PRL TECHNICAL NOTE

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MAY 2000

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Preface

A field station (for example an observatory housing an optical or a radio telescope) is necessarily situated at an isolated site. Apart from many scientific considerations, isolation of a field station from human civilization is of paramount importance. This is done to avoid any interference or pollution of the valuable data gathered at the station from the noise voltages produced by the human population around.

The contact of a field station to the outside world is through a high voltage power line, or the telephone lines for voice and data transmission and occasionally a set of radio/microwave communication antenna and receiving equipment. Due to the remoteness of the station site, the observation and maintenance staff reporting there for their routine work needs utmost protection from hazardous voltages reaching the site. Such hazardous voltages are caused either by the phenomenon of lightning or by the faults developed in the electrical installation and instruments around. These voltages can also cause fire in the building.

On the rainy days the station is likely to receive lightning strokes quite frequently. If the lightning discharge current were not diverted to the ground through an arrester it would have destructive effects on the building, the equipment inside and the personnel on duty. The radio antenna at the rooftop is highly vulnerable to a lightning strike and dangerous voltages through the cable connected to it may enter the interior of the observatory building. The telephone and the overhead power lines may propagate high voltage transients produced by lightning strokes picked up by them at long distances.

The substation transformer at the site provides electrical power to the field station building through cables. A momentary direct contact with the ac supply voltage can cause an electrical shock or electrocution of a person if he touches an open wire, a damaged socket or a leaky instrument. Traditionally, the ac supply voltages are referred to the ground to avoid any floating voltages appearing on instruments. The metallic enclosure of any electrical instrument is connected to ground for enabling a prompt action of a circuit breaker in case of a direct contact of a live wire with it.

The Institute of Electrical and Electronics Engineers (IEEE) makes a distinction in defining *ground* and *earth*. *Earth* refers to planet Earth, and *ground* refers to the equipment grounding system, which includes equipment grounding conductors, metallic raceways, cable armor, enclosures, cabinets, frames, building steel, and all other non-current carrying metal parts of the electrical distribution system [1].

PREFACE

Earthing of the lightning arrester and AC power neutral has been a very standard engineering practice. This is done on the assumption that the earth is a very good conductor of electricity and can absorb or supply any amount of charge without changing its potential. This assumption, however, has its limitation due to the resistivity of the soil around the earth electrode system and hence the capacity of the soil to absorb the current impressed in it. Moreover, the use of earth as a zero reference potential for sensitive electronic circuits for suppressing any interference from noise voltages present at the site is seldom possible without employing elaborate techniques and peripheral devices.

The practice of the earthing at a field station is thus a multidisciplinary requirement. The electrical engineer, the computer hardware engineer, the communications engineer, the telephone exchange (EPABX) engineer, the supplier of a diesel generator or an Uninterruptible Power Supply (UPS) etc. install their equipment in the same field station and all have the same requirement of a ground reference. However, it is strange that the installation of an earth electrode is still considered to be a job of an electrical engineer who does it mostly from a safety point of view. Later, it is quite a general tendency found in the engineers in the other disciplines to promptly attribute all the logically inexplicable functional problems in the various electronics and data processing instruments to a poor grounding/earthing at the field station site.

This, we believe, is the result of a few gaps in the wide amount of literature available on the subject matter of grounding and earthing. These gaps need to be plugged in and this write-up has essentially tried to do that in a very humble way. This write-up is a compilation of information collected on the related topics and presented with a goal of making a useful reference document for all the practicing engineers working in a field station.

This write-up is a result of years of efforts by all the contributors in surveying the technical literature on the matter, carrying out extensive tests in the field stations and thrashing out the discrepancies observed in the tricky measurements and concepts after hours of brainstorming discussions.

The write-up tries to discuss the fundamentals of the earthing practice and its effects on the overall performance of a field station installation. The first chapter of the write-up develops the necessary equations for finding the resistance of any earth electrode system and describes the operation of an Earth Tester instrument available for this purpose.

The chapter 2 elaborately describes the phenomenon of lightning on the basis of a global model and the various techniques for protecting the equipments and personnel in a field station in the event of a lightning strike in its vicinity.

The result of a direct contact of a human operator with an electrically live object depends upon the amount of current passing through the body of the person which in turn depends upon the resistance of the body between the points of contact. The chapter 3 provides the information on this with useful tables and curves. It also describes a few general guidelines for safety of a human operator while using electrical equipment.

The chapter 4 describes various types of circuit breakers (like fuses, MCBs and ELCBs) and surge suppressors (MOVs, spark gaps and co-axial type suppressors) for protecting sensitive electrical/electronic instruments.

The chapter 5 reviews the sources of noise voltages and currents in a field station that houses sensitive instruments like computers and or data acquisition and processing instruments and discusses standard techniques for suppression of noise voltages by using accessories like power line EMI/RFI filters and isolation transformers.

At the end, the chapter 6 illustrates and describes a few practical layouts of wiring and earthing networks used in a modern field station for achieving the intended goals.

D. V. Subhedar

May 21, 2000.

THE EARTHING PRACTICE
AND ITS EFFECTS ON A FIELD STATION PERFORMANCE

Contents

1. The earthing practice

In the field of instrumentation the conducting properties of the earth are used in a variety of useful ways. It is used as a terminal for grounding the neutral conductor of the ac power systems to limit touch voltages to safe values. It absorbs a lightning discharge through a controlled path and saves the human life and building structures. It is also used as a zero voltage reference in sensitive electronic instruments where signal common points are connected to metallic shields that are earthed. When the charge is suddenly transferred to earth or a grounded structure it seeks to spread outward until neutralized by the ambient charge of the whole earth mass. The earth is thus, the medium that dissipates electrical energy without changing its potential.

