches)	Moisture %	pH	Resistivity Ω-cm
31	Fine sand	0.012	0.03	0.019	0.35	0.26	69	47	3	4.7	20,500
66	Fine gravely loam	0.08	0.18	0.025	3.08	0.73	70	8	16	8.7	23.2
6	Gravely sandy loam	0.014	0.02	0.018	0.16	0.08	51	34	12	5.9	45,100
4	Loam	0.03	0.20	0.19	0.84	1.48	54	40	22	5.6	6,670
35	Loam	0.02	0.03	0.02	0.16	0.26	62	15	18	7.3	2,060
23	Silt loam	0.18	1.06	-	2.54	4.76	65	6	25	9.4	278
1	Silt loam	0.08	0.14	0.18	1.22	1.89	49	34	29	7.0	1,215
20	Silt loam	0.05	0.06	0.28	0.80	1.10	49	34	22	7.5	2,870
19	Silt loam	0.05	0.17	0.04	0.46	0.60	50	32	28	4.6	1,970
18	Silt loam	0.010	0.03	0.016	0.35	0.47	51	28	28	7.3	1,410

Type of Soil - Cinders caused the worst corrosion although their sulphate and chloride contents were not always high. It is thought that the presence of sulphide caused the aggressive environment. Some of the problems could also be caused by galvanic action between the copper and carbon which formed 26% of the cinders.

*** 'Muck'** Soils with a high content of muck (US term for decaying vegetation) and other high humus soils were aggressive. Of the other soils the clay (No 64) that is strongly alkaline and badly drained was aggressive.

Drainage - The worst cases of corrosion occurred in soils with very poor drainage.

Moisture Equivalent - High moisture is usually associated with poor drainage and high humus content, conditions favourable to corrosion.

Annual rainfall - When between 30 and 60 inches per year the effect is not significant. Where less than 21inches, the soil was often very alkaline.

Mean temperature - not very significant, effects more dependant on range from summer to winter.

Water composition - analysis was given for sodium, potassium, calcium magnesium, carbonate, chloride and sulphate. High sulphate and chloride, generally associated with poor drainage and high humus, was often present when corrosion rates were high.

pH value - 7.0 is neutral, smaller numbers show greater acidity, higher numbers greater alkalinity - values were found to vary with measurement techniques and exposure of the soil to air. Soils with high sulphate and chloride were generally acid and the remarks above also apply. Neutral soils caused few problems.

Soil Resistivity - The figures given are for saturated soils at 60^{o}F. These soils would have higher resistivities most of the year. Very low resistivity (less than 10 Ohm-cm) is always associated with severe corrosion.

Field tests in the U.K. Test results after a series of tests by the British Non-Ferrous Metals Research Association on copper and lead in British climatic conditions gave conclusions that were similar to those reported above when related to type of soil, humus content, acidity, alkalinity and contents of sulphate and chloride. Estimates of the effect of time on corrosion rates showed that generally they decreased after acquiring protective scales. Only in wet acid peat was this effect not found.

12 Types of Copper and Typical Applications

12.1 Coppers

Copper has the highest conductivity of any of the commercial metals. It has good mechanical properties at low, ambient and elevated temperatures and has excellent resistance to corrosion. It is mined in every inhabited continent. Ore reserves, and the continuing development of mining techniques, are such that future supplies are assured.

There are three popular types of copper, high conductivity, phosphorus deoxidised and oxygen-free, each suitable for earthing applications. In addition, there are a wide variety of less-common high conductivity copper alloys with improved properties for special applications.

12.1.1 High conductivity coppers

High conductivity (HC) copper, with a nominal conductivity of 100% IACS (International Annealed Copper Standard), is first choice material used for electrical applications such as earthing strip and wire, busbars, cables and windings for motors and transformers. It was designated C101 in British Standards, Cu-ETP in BS EN specifications and CW003A and CW004A in the BS EN computer designations. HC copper is very readily worked hot and cold. In annealed form, it has excellent ductility which means that it can easily be bent to shape. It is available in all fabricated forms.

It work hardens relatively slowly and can be annealed in neutral or oxidising atmospheres. Oxygen is intentionally present in HC copper to combine with residual impurities so that they have no effect on conductivity. This oxygen can be reduced to steam if copper is annealed in atmospheres containing excess hydrogen, causing embrittlement. 'Bright' annealing atmospheres therefore have to be carefully controlled.

Most copper is now cast continuously and the desirable oxygen content is reduced. In cast form, copper has a slightly lower conductivity than that after being worked and annealed. Adding small quantities of silver to copper improves its elevated temperature properties, especially creep strength.

12.1.2 Deoxidised copper

The use of deoxidants when casting copper ensures that excess oxygen is removed. This produces a material that can readily be brazed or welded without fear of embrittlement. Phosphorus is the preferred deoxidant and when used the conductivity of copper is slightly reduced. This copper, termed C106 (Cu-DHP, CW024A), sometimes also called ‘DONA copper’, is used in tubes for fresh water services. It is also available in rod, sheet and strip form. The phosphorus content reduces conductivity to about 92% of that of HC copper for the minimum of 0.013% or to 73% if at the maximum of 0.05% phosphorus. This is still a better conductor than many other materials. For castings, boron is frequently used as a deoxidant and many other additions also have a deoxidising effect.

12.1.3 Oxygen-free High Conductivity copper

Designated C103, (Cu-OF, CW008A), this copper is made only by casting in a controlled atmosphere. It can subsequently be worked exactly as normal high conductivity copper. It is used for applications where high conductivity of over 100% IACS is required in addition to freedom from the possibility of embrittlement in reducing atmospheres. It may be welded or brazed without the special precautions needed for normal high conductivity copper, C101 (Cu-ETP, CW003A & CW004A). There is a grade of higher purity still, C110 (Cu-OFE, CW009A) that is normally only required for high-vacuum electronic applications such as transmitter valves. This is certified to have a very high purity and low residual volatile gases. Oxygen free coppers are suitable for earthing applications but, depending on production volumes, may sometimes command a premium price.

