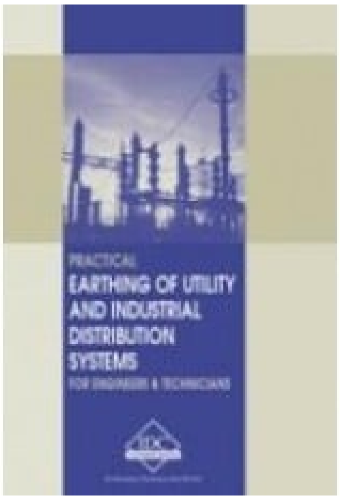
US-E - Practical Earthing of Utility and Industrial Distribution Systems



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Short Description

This manual demystifies the concepts of earthing/grounding as applicable to utility networks and industrial plant distribution systems as well as their associated control equipment. It contains sections on system earthing/grounding, protective earthing/grounding and surge/noise protection of power and electronics systems normally found in distribution networks.

A brief introduction to the design of substation earthing/grounding has been included. Detailed information on ground electrodes and measurement of earth/ground resistance is also available.

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First Chapter
An Overview - Earthing of Utility and Industrial Distribution Systems

1 Overview

This chapter contains an overview on the subject of grounding. Basic principles of grounding and their role in electrical safety are discussed. The reader will be introduced to the objectives of substation grounding design. Use of grounding in mitigating lightning effects and static accumulation is also covered. Principles of surge protection and noise control are touched upon.

Learning objectives

- Basics of grounding and its role in safety
- Bonding
- Ground electrodes, configurations and ground electrode resistance
- Grounding design of electrical substations-objective
- Lightning and grounding of lightning protection systems
- Static electricity and grounding needs for safety against static discharge
- Surge protection approach
- Noise mitigation by proper grounding practices

Important note:

The terms '*earth'* as well as '*ground'* have both been in general use to describe the common signal/power reference point and have been used interchangeably around the world in the Electro-technical terminology. However, the IEEE Green Book presents a convincing argument for the use of the term 'ground' in preference to 'earth.' An electrical 'ground' does not necessarily need to be close to the 'earth' (meaning soil). For a person working in the top floor of a high-rise building, electrical ground is far above the earth. In deference to this argument, we will adopt the term 'ground' in this manual to denote the common electrical reference point.

1.1 Introduction

The practice of grounding of electrical systems is almost as old as the development and widespread use of electric power itself. Grounding has many objectives: it provides a common point of reference to the live electrical conductors of a power supply network, it provides a path for surge currents to flow to the soil mass and it ensures safety by clamping the exposed conducting enclosure of electrical equipment at ground potential. Correct grounding practices go a long way in controlling and mitigating electrical noise, while improper grounding can result in many problems in the power system and associated control and communication systems. An engineer dealing with power supply networks needs to understand the basic principles of grounding system design and its role in ensuring safety of equipment and personnel. A correct understanding of the basic principles involved will help them to avoid mistakes in grounding system design: mistakes that could lead to expensive failures and long downtime.

In this course we will try to demystify the concepts of grounding as applicable to utility networks, industrial plant distribution systems and their associated control equipment. In fact a lot of myths have been built around this subject: however it is quite a simple one when approached from basic principles. Our endeavor is therefore to explain the fundamentals of grounding, which we hope will enable readers to gain a correct perspective of the subject, and thus give them the knowledge needed to solve real-life grounding problems.

1.2 Basics of grounding

Grounding serves the following principal purposes:

- It provides an electrical supply system with a reference to groundmass. For example, connecting a particular point of the supply source to the ground (such as the neutral of a three phase generator) ensures that any other point of the system stays at a certain potential with reference to the ground. This is called System Grounding.
- Metallic enclosures of electrical equipment are grounded to ensure that they always stay at or near ground potential and are thus safe to persons who may come into contact with them. Grounding also enables the flow of fault current in the event of a failure thus making the detection and tripping of the faulty circuit possible. This is known as Protective Grounding.
- It provides a low impedance path for accumulated static charges and surges caused by atmospheric or electrical phenomena to the ground, thus ensuring that no damage is caused to equipment and personnel.
- Correct grounding also helps in mitigating the generation and propagation

of noise emanating from the power system flowing into sensitive circuits used for control and communication.