The ability of the earth to accept the energy depends on the resistivity of the soil at the particular location where the leakage (or lightning discharge) current enters the earth.

1.1 Resistivity of soil

The resistivity of the soil is a variable quantity that can be determined accurately only by measurements. The principal factors affecting soil resistivity are the following:

- Soil type
- Concentration and composition of dissolved salts
- Moisture content
- Temperature
- Texture or grain size and
- Compactness

The rocky terrain can have high resistivity of the order of 10^5 to 10^6 Ω-cm and ordinary clay can have only 500 Ω-cm resistivity [2].

The Table 1.1 [3] below gives the resistivity values of a few types of soils normally encountered in earthing systems.

TABLE 1.1

Material	Specific Resistance in ohm-cms
Ashes	350
Coke	20-800
Peat	4,500-20,000
Garden earth-50% moisture	1,400
Garden earth-20% moisture	4,800
Clay soil-40% moisture	770
Clay soil-20% moisture	3,300

London clay	400-2,000
Very dry clay	5,000-15,000
Sand-90% moisture	13,000
Sand- normal moisture	300,000-800,000
Chalk	5,000-15,000
Consolidated sedimentary rocks	1,000-50,000

Usually, a driven rod or pipe is used for earthing an electrical system. High voltage systems use a number of ground rods properly spaced and connected in parallel. More sophisticated systems employ both rods and horizontal conductors.

1.2 Earth electrode resistance and is its measurement

The process of connecting the grounding system to Earth is called earthing, and consists of driving or immersing a metal electrode or system of electrodes into the earth. The conductor that connects the grounding system to earth is called the *earth electrode*.

The basic measure of effectiveness of an earth electrode system is called *earth electrode resistance*. *Earth electrode resistance* consists of the sum of the resistance of the metal electrode (negligible) plus the contact resistance between the electrode and the soil (negligible) plus the soil resistance itself. Thus, for all practical purposes, earth electrode resistance equals the soil resistance. Alternately, the *earth electrode resistance* is the resistance between the point of connection to the earth and the *remote earth*. *Remote earth* is the point away from the driven electrode where the *earth electrode resistance* does not increase appreciably when this distance is increased [1].

The equations for the resistance of any complex system of earth electrodes can be developed from the fundamental principles as done by Marshall [2]. The starting point for such a development is the use of a buried metallic electrode with a hemispherical base of radius r. It is assumed that the hemispherical base is completely buried in the soil.

When a current I enters the earth through such an earth electrode, due to its hemispherical base, the current flows radially outward as shown in the sketch below.

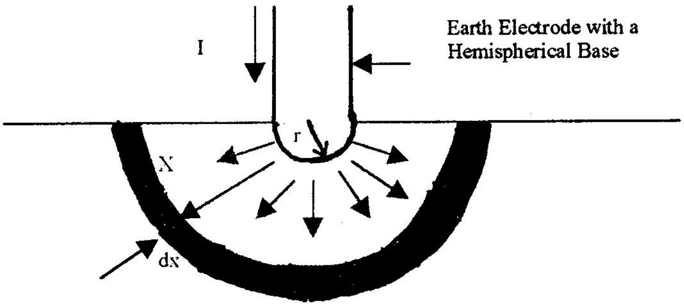


Fig. 1.1

If ρ is the resistivity of the soil, the resistance offered by a hemispherical shell of thickness dx at a radial distance x from the electrode is given by

$$dR = \frac{\rho\, dx}{2\pi x^2}$$

Hence, the resistance encountered by the earth electrode up to the depth of r_1 can be had by

$$R = \frac{\rho}{2\pi}\int_{r}^{r_1}\frac{dx}{x^2}$$

$$R = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{r_1}\right]$$

If r_1 is made ∞, the total resistance of the earth electrode will be

$$R_\infty = \frac{\rho}{2\pi r}$$

This is the maximum resistance of the earth electrode.

The general equation of the resistance shown above can be modified to a suitable form as shown below.

$$R = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{r_1}\right]$$

$$R = \frac{\rho}{2\pi r}\left[1 - \frac{r}{r_1}\right] = R_\infty\left[1 - \frac{r}{r_1}\right]$$

If a current I enters the earth electrode, the potential drop up to the shell radius of r_1 will be had by

$$V = IR = IR_\infty\left[1 - \frac{r}{r_1}\right]$$

At very high values of r_1, the resistance value will approach the value R_∞, beyond which true earth can be assumed to be present. The figure below shows the plots of R, V

and V_{abs}, the absolute potential with respect to the true earth against the radial distance r_1 from the electrode.