12.1.4 High Conductivity copper alloys

For electrical applications such as resistance welding electrodes where service is at high temperatures under heavy stress, special alloys are available. The most popular of these is copper-chromium, CC101 (CW105C), which contains up to 1% of chromium and is fully heat treatable to room temperature properties which are maintained as the operating temperature rises. Conductivity is around 80% IACS, which means that the material is not often used for earthing, but is suitable for applications such as rotor rings for use in heavy-duty rotating electrical machines.

Further details of all these materials are available in the CDA Technical Note TN 29 'High Conductivity Coppers, referred to in chapter 16.

12.2 Standard Copper Designations

The product forms covered by the BS designations contain compositions, specified mechanical properties, dimensional tolerances and special test methods. These are shown in Table 12-1.

12.2.1 BS EN Standards

European standards are produced for relevant copper product forms and become British Standards with a ‘BS ENxxxxx’ number. Eventually there will be no differences between national standards for these materials.

In the new BS EN standards the opportunity has been taken to consider and include the materials and requirements most commonly needed. Each document forms a complete product standard, so there is no need to cross-refer between separate documents covering compositions, properties, tolerances etc.

In addition to the use of the International Standards Organisation (ISO) compositional designation system, there is a new common numbering system for coppers and copper-based materials. This is much more easily identifiable by computer database systems.

CDA Publication TN 10 gives a useful cross-reference between the different numbering systems.

American standards and UNS numbering system for metals remain unaffected in the foreseeable future. For coppers and copper alloys, the UNS numbering system is administered by CDA (Inc.), New York.

Table 12-2 shows the wrought coppers and copper alloys most common in Europe and being included in the BS EN standards, together with their designations and proposed material identification numbers.

Table 12-1 Present British Standards for Copper and copper Alloys for general and electrical purposes

Copper Refinery Shapes		
Current Standard		Subject
6017		Copper Refinery Shapes (This standard is also occasionally referred to when copper is being ordered by composition only, with no mandatory properties)
Copper and Copper Alloys for General Purposes		
Current Standard		Subject
1400		castings
3146		investment castings
2870		sheet, strip and foil
2871	Part 1	copper tube for water, gas and sanitation
	Part 2	copper and copper alloy tube for general engineering
	Part 3	copper and copper alloy tube for heat exchangers
2872		forging stock and forgings
2873		wire
2874		rods, bars and sections
2875		plate
Copper for General Electrical Purposes		
Current Standard		Subject
159		busbars and busbar connections
1432		strip with drawn or rolled edges
1433		rod and bar
1434		commutator bar
1977		high conductivity tubes
3839		oxygen free high-conductivity copper (electronic grade)
4109		wire
4608		rolled sheet, strip and foil
6929		high conductivity copper wire rod

12.3 Properties

The properties of copper and some other materials are shown in tables 12.3, 12.4 and 12.5. The properties which are more relevant to earthing are now discussed below.

12.3.1 Electrical conductivity and resistivity

The mandatory electrical property for high conductivity copper is now mass resistivity for which the unit $\Omega g/m^2$ is used. This property is chosen because it can be the most accurately measured. It is shown in BS 5714 that the error in measurement of mass of small sections such as wire or strip is likely to be less than that for volume. The use of volume measurements quoted in IEC publication No. 28 (1913) assumes a standard density for copper in the wrought form used for the test of 8.89 grams per cubic centimetre (g/cm^3). This was valid when originally published in 1913 when oxygen contents were typically 0.06%.

Modern coppers now contain only about 0.02% oxygen, so the density is nearer 8.91 g/cm³. For oxygen-free coppers 8.94 g/cm³ is more realistic.

The values given in Table 12-5 for volume resistivity and conductivity are interpreted using the IEC standard density value of 8.89 g/cm³ which may be subject to revision. Conductivity values are shown in both SI units of Siemens per metre and "per cent IACS (International Annealed Copper Standard)", this latter being the traditional way of comparing the conductivity of other metals and copper alloys with high conductivity copper. With the improvements in purity previously mentioned, most commercial high conductivity copper has a conductivity around 101.5% IACS in the annealed state. Work hardened material will have a lower value due to internal strain effects. Cast material also has a lower value due to grain boundary and porosity effects.

For high conductivity copper, electrical conductivity checks are carried out in rod mill laboratories on samples drawn to 2 mm diameter and given a specified anneal. An accurately calibrated Kelvin double resistance bridge is usually used for the measurement.

Conductivity measurements made on larger sections or by other techniques are generally less accurate. Tests made using an eddy-current instrument are normally accurate to about ±3% on flat surfaces.

12.3.2 Thermal conductivity

Thermal conductivity is rarely measured routinely but can be taken as being proportional to electrical conductivity with the effects of alloying additions, temper and temperature.

12.3.3 Temper designations

The types of copper preferred are to BS 1432 (annealed), BS 125

Copper strip for use below ground is normally required to be soft so that it can easily be bent around obstructions. For above ground use, harder material is required such that shape will be maintained on structures. This property is also necessary to avoid movement due to the mechanical forces which accompany the passage of sudden, large electrical currents.

12.3.4 Tensile strength

Properties quoted in standards are normally minima typical for the size and temper stated and are for quality control purposes. They are suitable for use in designing for general engineering applications. For particular requirements, realistic typical figures can generally be obtained from the manufacturers at the time of discussing an order. For economically large quantities it may be possible to meet special requirements for any properties.

Table 12-2 New BS EN designations for Wrought Coppers

The shaded materials are those most often used. Materials standardised are marked '*' and '0', those with the '0' being most easily available.