Electrical systems were not always grounded. The first systems were ungrounded and had no ground reference at all. Even though such systems still exist in specific areas, and for specific objectives, they are the exception rather than the rule. By and large, some form of grounding is adopted for all power systems. We all know that the insulating layer around the current carrying conductors in electrical systems is prone to deterioration. Thus when a failure of insulation takes place due to aging, external factors or because of electrical or thermal stress, it is necessary to detect the point of failure so that repairs can be undertaken. In a system that has no ground reference at all, it is not easy to correctly pinpoint the faulted location. Figure 1.1(a) shows such a system. It can be seen that due to the absence of a conducting path through ground the fault remains undetected. If however a second fault occurs in the unaffected line at some other point in the system, it can cause a shorting path and results in the flow of high-magnitude fault currents that can be detected by protective devices.

Figure 1.1

(a) Fault in ungrounded system, (b) Effect of grounding the neutral.

To detect the first fault point as soon as it happens without waiting for a second fault to develop, we ground one of the two poles of the source S (refer Figure 1.1b). The pole that is grounded is generally called the, ‘neutral’ and the other, ‘line’. It is of interest to note that the connection between neutral and earth is only at the source. The return current from the load flows only through the neutral conductor back to the source. For this reason the neutral is always insulated from ground and usually to the same degree as the line conductor. When there is an insulation failure in the line conductor a high current flows through the electrical circuits and through the ground path back to the source. Depending on the resistance of the ground path, the current flow in this path can be detected by appropriate protective equipment. Similar principles also apply to faults created in systems with bare exposed conductors supported by using solid insulators, either due to failure of insulator, or snapping of overhead conductors.

Thus one of the primary purposes of grounding is to permit easy detection of faults in electrical systems – by providing a path for the flow of currents from the fault point through the ground (and sometimes the earth mass) back to the neutral point of the source.

Now let us take a step further and see why it is necessary for this ground reference to be extended to a consumer installation. While Figure 1.1b shows that the source is grounded, it does not indicate another point of connection to ground. However in practical systems, the fact that a failure of insulation takes place does not mean that a ground connection is automatically established. This can only be done if the point of failure is connected to ground through a low impedance ground path. Such a path is created using a reference ground bus at the consumer-end and connecting the metallic housing of all electrical equipment to this bus (refer Figure 1.2). Any fault current flows into the ground bus and then back to the source neutrally through the soil mass.

Figure 1.2

Fault current flow in a grounded system.

In fact it is preferable to have the ground terminal of a Low Voltage consumer installation directly connected to the neutral of the source, to ensure that the ground fault current has a low impedance path not involving the soil mass. It is difficult to predict accurately the resistance of groundmass to the flow of currents, therefore except for high voltage systems, the emphasis will be on obtaining direct metallic continuity. This approach enables an adequate magnitude of fault current permitting positive detection and tripping. It should be noted that the neutral of the electrical load is isolated from the ground and the connection between neutral and ground is still at the source point only. We will cover the different ways in which the neutral and ground references are distributed by a supply system to its consumers (giving rise to different categories of systems).

In a subsequent chapter we will also cover why the grounding of metallic enclosures of current-carrying equipment is necessary from the safety point of view. We will discuss how it makes the system safe for operation without fear of electrocution in the event of an insulation failure in live components. In this context we will learn in detail about electric shock, about the voltages that can develop in the event of a ground fault, and the meaning of the terms: Touch Potential, Step Potential and Transferred Potential. The sizing of grounding conductors is another important issue and it should be ensured that the conductors can withstand electrical, mechanical and environmental conditions under which they are required to operate. We will discuss the role of ground fault protection in ensuring safety and how a properly designed grounding system helps to achieve this objective without any premature failures.

1.3 Bonding

Bonding refers to the practice of connecting various grounding systems as well as non current carrying metal or conductive parts together – so that there will be no potential difference between different accessible conducting surfaces or between different grounding systems. Such potential differences can be hazardous if a person comes into contact simultaneously with two surfaces between which a potential difference exists. Equipotential bonding achieves potential equalization between all surfaces, which are thus bonded. This topic is covered in detail in the chapter on protective grounding.