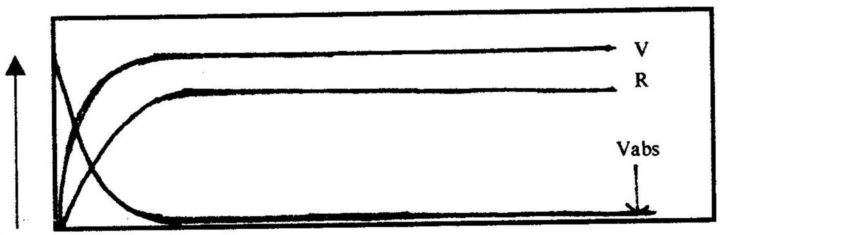


Fig 1.2

The expression for the absolute potential can be obtained from that for the potential drop and is shown below.

$$V_{abs} = IR_{\infty}\left[\frac{r}{r_1}\right]$$

$$V_{abs} = \frac{I\rho}{2\pi r}\left[\frac{r}{r_1}\right]$$

$$V_{abs} = \frac{I\rho}{2\pi r_1}$$

The potential of a shell for the current leaving the earth will be of the same magnitude but of negative polarity i. e. $-I\rho/2\pi r_1$, where I is the current leaving through a point on the earth.

1.3 The 'Fall of Potential' method for measuring earth resistance

The most reliable method of measuring the resistance to earth of a driven electrode is the 'fall of potential' method. Figure 1.3 below shows an arrangement of three electrodes. Let E be the electrode whose resistance to earth is required to be measured and let P and C be the auxiliary rods driven into the earth. A known value of current I is circulated between C and E, and the voltage drop V between E and P is measured. The resistance of the electrode E to the earth is V/I. The optimum location for the potential electrode P is 0.62 of the distance from E to C when the distance D is at least 30 times the depth of the electrode E.

Let the base of the electrode E be a hemisphere of (equivalent) radius r and the other two electrodes designated as shown in the figure.

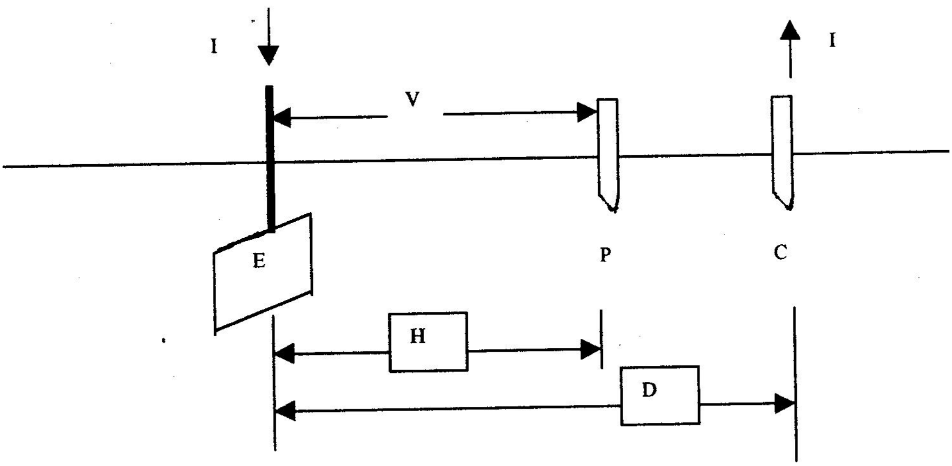


Fig. 1.3: Arrangement of the Electrodes for the 'Fall of Potential' Method

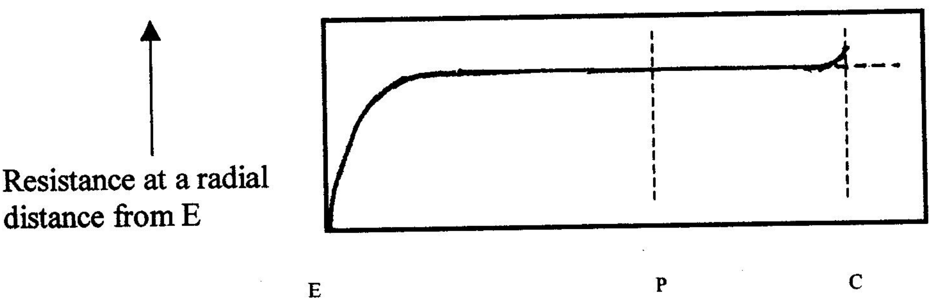


Fig. 1.4: Resistance as a function of the distance from the electrode E

The potential at E due to the entering current is $I\rho/2\pi r$ and due to the current leaving at C is - $I\rho/2\pi D$. The total potential at E can be given by

$$V_E = \frac{I\rho}{2\pi r} - \frac{I\rho}{2\pi D}$$

Similarly the total potential at P due to the current entering at E and that leaving at C can be given by

$$V_P = \frac{I\rho}{2\pi H} - \frac{I\rho}{2\pi(D-H)}$$

The net potential difference between *E* and *P* will be given by

$$V = V_E - V_P$$

$$V = \left[\frac{I\rho}{2\pi r} - \frac{I\rho}{2\pi D}\right] - \left[\frac{I\rho}{2\pi H} - \frac{I\rho}{2\pi(D-H)}\right]$$

$$V = \frac{I\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{D} - \frac{1}{H} + \frac{1}{(D-H)}\right]$$

If the resistance curve (Fig. 1.4) between *E* and *C* is observed, it flattens beyond *P* (if located optimally between *E* and *C*) and the resistance of the earth electrode between E and *P* and that between *E* and *C* are nearly same. An upward bend in the resistance curve above, near the point C is due to the resistance of the auxiliary rod C itself and does not affect measurement of the resistance of the main electrode E.

Therefore the potential difference between *E* and *C* and between *E* and *P* will also be the same. Hence, the measured resistance of the electrode *E* will be

$$R = \frac{V}{I}$$

$$R = \frac{\rho}{2\pi}\left[\frac{1}{r} - \frac{1}{D} - \frac{1}{H} + \frac{1}{D-H}\right]$$

$$R = \frac{\rho}{2\pi r}\left[1 - \frac{1}{c} - \frac{1}{p} + \frac{1}{c-p}\right]$$

where $c = D/r$ and $p = H/r$.