Alloy Designation			Common British Description	Typical properties			Remarks	Availability					
ISO/CEN Designation	Nearest BS equivalent	Proposed EN Number		Tensile strength N/mm^2	Elongation %	Hardness HV		Tube	Rod	Forg-ings	Prof-iles	Wire	Plate sheet strip
Cu-ETP	C101 & C100	CW003A	Electrolytic, tough pitch high conductivity copper	200-360	42-3	40-110	High conductivity copper for strip, rod, wire and other fabricated electrical components. C100 is standardised only for high conductivity rod for electrical applications but satisfies the requirements of Cu-ETP.	*	O	*	O	O	*
Cu-Ag(0.04)	C101	CW011A	Silver bearing copper	200-360	42-3	40-110	Silver improves creep strength and raises softening temperature. Available to special order to same standards as Cu-ETP.	*					
Cu-Ag(0.07)		CW012A					ditto	*					
Cu-Ag(0.10)		CW013A					ditto	*					
Cu-FRHC	C102	CW005A	Fire refined, tough pitch, high-conductivity copper	200-360	42-3	40-110	Not commonly available but C101 satisfies the requirements.	*				*	
Cu-HCP		CW021A		200	30	40	Deoxidised copper with good conductivity.	*		*			
Cu-DLP		CW023A	Low phosphorus deoxidised copper	200-360	42-3	40-110	Deoxidised copper with good conductivity.		*		*		*
Cu-FRTP	C104	CW006A	Tough pitch, non-arsenical copper	200-360	42-3	40-110	General engineering and building applications where high electrical conductivity is not required. Oxygen content will cause embrittlement if heated in a reducing atmosphere.		*				*

Alloy Designation			Common British Description	Typical properties			Remarks	Availability					
ISO/CEN Designation	Nearest BS equivalent	Proposed EN Number		Tensile strength N/mm^2	Elongation %	Hardness HV		Tube	Rod	Forg-ings	Prof-iles	Wire	Plate sheet strip
Cu-DHP	C106	CW024A	Phosphorus deoxidised non-arsenical copper	200-400	42-3	40-110	General engineering applications where highest conductivity not required. No oxygen, therefore no embrittlement.	O	*	*	*	*	*
Cu-OF	C103	CW008A	Oxygen free, high conductivity copper	200-360	30-10	40-100	High conductivity. Does not suffer from embrittlement when heated in reducing atmosphere.	*		*		*	

12.3.5 Other properties

- **Elongation**. As with tensile properties, elongation figures in specifications are typical minima. It must be remembered that, as the tensile strength or hardness of a material is increased by cold working, so the elongation generally decreases. Elongation is normally measured on a length of $5.65\sqrt{So}$, So being the cross sectional area of the section of a proportional test piece.
- **Hardness** Hardnesses of cast coppers and copper alloys are generally measured using the ball indenter technique of the Brinell method because of the need to cover a representatively large area. Hardnesses of wrought materials are usually measured using the diamond indenter of the Vickers method which makes a smaller impression. Comparisons between these two techniques should be used with caution and comparative tests on actual components are needed for verifying conversions. Similar considerations apply to the relationship between hardness and tensile strength. For high conductivity copper alloys, BS 4577 includes a useful appendix showing approximate conversions and the scatter of results found.
- **Compressive Strength.** This property is not often measured directly, but it may be roughly estimated that the stress for 0.2% permanent set in compression is equal to the 0.2% proof stress.
- **Shear Strength**. This property is also rarely measured, but, for sheet and strip, shear strength may be estimated at two thirds of the tensile strength.
- **Proof Stress**. Typical values can be obtained from manufacturers. Proof stress values quoted in documents are usually given relative to either 0.1 or 0.2% permanent deformation, the latter being more common. Conversions should be used only where calibrated curves or tables are available relevant to the material.
- **Properties at Elevated Temperatures**. Coppers and copper alloys can all be used at temperatures well above ambient. Maximum working temperature depends on composition, stress and time at temperature. Coppers can be used at temperatures over 100^{o}C for many years. Alloyed coppers such as copper-chromium and copper-beryllium can be used at much higher temperatures.
- **Properties at Low Temperatures**. Coppers and copper alloys do not become brittle at low temperatures.

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Table 12-3 Typical Properties of High Conductivity Copper and Aluminium

Property	Unit	Copper	Aluminium
Electrical conductivity (annealed)	% IACS	101	61
Electrical resistivity (annealed)	μΩcm	1.7241	2.826
Temperature coefficient of resistance (annealed)	/°C	0.0039	0.004
Thermal conductivity at 20°C	W/mK	397	230
Coefficient of expansion	/°C.10^6	17	23
Tensile strength (annealed)	N/mm^2	200-250	55-60
Tensile strength (half hard)	N/mm^2	260-300	85-100
0.2% proof stress (annealed)	N/mm^2	50-55	20-30
0.2% proof stress (half hard)	N/mm^2	170-200	60-65
Elastic modulus	MN/mm^2	118-130	70
Specific heat	J/kgK	385	900
Density	g/cm^3	8.91	2.70
Melting point	°C	1063	660
Fatigue strength (annealed)	N/mm^2	62	35
Fatigue strength (half hard)	N/mm^2	117	50

For copper, many properties such as strength, conductivity and fatigue strength are significantly better than that of aluminium. The density difference means that for a given conductor rating the size of aluminium will be greater but still lighter. However, copper needs fewer supports to restrain it which can affect installation economics. The capability of copper to absorb heavy electromagnetic and thermal stresses generated by heavy currents gives a considerable factor of safety, as does the ability to resist mechanical or thermal cycling.

Table 12-4 Comparison of Creep Properties

Material	Testing temperature ^oC	Min Creep Rate % per 1,000 hrs	Stress N/mm^2
Aluminium	20	0.022	26
Copper	150	0.022	26
Copper - 0.086% silver	130	0.004	138
Copper - 0.086% silver	225	0.029	96.5

High conductivity aluminium shows evidence of significant creep at ambient temperatures if heavily stressed whereas copper can be used at up to 150^{o}C at the same stress level, a temperature often used for electrical equipment. For even higher temperatures or stresses copper-silver can be used without significant loss of conductivity. (Note: The values shown are typical for electrolytic tough pitch high conductivity copper (C101) usually used for earthing purposes. Values for other grades of copper may differ from those quoted.