Another problem which can occur in the absence of bonding is that two parts of sensitive equipment can develop a large potential difference between them under abnormal conditions. The currents that flow through inter-system insulation resistance or capacitance can cause damage to sensitive components and printed circuit boards. This type of problem generally occurs when ground current surges happen as a result of lightning discharges or other atmospheric phenomena. We will deal with this topic as a part of the module on surge protection.

1.4 Ground electrodes

A common thread in the above discussions is the need for a good connection to the groundmass. Such a connection is normally achieved by a ground electrode system. Several types of ground electrodes using different materials, physical configurations and designs are in widespread use and usually follow local standards that govern electrical installations. In most local standards, a metallic rod, driven into the ground to a depth where adequate moisture is available in the soil throughout the year (in both wet and dry seasons) is recommended for use as a ground electrode. A typical electrode is shown in Figure 1.3.

Figure 1.3

A typical ground electrode used in electrical installations

The performance of such electrodes (considering the ground resistance of the electrode as an indicator) depends on the type of soil, its composition, conductivity, presence of moisture, soil temperature and so on. Several ground electrodes, bonded together to form a cluster, are usually provided for achieving satisfactory results. The general requirements that influence the choice of earth electrodes are as follows:

- The type of soil where the grounding is carried out (in particular its electrical resistivity)
- The need for achieving minimum acceptable earth resistance appropriate to the installation involved
- The need to maintain this resistance all year in varying climatic conditions
- Presence of agents that can cause corrosion of elements buried in ground

The electrode design and methods of installation will be dependent on these requirements. This will be addressed in detail in a later chapter.

To improve the conductivity of ground electrodes, several forms of electrode construction are in use in which the layer of soil surrounding the electrode is treated with chemical substances (for improving conductivity). These are known as Chemical Electrodes. The basic principle of these electrodes is the use of substances that absorb moisture and retain it over long periods. They are packed as backfill around the electrode. Materials containing carbon (charcoal/coke) and electrolyte salts such as sodium chloride are typically used as backfill. Figure 1.4 shows such an electrode construction. It may also be noted that in this construction a provision has been made to add water externally to keep the backfill material wet during prolonged dry weather conditions.

Figure 1.4

A typical chemical ground electrode

It will also be evident from the above discussions that as a critical factor in the safety of installation and of personnel, the grounding system will have to be constantly monitored to ensure that its characteristics do not drift beyond acceptable limits. The practical methods adopted for measurement of soil resistivity and the resistance of a ground electrode/grounding system will also be covered in detail later.

Several international codes deal with grounding practices. We will have a brief overview of some the typical codes and various suggested ground electrode configurations, as well as the theoretical basis for limiting ground electrode resistance to ensure proper operation of ground fault protection.

1.5 Grounding of electrical substations – objective

Substations are an important component in any electrical distribution network. They contain transformers which step up or step down the system voltage from one level to another. Hence the transformer also becomes a source point for the downstream electrical system. Therefore system grounding is an important design issue while planning substations. Also most substations handle electricity at very high voltages and a fault within a substation can greatly endanger the operating personnel because of the high touch/step potential differences which a fault will entail between different parts of the substation. The design of a grounding system should ensure that such dangerous potentials are not allowed to occur during faults. We will devote a chapter to the design of substation grounding systems. This discussion is based on IEEE 80, a standard dealing with substation grounding. We will also briefly discuss the grounding requirements of special electrical supply installations such as those incorporating Gas Insulated Switchgear (GIS) and those feeding High-Voltage Direct Current (HVDC) transmission systems.

1.6 Static charges and the need for grounding

Certain types of non-electrical machinery can cause a build up of static charge during their operation and this charge accumulates on the surface of the equipment parts: for example a flat rubber belt around two metal pulleys. This is a very common type of motive power transmission that generates a lot of static electricity. When a sufficient amount of charge is built up, a spark-over can occur between the charged part and any grounded body nearby. Figure 1.5 illustrates the principles involved.

Figure 1.5 a, b & c

Example of static electricity build up and prevention

Body A has a positive charge while no charge is present on the nearby body B both of which are insulated from the ground (Figure 1.5 a). Let us now assume that body B is connected with ground. When body A acquires a sufficient quantum of charge that can cause a breakdown of the medium separating A and B or A and ground, it will result in a spark discharge (Figure 1.5 b).