But the resistance of the earth electrode is $R_\infty = \rho/2\pi r$.

If the measured value *R* is to be equal to R_∞, the condition to be satisfied will be

$$\frac{1}{c} + \frac{1}{p} - \frac{1}{c-p} = 0$$

$$p^2 + pc + c^2 = 0$$

$$p = \frac{-c \pm \sqrt{c^2 + 4c^2}}{2} = \left(\frac{\sqrt{5} - 1}{2}\right)c = 0.618c$$

From this, it follows that $H = 0.618D$ will satisfy this condition. This indicates that for any separation of the current electrodes (E and C), the true resistance of one of them is obtainable when the potential electrode (P) is 61.8% of the distance toward the other.

1.4 Measuring specific resistivity of soil at a site

Before sinking an earthing electrode into the ground for a new installation it is often advantageous to make preliminary survey of the soil resistivity of the surrounding site. Such a survey may produce considerable savings in electrode and installation costs necessary to achieve a required earth resistance value.

The most generally used method of measuring earth resistivity is the 'four electrode' method. As shown in the Fig. 1.5 below, four metal rods whose diameter is small relative to their length and which are exposed only at the end are driven into the ground. A known current is passed from electrode C_1 to electrode C_2 and the potential drop is measured across electrodes P_1 and P_2.

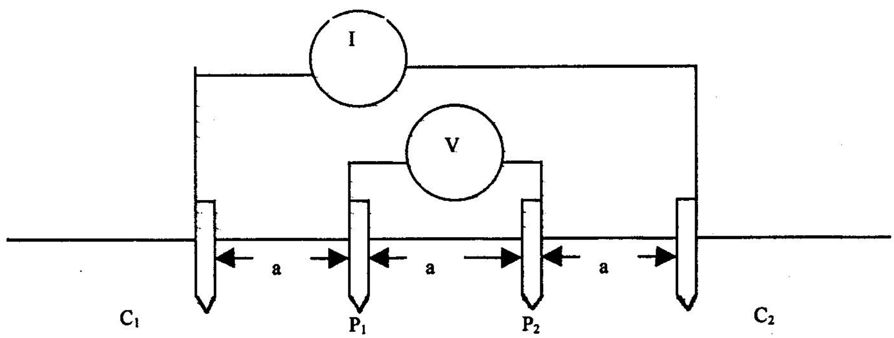


Fig. 1.5: Arrangement of the electrodes for measuring the resistivity of the soil

Fig. 1.6 below shows the resistance of the earth between the points C_1 and C_2. In order to avoid the effect of the current rods at C_1 and C_2, the measurement of the resistance is carried out on the flat portion of the resistance curve.

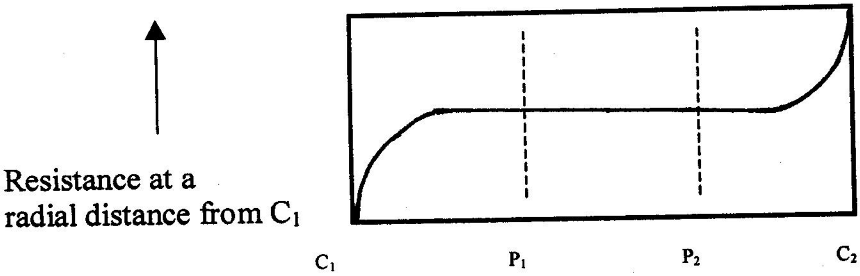


Fig. 1.6

The total potential at P_1 due to the current entering at C_1 and that leaving at C_2 will be

$$V_{P1} = \frac{I\rho}{2\pi a} - \frac{I\rho}{2\pi(2a)}$$

Similarly the total potential at P_2 will be

$$V_{P2} = \frac{I\rho}{2\pi(2a)} - \frac{I\rho}{2\pi a}$$

Hence, the potential difference between P_1 and P_2 will be

$$V = V_{P1} - V_{P2} = \frac{2I\rho}{2\pi}\left[\frac{1}{a} - \frac{1}{2a}\right] = \frac{I\rho}{2\pi a}$$

But for the circulating current I, if we tap the potential difference between the points P1 and P2, then $V/I = R$ should give the resistance between P1 and P2 which is a constant.

But, $V/I = R = \rho / 2\,\pi\,a$ and hence,

$$\rho = 2\pi a R$$

For increasing the accuracy of measurements the four rods are spaced in a row at a spacing of about 20 to 30 m if 30 cm solid spikes of mild steel are used as the current and potential electrodes.

1.5 The resistance of a driven rod

As seen above, the driven rod with the hemispherical base is not the only earth electrode type that is used. This type was chosen to derive the basic equations for further development of the field. The similarity between the derivations for finding the capacitance of a charged sphere and the resistance of a (hemi) spherical base electrode suggests a method of finding an equivalent radius of an earthing electrode (or a combination of electrodes) of any complex arrangement. To begin with the electrode (or a combination of electrodes) is assumed to have a uniform charge spread over its surface. From this, the potential and hence the capacitance of the system of electrodes is derived. This finally leads to the estimation of the equivalent radius of the system of electrodes under consideration.