Table 12-5 Physical properties of copper

Property		
Atomic number	29	
Atomic weight	63.54	
Lattice structure:	face centred cubic	
Density: standard value (IEC)	8.89	g/cm^3
Density: typical value	8.92	g/cm^3
at 1083°C (solid)	8.32	g/cm^3
at 1083°C (liquid)	7.99	g/cm^3
Melting point	1083	°C
Boiling point	2595	°C
Linear coefficient of thermal expansion at:		
-253°C	0.3×10^{-6}	/°C
-183°C	9.5×10^{-6}	/°C
-191°C to 16°C	14.1×10^{-6}	/°C
25°C to 100°C	16.8×10^{-6}	/°C
20°C to 200°C	17.3×10^{-6}	/°C
20°C to 300°C	17.7×10^{-6}	/°C
Specific heat (thermal capacity) at:		
-253°C	0.013	J/g°C
-150°C	0.282	J/g°C
-50°C	0.361	J/g°C
20°C	0.386	J/g°C
100°C	0.393	J/g°C
200°C	0.403	J/g°C
Thermal conductivity at:		
-253°C	12.98	Wcm/cm^2 °C
-200°C	5.74	Wcm/cm^2 °C
-183°C	4.73	Wcm/cm^2 °C
-100°C	4.35	Wcm/cm^2 °C
20°C	3.94	Wcm/cm^2 °C
100°C	3.85	Wcm/cm^2 °C
200°C	3.81	Wcm/cm^2 °C
300°C	3.77	Wcm/cm^2 °C
Electrical conductivity (volume) at:		
20°C (annealed)	58.0-58.9	MS/m (m/Ohm mm^2)
20°C (annealed)	100.0-101.5	% IACS
20°C (fully cold worked)	56.3	MS/m (m/Ohm mm^2)
20°C (fully cold worked)	97.0	% IACS

Electrical resistivity (volume) at:		
20°C (annealed)	0.017241-0.0170	Ohm mm²/m
20°C (annealed)	1.7241-1.70	μΩ cm
20°C (fully cold worked)	0.0178	Ohm mm²/m
20°C (fully cold worked)	1.78	μΩ cm
Electrical resistivity (mass) at:		
20°C (annealed) Mandatory maximum	0.15328	Ωg/m²
Temperature coefficient of electrical resistance (a) at 20°C:		
annealed copper of 100% IACS (applicable from -100°C to 200°C)	0.00393	per °C
fully cold worked copper of 97% IACS (applicable from 0°C to 100°C)	0.00381	per °C
Modulus of elasticity (tension) at 20°C:		
annealed	118,000	N/mm²
cold worked	118,000-132,000	N/mm²
Modulus of rigidity (torsion) at 20°C:		
annealed	44,000	N/mm²
cold worked	44,000-49,000	N/mm²
Latent heat of fusion	205	J/g
Electro chemical equivalent for:		
Cu^{++}	0.329	mg/C
Cu^{+}	0.659	mg/C
Normal electrode potential (hydrogen electrode) for:		
Cu^{++}	-0.344	V
Cu^{+}	-0.470	V

12.4 Joining Coppers

Table 12-6 shows that coppers can be easily joined by soldering, brazing and welding. Some care is needed with C101 HC copper that it is not heated in a reducing atmosphere such as that in most gas torch flames or controlled atmosphere furnaces. The reason for this is that the high conductivity is ensured by the presence of small particles of copper oxide in the metal. They absorb impurities during solidification, preventing them from adversely affecting conductivity. The copper oxide can be reduced, one of the products of the reaction being steam which expands and embrittles the copper. The use of conventional gas shielded arc processes (Tungsten Inert Gas [TIG] or Metal Inert Gas [MIG]) avoids the problem.

Since copper has such a high conductivity for heat as well as electricity, care must be taken to ensure plenty of heat input to ensure full melting and adhesion of solder, brazing filler or weld metal. For soldering and brazing, usual precautions should be taken to clean and flux the surface. Further details of recommended joining practice are included in CDA Publication No 98.

Table 12-6 A Guide to the suitability of joining processes for coppers

BS designation	C101	C106	C103
BS EN designation	Cu-ETP	Cu-DHP	Cu-OF
Proposed EN designation	CW003A & CW004A	CW024A	CW008A
Type of copper	High conductivity Copper	Deoxidised Copper	Oxygen-free copper
Soldering	1	1	1
Brazing	2	1	2
Bronze welding	X	2	3
Oxy-acetylene welding	X	2	X
Gas shielded arc welding (TIG & MIG)	3	1	X
Manual metal arc welding	X	X	X
Resistance welding	X	2	X
Cold pressure welding	2	2	2

Key 1 - Excellent
2 - Good
3 - Fair
X - Not recommended, though may be possible.

13 Measuring the Impedance of Earth Electrode Systems

13.1 Introduction

Measurement of the Ohmic value of a buried electrode is carried out for two reasons:-

- To check the value, following installation and prior to connection to the equipment, against the design specification.
- As part of routine maintenance, to confirm that the value has not increased substantially from its design or original measured value.

The most common method of measuring the earth value for small or medium sized electrodes is known as the "fall of potential" method; described in detail in section 13.4. For this method to be successfully applied at large area sites, test leads may be required to be routed to 8 00m or even 1,000 m away and at many locations this is not practicable. Other methods may then have to be used and some of these are described briefly in section 13.5.

13.2 Equipment Required

For small and medium sized electrode systems, a normal four-terminal composite earth resistance tester is suitable. This may be the same instrument as used for soil resistivity measurement. There are two potential terminals P1 and P2, and two current terminals C1 and C2. As part of the package, the manufacturer normally provides four earth spikes and some drums of trailing lead. Composite instruments normally only measure the resistive value of the electrode impedance.

To protect the instrument against possible over-voltage during the test period, modern instruments include a 100 mA fuse in the test lead circuits (terminals C2 and P2). If the instrument is not provided with these fuses, it is recommended that they be connected externally.

For large electrode systems, more sophisticated equipment is normally required. This has to measure quite small impedances and will have to pass more current than the composite instrument. Discrete components, which include a power amplifier, a variable frequency source and frequency selective measurement instruments are normally required.

13.3 Safety

The test procedure involves bringing a connection from remote earth spikes which are at or about true earth potential, into the area immediately adjacent to the electrode to be measured. Whilst testing is taking place, should an earth fault occur which involves equipment connected to the main electrode, the potential on and around the electrode would rise. For small electrodes, this may not introduce any significant difficulty. However, in larger electrode systems or those associated with power networks, the voltage rise may be significant. Depending on the stage of testing at that time, one of those persons carrying this out may be subjected to a possibly dangerous potential difference, say between hands. To ensure that this does not occur, a rigorously policed safety procedure is required which includes the following elements:

- One person in charge of work.
- Communication between those carrying out the tests, via radio or portable telephone.
- Use of rubber gloves and adequate footwear.
- Use of a suitably voltage rated ganged double switch to which the trailing leads are connected to the instrument.