Such spark-over carries sufficient energy that can cause explosions in hazardous environments and fires in the event combustible materials are involved. It is therefore necessary to provide bonding of the parts where charge build up can occur by employing suitable metallic connections to earth. Bonding bodies A and B with a conducting metallic wire directs the charge to flow on to body B. This causes the charge to continuously leak into the ground so that build up of dangerously high voltages is prevented (refer to Figure 1.5 c).

Some of the practical cases of static build-up that occur in industrial and consumer installations and ways and means of avoidance will be dealt with in further detail in a subsequent chapter. Another important issue is how unsafe conditions can be caused by charges induced in a dead line due to weather conditions, such as snow, dust storms or a nearby thundercloud. Precautions must therefore be taken to prevent electric shock to personnel working on these lines. We will briefly cover this issue while discussing static electricity.

1.7 Lightning and its effects on electrical systems

Lightning is the result of the development of cells of high potential in cloud systems as a result of charge accumulation and the consequent discharge between cells carrying opposing charges or to ground. The high potential difference causes ionization of air between these cells and ground, which then becomes conductive and allows a short burst of extremely high current to flow, resulting in instantaneous dissipation of the accumulated charge. Usually, the first lightning strike allows further multiple strikes along the same path when the charges from nearby cloud cells also discharge through it to ground.

Lightning strikes to ground usually involve some tall structure or object such as a tree. While the strike on a conducting structure (that provides an extremely low impedance path to ground) does not result in major damage, the results are disastrous in the case of structures that are not fully conductive. The damage occurs mainly because of extreme heating that takes place due to the high current flowing through the object. This in turn causes any moisture present in the structure to evaporate suddenly. The resulting explosive release of steam causes extensive damage to the object. For example, in a tree that suffers a lightning strike, the moist layer under its bark vaporizes instantaneously which causes the bark to fly away.

A more serious result can occur if the strike is near or on a container carrying flammable materials. The high temperatures can ignite flammable materials causing severe explosions and secondary damage. Such structures need special protection against lightning.

Of greater interest to us in this course is the effect lightning discharge has on electrical systems and how electrical equipment as well as installations can be protected against damage from destructive surges that follow a lightning strike. This will be dealt in detail in a subsequent chapter.

1.8 Surge protection

Modern day power generation and distribution systems rely largely on electronic systems for their smooth functioning: be it industrial drives, distributed control systems, computer systems or networking/communication electronics of SCADA systems. These electronic devices often work at very low power and voltage levels for their control and communications and cannot tolerate even small over voltages or currents. Such over voltages (called as surges or transient over voltages) can originate from the power source, travel through the distribution system and ultimately damage sensitive circuits. A typical example of an external voltage disturbance is a lightning strike near an overhead power transmission system. Such transients can also happen due to switching (on or off) of large transformers. The transformers when charged draw a momentary in-rush current and this can reflect as a voltage disturbance. Similarly, switching off an inductive load (say a coil energizing a contactor) causes a brief voltage spike due to the collapse of the magnetic field in the magnetic core. If other equipment is connected in parallel with the inductance (after the switching point) they too will experience the surge. Figure 1.6 below shows the principle involved.

Figure 1.6 a & b

Inductive load causing a transient surge

Any installation can be divided into various zones depending on the severity of surges to which equipment in the zone can be subjected. Surge protective devices and grounding are arranged in such a way that surge levels gradually get reduced from the most severe magnitudes in Zone 0 to the highly protected Zone 3 that houses the most sensitive and vulnerable systems. This is explained in detail in the chapter on surge protection, different types of surge protective devices available and their application areas will also be touched upon.

1.9 Noise mitigation

Induced voltages from nearby power circuits experiencing surges or harmonic currents can also cause interference in the systems carrying communication signals and can result in malfunctions (due to erroneous or noisy signal transmission). Due to this sensitive nature of electronic and communication equipment, any facility that houses such equipment needs to have its electrical wiring and grounding systems planned with utmost care – so that there are no unpredictable equipment failures or malfunctions. Noise can occur due to improper grounding practices resulting in the creation of ground loops. Figure.1.7 shows an example of a ground loop.