The resistance of a driven rod or a pipe to earth is

$$R = \frac{\rho}{2\pi l}\left(\ln\frac{4l}{a} - 1\right)\Omega$$

And the radius of its equivalent hemisphere is given by

$$r = \frac{l}{\left(\ln\frac{4l}{a} - 1\right)}$$

where l is the driven length of the rod, a is the radius of the rod and ρ is the resistivity of the soil around the driven rod.

The equivalent radius is the radius of the hemispheric base of the driven electrode equivalent to an electrode or system of electrodes that might be rods, wires, plates or other shapes giving the same resistance as that of the electrode with the hemispherical base.

Table 1.2 below [2] gives equivalent radii of the rods of various sizes.

TABLE 1.2

Length of Rod or Pipe (ft)	Radius (ft) of Equivalent Hemisphere for Rod or Pipe Radius of		
	0.5 in.	1 in.	2 in.
3	0.56	0.64	0.76
4	0.71	0.81	0.94
5	0.85	0.97	1.12
6	0.99	1.12	1.29
7	1.13	1.27	1.45
8	1.26	1.42	1.62
9	1.41	1.56	1.77
10	1.52	1.70	1.93

For a 1 in. diameter rod driven 6 ft. into the earth of soil resistivity 2000 Ω-cm, the earth electrode resistance can be estimated to be 10 Ω which is much higher than 1 Ω normally required for a grounding system used in an equipment building in a field station.

1.6 Multiple driven rod electrodes

Elaborate ground systems require multiple electrodes.

For two rods of hemispherical equivalent radius r, in parallel spaced at a distance d, the combined resistance is given by

$$R = \frac{\rho}{4\pi r}\left(1 + \frac{r}{d}\right)$$

The lowest value of the combined resistance attainable is half the value given by a single rod.

Similarly, expressions for 3 rods in parallel arranged in a row or placed at the corners of an equilateral triangle can be found out or can be referred from the standard textbooks on the subject.

More number of rods can be arranged in a row or open square arrangement. For four rods, the maximum improvement is 2.5 times the single rod. Eight rods can be used in place of a single rod to get a factor of 5 improvement in earth resistance for the same soil. As a further example of resistance values, twenty ½-in. rods buried to a depth of 8 ft and having a spacing of 8 ft, provides 4 Ω resistance to the earth for ρ = 10,000 Ω-cm.

Multiple ground rods can be arranged in a circle also.

The buried wire type of ground conductor is applicable to high-voltage power-transmission lines and in areas where the surface soil is shallow. The wires fan out radially from a central connection point.

Conductors carried along the surface of the earth also make good connections to earth. A 150-ft run of ½-in conductor buried 2 ft below the surface yields a theoretical 4 Ω resistance to earth. For this reason, various star arrangements from a central point make practical earth connections. As an example, an 8-arm star of 1-in conductor buried at a depth of 3 ft yields a 1 Ω theoretical resistance to the earth if the resistivity is 10,000 Ω-cm.

Very low value of an earth electrode resistance (around 1 ohm) is very difficult to achieve and maintain particularly during a dry season.

1.7 Buried electrodes in nonhomogenous earth

In nonhomogenous soil, the soil resistivity varies with depth and the earth electrode should be put at depths that are the best compromise between low resistance and economy. However, it has been found by practice that the top layer of soil has the most influence on electrode resistance and the second or lower layers in contact with the rod have only minor effect [2].

1.8 Salting of ground electrodes

Salting the soil near the electrode can reduce the resistance of a ground electrode. This situation arises when the soil resistivity is high or the depth of the electrode is limited. Reductions in the ground system resistance by a factor of 50 or more can be achieved by heavy salting. In the earth pit specially made for good earthing, alternate layers of charcoal (or coke) and salt are formed. A funnel brought over the surface of the earth and a pipe connected to it is also inserted into the pit for dripping water continuously in it to keep the soil in the pit moist. This arrangement maintains a low value of the earth resistance at the installation throughout the year. Its action is to enlarge the effective radius of the electrode [4].

1.9 Methods of installing the earth electrodes

The method of installing ground electrodes depends on the kind of soil and the size of the ground system. If the soil is free from rock, ground rods can be driven in with a sledgehammer. Ground rods are made in various diameters and lengths, the diameter increasing with length so as to provide the mechanical strength for driving. Rods up to 1 in. diameter and 16 feet length are available and are made of copper; galvanized steel or copperclad steel (this type combines mechanical strength and good resistance to corrosion).

Horizontal ground conductors are buried in trenches. The impedance of several buried radial wires is lower than one long wire of same length [2].

The standard methods for earthing in a field station are the pipe earthing and the plate earthing. A GI pipe or a copper or GI plate is buried in the ground at a depth of about three meters. Alternate layers of charcoal (or coke) and salt are laid around the electrode. A permanent arrangement is made with a funnel to pour water periodically in it to keep the soil around the electrode moist throughout the year.

Both these arrangements [4] are schematically shown below.