- Use of a metal plate to ensure equipotentials in the test position. The plate should be large enough to house the instrument, switch and operator during the test. It should have a terminal installed, so that the plate can be bonded to the electrode.
- Postponement of testing during lightning or other severe weather conditions.

13.4 Measurement of Small and Medium Sized Electrodes

The method normally used is the "fall of potential" method. The procedure recommended is as follows:-

- The plate is placed at the test position. The instrument, switch and (if appropriate) the fuses, should also be placed on the plate. The P1 - C1 terminals of the tester should each be connected to the electrode to be tested and one connection made to the plate.
- The current spike should normally be installed a minimum of 100 m away, at least five times the largest dimension of the electrode system being measured. When measuring the resistance of a few earth rods, then a distance of 40 m to 50 m may be sufficient. The current spike position should be preferably across open ground or fields, chosen such that a line between the spike and the test position will cross, rather than run parallel to, existing cable routes or other buried metal pipes.
- The voltage spike should be positioned approximately 2m away from the line between the test point and the current spike, initially at a distance of 61.8% of that between the test point and the current spike. (Note:- The reason for choosing 61.8% distance is based on mathematical theory, applied to soil of uniform resistivity).
- Trailing leads should then be run out between the instrument at the test point and the two spikes and be connected to them. With the ganged switch open, the trailing leads should be connected to the switch, which is then connected to the P2-C2 terminals of the instrument.
- The operator should stand with both feet on the plate. Having informed the other persons involved, the ganged switch is closed, the test instrument operated and the reading taken. The switch is then re-opened.
- This procedure should be repeated, with the voltage spike first moved to a position 10m nearer to the test position and then 10m nearer to the current spike. If the three readings are within 5% of each other, the 61.8% reading may be accepted as a representative value.
- If the readings vary outside 5%, then the procedure must be repeated, with the current spike at a new position, normally further away than for the previous test.

The most common cause of error arises due to placing the current spike too close to the electrode under test. The influence of the earth electrode and current spike will overlap and the measured resistance will normally be a lower value than the real one. The second most common mistake is placing the voltage spike too close to the test electrode which produces a much lower reading than the true value. Other sources of error include not accounting for buried metal which is in parallel with the test traverse, having the voltage and current leads too close together and damage to the trailing lead insulation.

The theory (and hence the 61.8% rule) does not hold if the soil is not uniform, the grid is large or (as stated above) the current electrode is too close. Computer simulation can assist here, by predicting the distance from the grid at which the voltage spike can be positioned to obtain the actual impedance.

In practice, the measured value may be considerably lower than the design value predicted for the electrode system, because there may now be a number of parallel electrode paths connected, including the sheaths of underground cables etc.

13.5 Measurement of Larger Area Electrode Systems

The fall of potential method can be used on larger electrode systems, but it is suggested that the current electrode is positioned at a distance of between six and ten times that of the diagonal distance across the electrode system. This is not normally practical, so several derivatives of the fall of potential method have been developed. These include the slope method (where the gradients between adjacent measurement points are computed) and the intersecting curves method.

In another variation of the test, the voltage spike is moved out at right angles to the grid/current spike traverse. The distance of the spike from the grid is progressively increased until the measured value barely changes. This figure should then be just below the actual electrode impedance.

If metallic underground pipes or cables are running in the same direction as any of the test routes, this will again produce an incorrect earth reading.

Where the earth grid is large or has long radial connections, e.g. to cables or tower line earth wires, the resulting size of the earth grid is so large that traditional fall of potential measurement is impractical. Estimation can still sometimes be achieved by a series of on site measurements backed up by computer simulation.

Another method is called high current injection where several hundred Amperes are passed into the electrode system using a power circuit and another electrode system some distance away. The actual rise of potential is measured by reference to a remote electrode (normally via a metallic telephone circuit), from which the electrode impedance can be calculated. However, this method is costly to carry out and can still be subject to errors. One common error is not accounting for the impedance of metallic circuits which interconnect the two electrode systems being used (communication circuits, low voltage interconnection etc.).

14 Artificial Method of Reducing Earth Resistivity

14.1 Introduction

This chapter is to describe briefly the conditions in which additives can help in reducing the earth impedance. Some salts are naturally occurring in the soil, but those considered here are deliberately added with the intention of changing the resistivity of the soil in the vicinity of the electrode. In general, despite the generally held belief to the contrary, the number of real applications for additives are quite small and this is an over-emphasised option. Some of the additives used in the past have been corrosive and if used now could cause environmental difficulties.

In old (1930's) books on earthing, it is sometimes suggested that the resistance of electrodes can be decreased by up to 90% by chemical treatment. The chemicals traditionally recommended and used were sodium chloride (salt), magnesium sulphate (epsom salts), copper sulphate, sodium carbonate (washing soda) and calcium chloride. In most cases the cheaper chemicals were used. They were spread around the electrodes and dissolved by adding water before backfilling or it was left for natural waterflow (rain etc.) to dissolve them. The chemicals have the effect of reducing the resistivity of the surrounding soil. The new resistivity can fall to 0.2Ω-m using washing soda (sodium carbonate) or to 0.1Ω-m using salt. A particularly high concentration of dissolved salts is not necessary to see an appreciable reduction in resistivity, for example:

1.2 g/litre salt in distilled water has a resistivity of 5Ωm.

6 g/litre salt in distilled water has a resistivity of 10Ωm.

This reduction in soil resistivity will, in turn, reduce the impedance of the electrode system. The improvement depends mainly on the original resistivity of the soil, its structure and the size of the electrode system. However, since the chemicals used are chosen because they are soluble, they will continue to be progressively diluted by rainwater or movement of water through the area. The soil resistivity will then increase, until eventually it returns to its former value. This was recognised and the time for this to occur is sometimes only a few months. Regular maintenance and replenishment of the undiluted chemicals was recommended and sometimes a refillable man-hole was provided in which to place the chemicals. It has sometimes been the practice in some establishments to add chemicals just before an annual test measurement, but this does not help the earthing system perform its function correctly during the rest of the year when it may be required to deal with fault current.