Figure 1.7

Ground loop problem

A and B are two Electronic Data Processing systems with a communication connection, C, between them. C is a cable with a metallic screen bonded to the enclosures of A and B. A and B are grounded to the building grounding system at points G1 and G2. Rg, is the resistance between these points. G1 and G2 are thus forming a ground loop with the cable screen and any current in the ground bus between G1 and G2 causes a current to flow through the communication cable screen, in turn resulting in spurious signals and therefore malfunction.

Multiple connections of the bare ground wire to the conduits and the conduits themselves with other building structures and piping is practiced in electrical wiring. This achieves a low ground-impedance and it has no adverse effect on power electrical devices. In fact many codes recommend such practices in the interest of human safety. However, as shown in the above example, the same practice can cause problems when applied to noise-sensitive electronic equipment.

Noise can be transmitted between circuits by galvanic coupling, electrostatic coupling, by electromagnetic induction and by radio frequency interference. Normal signals, surges and power frequency/harmonic currents can all affect nearby circuits with which they have a coupling. The design of certain types of signal connections has an inherent problem of galvanic coupling. Electrostatic coupling is unavoidable due to the prevalence of inter electrode capacitances especially in systems handling high frequency signals. Most power electrical equipment produce electromagnetic fields. The process of arcing in the contacts of a switching device producing electromagnetic radiation or high frequency components in currents flowing in a circuit setting up magnetic fields when passing through wiring are examples of such disturbances. This kind of disturbance is called Electromagnetic Interference (EMI). By and large equipment being designed these days has to conform to standards which aim to reduce the propagation of EMI, as well as mitigate the effects of EMI from nearby equipment (by using appropriate shielding techniques). Shielding against electrostatic coupling and electromagnetic interference works differently and should be applied depending on the requirements of the given situation.

The method of grounding the electromagnetic and electrostatic shield/screen is also important from the point of view of noise. Improperly grounded shield/screen can introduce noise into signaling and communication systems, which it is meant to protect.

Since electronic equipment involves the use of high frequency signals the impedance of the grounding system (as against resistance, which we normally consider) assumes significance. The ground system design for such equipment must take the impedance aspect into consideration also. We will discuss these issues in a separate chapter and how noise can be minimized by proper grounding techniques.

Special attention is needed when planning separately derived supplies, such as UPS systems which are normally provided for SCADA hardware. Improper grounding will result in noise from the power system being coupled into sensitive electronics. The issues relating to the grounding of these systems as separately derived sources have been extensively discussed in IEEE: 142 standard. We will discuss grounding methods of some of the commonly used UPS configurations in further detail.

1.10 Importance of grounding codes

While we covered the general physical principles involved in grounding of electrical systems and equipment, the actual practices adopted in different countries vary. Different local codes approach the issue of grounding in their own distinct ways, taking into account factors such as the local environment, material availability and so on. However all of them aim to achieve certain common objectives, most important of which being the safety of personnel. Generation, distribution and the use of electrical energy are subject to extensive regulatory requirements of each country such as the National Electrical Code (USA) and the Wiring Regulations (UK). It is mandatory on the part of electricity suppliers and consumers to adopt the practices stipulated in these regulations and any deviations might cause the installation in question to be refused permission for operation. Thus anyone engaged in the planning and design of electrical systems must be well versed with applicable local codes and must take adequate care to ensure conformity to the codes in all mandatory aspects.

1.11 Summary

Grounding has many objectives. It provides a common point of reference to the live electrical conductors of a power supply network. It provides a path for surge currents to flow to the soil mass. It ensures safety by clamping the exposed conducting enclosure of electrical equipment at ground potential. Correct grounding practices go a long way in controlling and mitigating electrical noise. Improper grounding can result in many problems in the power system and associated control and communication systems. Grounding is thus variously classified depending on the function performed by it as system grounding, protective grounding, lightning/surge protection grounding, or signal reference ground planes for noise mitigation in sensitive circuits. An engineer dealing with power supply networks must understand the basic principles of grounding system design and its role in ensuring safety of equipment and personnel. A correct understanding of the basic principles involved will help them to avoid mistakes in grounding system design. Mistakes that could lead to expensive failures and long downtime.