1.9A The Pipe Earthing

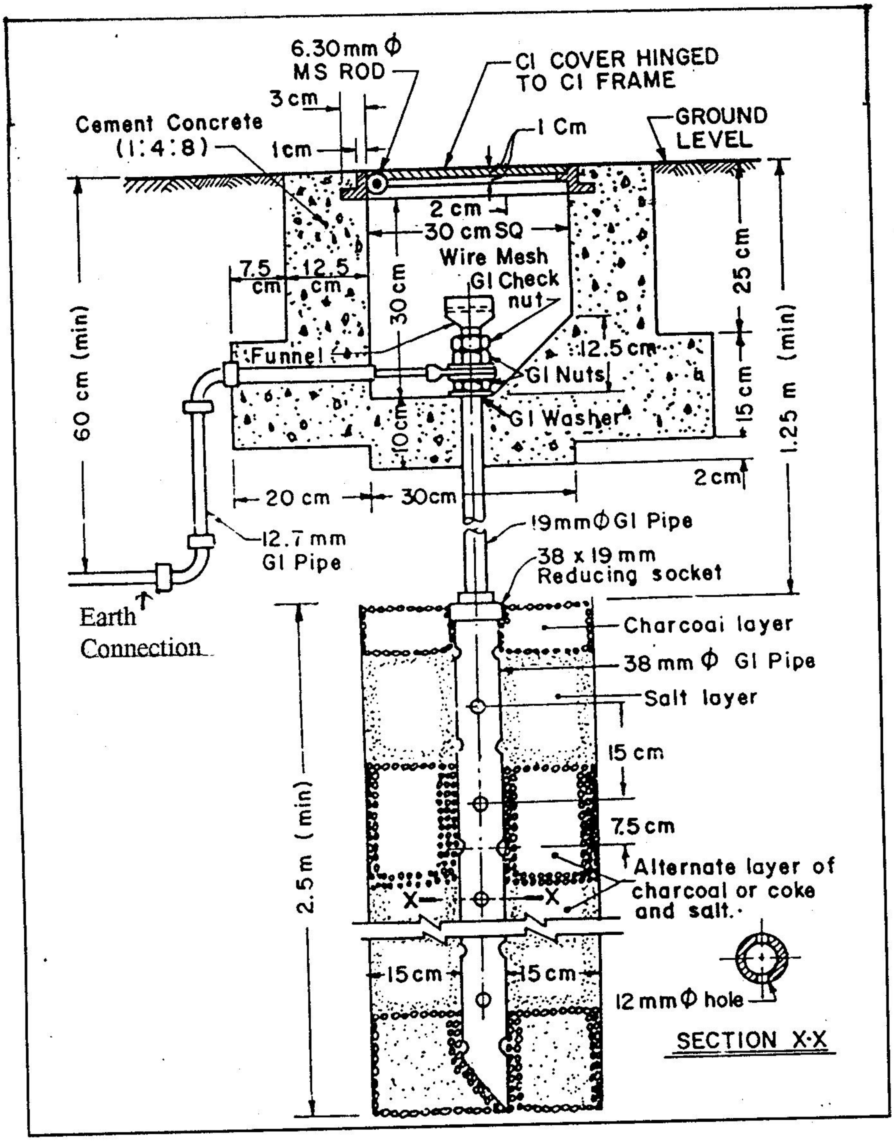


Fig. 1.7: The Pipe Earthing

In General, the Pipe Earthing is installed where moderate amount of fault current is expected to flow. For a substation earthing or a field station earthing where large fault currents are expected, the method of Plate Earthing is recommended.