In addition to the maintenance cost, the impact on the local environment should be considered and may conflict with the Environmental Protection legislation. Some of the chemicals used (such as salt) are known to cause rapid corrosion of the electrodes themselves - particularly steel, thereby reducing the available life of the installation. Indeed, in some of the older arrangements, this risk was recognised and pipe placed around some sections of the electrode to protect it - thereby reducing its effectiveness!

The actual effect on the resistance of the electrode may not be as dramatic as originally thought and to put this into perspective, reference back to Figure 6-5 in chapter 6 shows the actual effect of increasing the diameter of the electrode. The chemicals need to extend the effective volume of the electrode significantly to have a noticeable effect. As mentioned in chapter 6, there is a contact resistance between the electrode and the soil. Where a new rod has been driven into the ground, the sideways movement will have increased the width of the hole in which the rod lies. The gap between the rod surface and the compressed soil to its side will introduce a large contact resistance which will be apparent when testing the resistance of the rod.

Pouring a mixture of chemicals and soil into the area around the rod will provide an immediate and significant reduction in the rod's resistance. However, its resistance would fall anyway as the surrounding soil consolidates due to rainfall etc. A more environmentally acceptable way to accelerate this effect is to add a low resistivity material, such as Bentonite slurry, as the rod is driven in. As the earth electrode is driven into the soil the Bentonite is drawn down by the rod. By continuously pouring the mixture into the hole during the driving process, a sufficient quantity is dragged down to fill most of the voids around the rod and lower its overall resistance. Installing the rod a little deeper can sometimes achieve the same or a better, more permanent result than using low resistivity backfill material.

Adding Bentonite and similar materials, such as Marconite, in a trench or larger drilled hole around the electrode has the effect of increasing the surface area of the earth conductor, assuming the resistivity of the added material is lower than that of the surrounding soil.

14.2 Acceptable Low Resistivity Materials

As mentioned previously, fine sieved soil or garden loam is normally a suitable backfill material to surround the buried electrode. For special situations, there are a number of materials as follows:

14.2.1 Bentonite

This is a natural forming, pale olive brown clay which is slightly acidic, having a pH of 10.5. It can absorb nearly five times its weight of water and in so doing, can swell up to thirteen times its dry volume. Its chemical name is sodium montmorillonite. When in situ, it can absorb moisture from the surrounding soil and this is the main reason for using it, since this property helps stabilise the electrode impedance throughout the year. It has a low resistivity - approximately 5 Ohm-metres, and is non-corrosive. Under extremely dry conditions, the mixture can crack thereby affording little contact to the electrode. Fortunately the weather conditions in the UK are such that this is not normally a problem. Bentonite is thixotropic in character and therefore gels when in an inert state, so should not leach out. Bentonite is most often used as the backfill material for deep driven rods. It is easily compacted and adheres strongly.

14.2.2 Marconite

It is essentially a conductive concrete, in which a carbonaceous aggregate replaces the normal aggregate used in the concrete mix. It has some similar properties to Bentonite, i.e. causes little corrosion with certain metals and has a low resistivity. It was developed as a process which started in 1962 when Marconi engineers sought a material which conducted by movement of electrons rather than ions. It contains a crystalline form of carbon and the overall material has a low sulphur and chloride content.

There is stated to be some corrosion of ferrous metal and copper whilst the Marconite is in slurry form, but it is suggested that a thin protective layer forms. When the concrete has set, corrosion is said to cease. Metal should ideally be painted with bitumen or a bitumastic paint as it enters the Marconite structure to prevent corrosion at this point. Aluminium, tin coated or galvanised steel should not be installed in Marconite.

When Marconite is mixed with concrete, its resistivity can fall to as low as 0.1 Ohm-metre. It will retain its moisture even under quite dry conditions, so has been used in the hotter climates as an alternative to Bentonite. Its principle application in the UK is at locations where theft or third party interference is likely to be a problem, or to enclose electrodes in holes or voids within rock. When surrounding an earth rod with Marconite which has been installed in rock, the resistance of the rod will be reduced as the volume of Marconite used is increased.

For example, if a 1 m rod is installed at the centre of a hemisphere of Marconite of radius 1.5m, it would have a resistance of approximately 2,000 Ohm if the surrounding rock is of 2,000 Ohm-metres. If the radius of the hemishere is increased to 3 m and then 5 m, the resistance would fall to 1,080 Ohm and 650 Ohm respectively. Because of the prohibitive cost of removing such a volume of rock, it makes sense to make use of existing cavities for this purpose, where possible. Also, the void is likely to be part filled with other materials (such as concrete) to reduce the amount of proprietary material required. Marconite is normally considered as having a resistivity of 2 Ohm-metres.

Marconite is also sometimes used for anti-static flooring and electro-magnetic screening.

Note that Marconite is a registered trade mark of Marconi Communication Systems Limited.

14.2.3 Gypsum

Occasionally, calcium sulphate (gypsum) is used as a backfill material, either by itself or mixed with Bentonite or with the natural soil from the area. It has low solubility, hence is not easily washed away, and has a low resistivity (approximately 5-10 Ohm-metres in a saturated solution). It is virtually neutral, having a pH value of between 6.2 and 6.9. It is naturally occurring, so should not generally cause environmental difficulties in use. It is claimed that it does not cause corrosion with copper, although sometimes the small SO_3 content has caused concern about its impact on concrete structures and foundations. It is relatively inexpensive and is normally mixed with the soil forming the backfill around the earth electrode. The particle size is similar to coarse sand.

It is claimed that it assists in maintaining a relatively low resistivity over a long period of time, in areas where salts in the vicinity are dissolved away by water movements (rainfall etc.). However, the fact that the material is not easily dissolved will moderate the benefits achieved, since it will not permeate far into the ground. This means that the beneficial effect will be localised for say an area excavated around a buried electrode. This in turn means that the reduction in the resistance value of the electrode will not be dramatic but will be reasonably sustainable.