1.9B The Plate Earthing

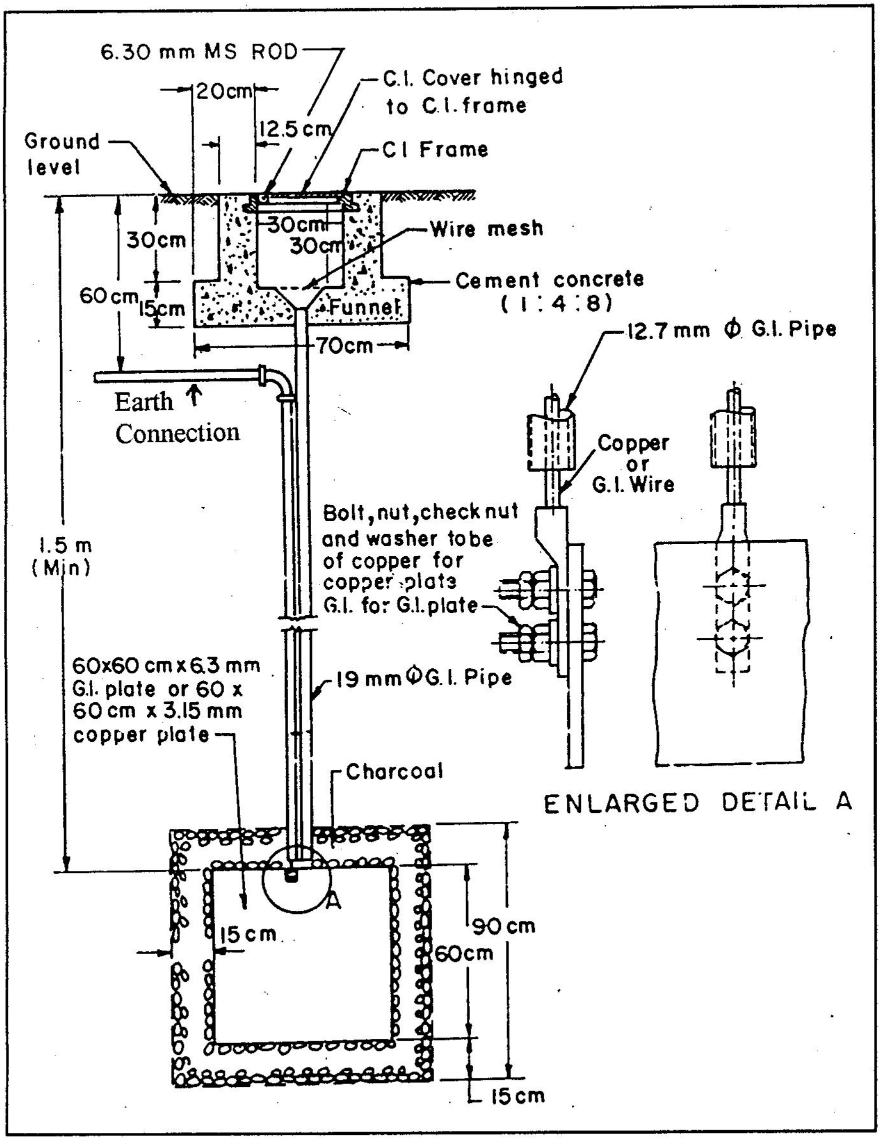


Fig. 1.8: The Plate Earthing

1.10 Direct reading Earth Resistance Tester

A normal method to measure earth electrode resistance is the 'fall of potential method and is explained earlier. A special field instrument is available for thi measurement and is known as a direct reading earth resistance tester. A current and potential spike are positioned in the soil near the earth electrode under test and ar connected by suitable cables to the earth resistance tester to complete the current an voltage circuit as shown in the figure below. For this measurement, the earth electrode is disconnected from the system it is earthing.

The voltage to be impressed in the soil is generated by a hand driven (at about 160 rpm speed) ac brushless generator or a battery operated vibrator. Most commonly, the generator output is about 500 volts at a frequency slightly above the normal supply frequency of 50 Hz. The output tapped from the soil is rectified and given to a moving coil galvanometer to directly read the earth resistance. Choosing the frequency above 50 Hz helps in minimizing the effects of stray currents induced in the soil by nearby ac power generation systems [2].

The normal spacing of the current electrode from the electrode under test is about 30 to 50 meters and the potential electrode is inserted at 62% of the distance in a straight line with the other two electrodes. The standard test spikes and cables for making temporary connections are supplied with the tester. These solid mild steel spikes, 45-cm long and 13-mm dia, are driven to the depth of 30 cm with rapid blows from 1-kg hammer [3].

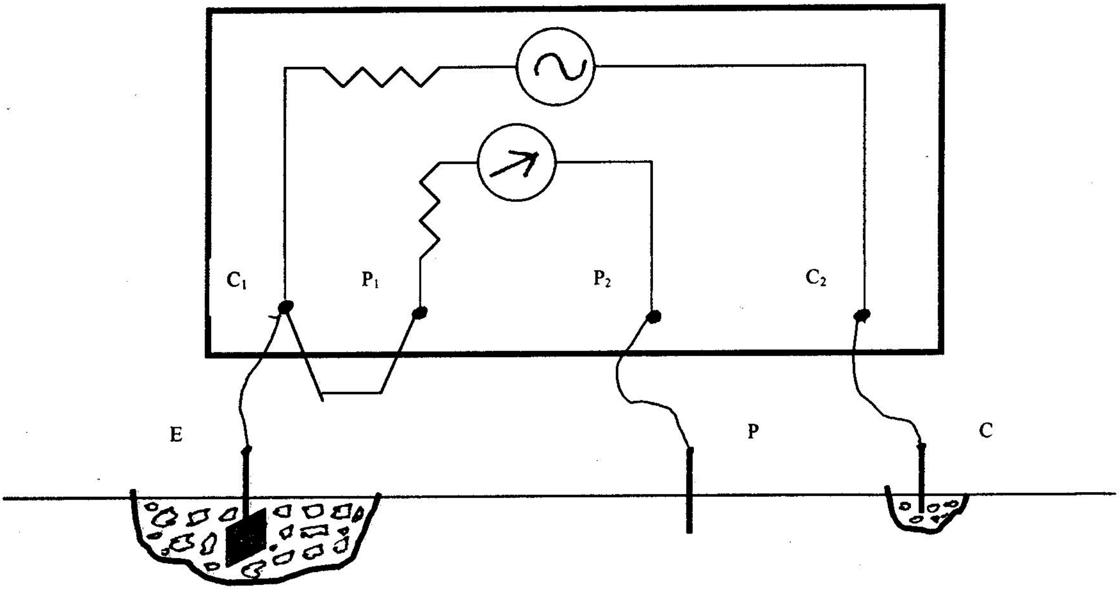


Fig. 1.9: The Direct Reading Earth Resistance Tester

This tester can be also used for measuring soil resistivity and neutral-earth loop tests for standard wiring regulations. The detailed circuit of this type of instrument is as shown below in Fig. 1.10 [2].