14.2.4 Others

Additional materials are often being introduced, for example a copper solution which when mixed with other chemicals creates a gel. These must satisfy environmental legislation and it is important to confirm the situations in which improvements in the electrode impedance can be expected when such products are used.

14.3 Unacceptable Backfill Materials

Some power station ash and clinker have been used in the past, when it was thought that their carbon content would be beneficial. Unfortunately, these materials may contain oxides of carbon, titanium, potassium, sodium, magnesium or calcium, together with silica and carbon. In moist conditions, some of these will almost inevitably react with copper and steel to cause accelerated corrosion.

15 Maintenance of Earthing Systems

15.1 Introduction

Where an electricity supplier provides an earth terminal at a premises, maintenance of the earthing and bonding system is confined to maintenance of the conductors and connections which form part of that system.

At special locations, e.g. on an IT or TT system, the occupant/owner is required to provide an independent earth electrode, and any maintenance procedure must include this electrode.

For electricity suppliers, or other owners of distribution networks, maintenance of their earthing and bonding systems involves work on both the bonding conductors above ground and the buried electrode. For the electrode, testing from above ground has been the accepted method of verifying its condition. However, as explained in chapter 11, corrosion can take place on some electrode components or joints. A test of the earthing system impedance will not necessarily detect this corrosion and is not, on its own, sufficient to indicate that the earthing system is adequate.

For electrode systems associated with the higher voltage networks, selected excavation and inspection of electrode systems is now recommended.

15.2 The Philosophy of Maintenance

Maintenance of earthing systems normally forms part of the maintenance of the overall electrical system. The quality and frequency of the maintenance should be sufficient to prevent danger, so far as is reasonably practicable. Recommendations on the type of maintenance required and the frequency for various types of installation can be found in the following documents:

- For domestic and commercial premises, in BS 7671.
- For factories, the HSE. has issued a "Memorandum of Guidance on the Electricity at Work Regulations 1989". In Appendix 2, a list is given of the various documents which should be referred to for a variety of specialist applications.
- The Electricity Supply Regulations, 1988 as amended, impose a duty on Electricity Suppliers to inspect their installations and works.

The frequency of maintenance and the recommended practice at any installation depend upon the type and size of the installation, its function and its voltage level. For example, it is recommended that domestic premises are tested every five years and industrial premises every three. Places with public access require more frequent inspection and those requiring an annual inspection include petrol stations, caravan sites, theatres, cinemas and launderettes. All forms of installation should be subject to two types of maintenance.

- Inspection, at frequent intervals, of those components which are, or can readily be made, accessible.
- Examination, to include a more thorough inspection than that possible by inspection, possibly including testing.

15.3 Inspection

Inspection of the earthing system at an installation normally takes place in association with visits for other maintenance work. It consists of a visual inspection only of those parts of the system which can be seen, particularly looking for evidence of decay, corrosion, vandalism or theft.

The following summarises the procedure at differing installations:-

- Domestic, Commercial Premises. Inspection normally takes place in association with other work on the premises, e.g. upgrading, extensions etc. An electrical contractor should not only thoroughly inspect, but also recommend changes where it is clear that an installation does not meet the standards required by BS 7671. A particular check recommended is to ensure that the bond between the supplier's and customer's earth terminals is of sufficient size to satisfy the regulations.
- Factories. Regular inspection of the electrical installation is recommended under the Electricity at Work Regulation 1989. A record should be maintained of the date and findings of each inspection.
- Installations with lightning protection. Again a regular inspection is recommended, and should be documented, to comply with BS 6651.
- Electricity company or industrial distribution substations. These require regular inspection, typically once a year, with the earthing arrangements being visibly inspected. Where the low voltage network is overhead, the earthing system on the network is checked as part of the regular line patrols.
- Electricity company main substations. These are continuously monitored from remote control rooms and inspected frequently - typically 6 to 8 times a year. Obvious examples of earthing system deficiency, such as that due to theft of exposed copper earthing conductors, if not detected by the continuous monitoring, would be identified during one of these visits.

15.4 Examination

Examination of an earthing system normally takes place as part of the examination of the whole electrical system.

The examination consists of a very thorough, detailed inspection of the whole earthing system. Apart from looking for the obvious, the examiner will check whether the system meets the current earthing standard. In addition to this thorough inspection, the system must be tested, as indicated, at the following types of installation.

- Domestic, Commercial Premises. Examination of these installations by an electrical contractor is normally made at the request of the customer. BS 7671 recommends that this is carried out not less frequently than once every 5 years. BS 7671 also recommends that all extraneous non-conductive metalwork, including gas, hot and cold water, central heating etc. pipework should be bonded together and then connected to the customer's earth terminal, with conductors of adequate size.
- Two separate test are required as part of the examination:

    An earth loop impedance test. Commercial testers are available for this purpose.

    A function test on all RCDs in the installation. This test has to be independent of the built-in push button on the RCD.

- Factories. Examination is required regularly according to the type of installation. A detailed record should be kept at each examination. The examiner will check that the existing earthing system complies with current Regulations.

    The following tests are required on the earthing system:-

    An earth loop impedance test.

    A function test on all RCDs installed.

A bonding test on all extraneous non-conductive metalwork, e.g. the metal enclosures, control cabinets, vending machines etc. This is carried out using a low resistance measuring (micro) Ohmmeter and the test is required between the customer's earth terminal and all extraneous non-conductive metalwork.

Earth Electrode Resistance. Should the installation have its own independent earth electrode, then as part of examination the value of this electrode should be measured and compared with its design value. This may mean isolating the earth electrode, and may thus require that the supply is switched off during the period of the test.

Installations with Lightning Protection. Examination is recommended to meet the requirement of BS 6651. As well as a very thorough inspection, to ensure that the installation complies with the current Regulations, the following testing is required.

> **Earth Electrode Value**. The value of the electrode should be measured. Previously this meant isolating the electrode from the main lightning protection conductors. This could not be carried out during any lightning activity and precautions were required when breaking the link between the electrode and the lightning conductors, since it was possible for an excessive voltage to appear across the open link, should there be a fault to earth on the electricity supply network. Clip on type impedance measuring instruments are now available for this and do not require the electrode to be disconnected.
>
> Once measured, the value of the earth electrode should be compared with the design value, or that obtained during the previous test.

Electricity company or industrial distribution substations. Examination is carried out less frequently - typically once every 5 or 6 years. A very thorough inspection is recommended, removing covers etc. where appropriate. The examiner is particularly required to check that the bonding of all normally accessible metalwork, transformer switchgear tanks, steel doors, steel fencing etc. meets the requirement of Technical Standard 41 - 24.

The following testing is typically carried out, with the equipment normally in commission. A special procedure has to be used to guard against possible excessive voltage occurring during the testing.

Bonding tests between the earth electrode and normally accessible metalwork.

Tracing of buried electrode and examination of this at some locations to ensure corrosion has not taken place.

The high-voltage earth electrode value is measured and compared with previous or design values.

Checking the pH value of the soil.

A separation test to ensure that the HV. electrode and LV electrodes are electrically separate. This test is not required if the design conditions permit the two electrode systems to be bonded together.

16 Further Reading

British and European standards can be obtained from the British Standards Institution, 389 Chiswick High Road, London, W4 4AL.

Engineering recommendations and technical reports can be obtained from Electricity Association Services Ltd., 30 Millbank, London, SW1P 4RD.

Standards and codes of practice

ANSI/IEEE Std. 80: 1986, IEEE Guide for safety in AC substation grounding.

ANSI/IEEE Std. 81: 1983, IEEE Guide for measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System.

BS 6651: 1992, Protection of structures against lightning.

BS 7354 1990, Code of Practice for Design of high-voltage open-terminals stations, Section 7: Earthing.

BS 7430 1991, Code of Practice for Earthing.

BS 7671: 1992, Requirements for Electrical Installations.

CLC TC/112 Chapter 9: Earthing Systems (February 1994 Draft).

DIN VDE 0141: 1989 (Technical Help to Exporters Translation) Earthing systems for power installations with rated voltages above 1 kV.

EA Engineering Recommendation S.34: 1986, A guide for assessing the rise of earth potential at substation sites.

EA ER G59, Recommendations for the connection of private generating plant to the electricity boards distribution system.

EA Technical Specification 41-24:1992 (Issued 1994), Guidelines for the design, testing and main earthing systems in substations.

ER S5/1, Earthing Installations within substations.

Memorandum of guidance on the Electricity at Work Regulations, 1989, Health and Safety Executive, ISBN 0-11-8833963-2.

The Construction (Design and Management) Regulations, 1994. Statutory Instruments 1994 No 33140.

The Distribution Code of the Public Electricity Suppliers of England and Wales, March 1990.

The Electricity Supply Regulations, 1988. Statutory Instruments 1988 No 1057.

Earthing within buildings and industry

ASEE Illustrated Guide to the IEE Wiring Regulations.

Earthing and bonding in large installations, S Benda, ABB Review, 1994.

Earthing of Telecommunications Installations, International Telegraph and Telephone Committee, 1976.

ECA/ECA of S/NICEIC Handbook on the 16th Edition of the IEE Wiring Regulations, Blackwell Scientific Publications.

Electrical Installation Technology, F G Thompson, Longman, 1992.

Grounding and Shielding in Facilities, R Morrison and W H Lewis.

IEE On Site Guide to the 16th Edition Wiring Regulations, 1992.

IEE Wiring Regulations, Explained and Illustrated, Brian Scadden, 1989.

IEEE Practice for grounding of industrial and commercial power systems, Standard 42 - 1991.

IEEE Practice for Grounding of Industrial Power Systems, IEEE Green book, Standard 141-1993.

Industrial Power Distribution and Illuminating Systems, Kao Chen.

Modern Electrical Installation for Craft Apprentices, Brian Scadden, Butterworths.

Protection against electric shock, guidance note number 5, Institution of Electrical Engineers, London.

Safety of Electrical Installations up to 1,000V, Rudolph, VDE Verlag, 1990.

The Design of Electrical Services for Buildings, F Porques, 1989.

Touch voltages in electrical installations, Jenkins, Blackwell.

Earthing within high voltage substations

J and P Transformer Book, S Austin Stigant and A C Franklin, Newnes-Butterworth, London.

Modern Power Station Practice, BEI Ltd, Third Edition.

Standard Handbook for Electrical Engineers,

Switchgear Manual, 8th Edition, ASEA Brown Boverie.

Books and papers on earthing in general

"Earthing Systems - Which Path to Follow", ERA report 93-0432, published by ERA Technology, Leatherhead.

ANSI/IEEE Std 100: 1992, New IEEE Standard Dictionary of Electrical and Electronic Terms.

Characteristics of different power system neutral grounding techniques : fact or fiction. F J Angelini and D D Ship, IEEE

Earthing Principle, and Practice, R.W.Ryder, Pitman and Sons, 1952.

Electrical Earthing and Accident Prevention, M G Say, Newnes.

Handbook of Electrical Installation Practice, Editor E A Reeves, Blackwell , Third Edition, 1996.

National Electric Code Handbook, McPartland, McGraw Hill, 1993,

Lightning

Lightning Protection for People and Property, M Frydenlund, Von Nostrand Reinhold, 1993.

Co-generation

EA ET 113, Notes of Guidance for the protection of private generating sets up to 5 MW for operation in parallel with Electricity Boards distribution networks.

Good Practice Guide 1, Guidance notes for the implementation of small scale packaged combined heat and power, Energy Efficiency Office.

Copper

Copper for Busbars, CDA publication number 22, Copper Development Association, Potters Bar, Herts. EN6 3AP.

Copper Underground : Its Resistance to Soil corrosion, (Out of print). Copper Development Association, Potters Bar, Herts. EN6 3AP.

Manufacturers publications

A Simple Guide to Earth Testing, Megger Instruments.

Earthing and Lightning Protection, Consultants Handbook, W J Furse, Nottingham.

Electronic Systems Protection Handbook, W J Furse, Nottingham.

Computer simulation of earthing systems

CDEGS suite of programmes, developed by Safe Engineering Services of Canada.

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