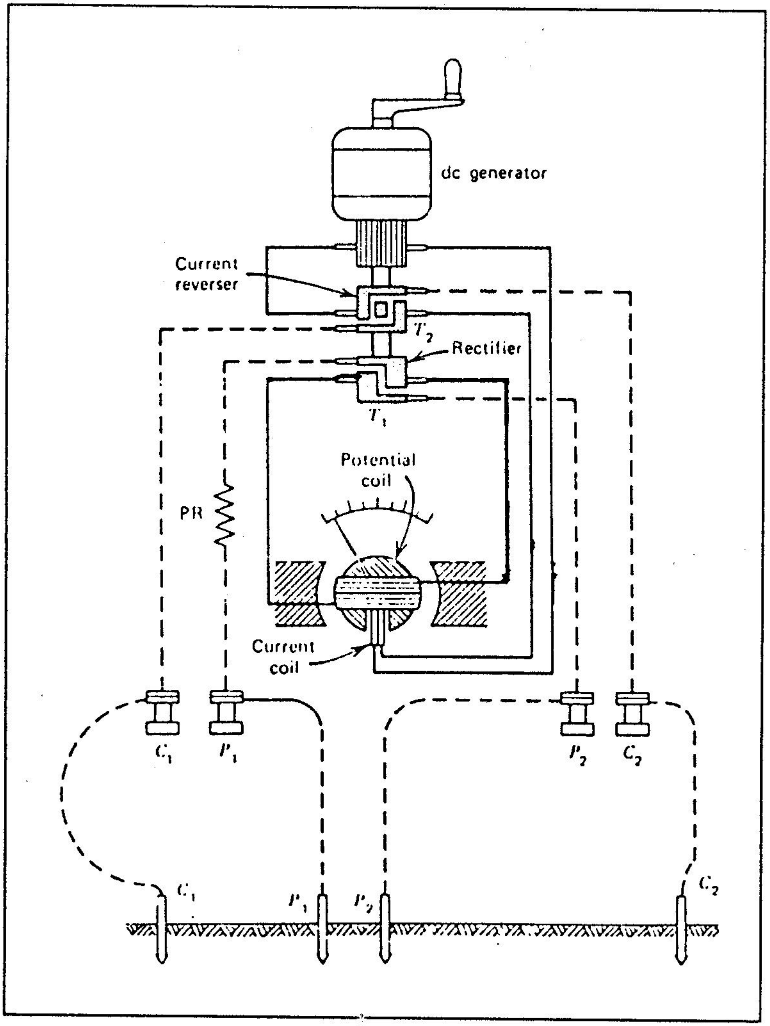


Fig. 1.10: Ohmmeter type Direct Reading Earth Resistance Meter

(Solid lines indicate Circuits carrying direct current and those carrying alternate current are shown by the broken lines).

2. Lightning and protection

Lightning is a transient high current electrical discharge, having path length of several kilometers. A lightning occurs when a region of atmosphere attains an electrical charge sufficient to cause breakdown of air between a charged cloud and the ground surface. Although spectacular in sight, the lightning causes destruction. It causes forest fires, building fires, physical damages to buildings, disruption of public services like electricity, telephone and communications etc. Above all, on many occasions, there is a significant loss of human life due to lightning.

2.1 Phenomenon of lightning

Lightning is typically an atmospheric phenomenon. The troposphere (12 km from the ground) and the stratosphere (from 12 km to 50 km from the ground) layers of the atmosphere play a major role in this. The top of the stratosphere and the surface of the earth are two very good conductors of electricity. Thus a giant capacitor (of 0.1 F) is formed by the top of the stratosphere and the surface of the earth with the layer of air between the two surfaces as a dielectric (see Fig. 2.1 [5]). The surface of the earth is negatively charged with a surface charge density of 10^{-9} coulomb/m^2. The total negative charge on the surface of the earth is 10^6 coulomb. All along the surface of the earth there is a downward vertical electric field of nearly 100 volts/meter. This field reduces with the height above ground and is quite negligible at a height above 10 km.

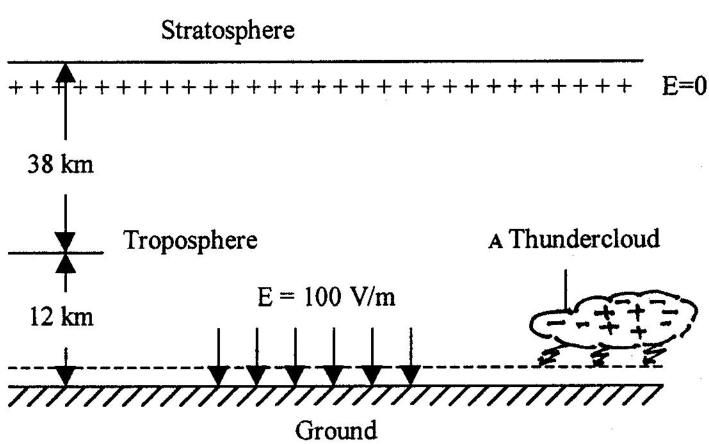


Fig. 2.1: The giant capacitor formed by the Stratosphere and the earth

The top of the stratosphere is an equi-potential surface. So is the surface of the earth. The air dielectric between the two surfaces however, contains ions, small nuclei of dirt, water-vapour carrying static charges etc. Due to the downward electric field, the positive ions continuously come down towards the earth and the negative ions keep on ascending up. This movement of charged particles gives rise to an average current of 3.5×10^{-12} coulomb/m^{2}second. At this rate, the surface of the earth will be neutralized in

10 minutes. But this does not happen in reality. Hence, there must be a natural phenomenon that helps to keep the negative charge on the surface of the earth unchanged. This natural phenomenon is that of thunderstorms and lightning. The lightning dumps average of –1800 coulomb charge every second on the surface of the earth to help maintain the potential difference between the stratosphere and the earth [5].

Thunderclouds are formed in a complex process known as a thunderstorm that on average lasts for about an hour. Towards the end of a storm an electrical breakdown of the air occurs and a large amount of negative charge is dumped into the earth along narrow pathways from the cloud to the earth. This is known as a lightning stroke.

Within each thundercloud, there is a separation of charged ions: positive charges and the negative charges form clusters in a peculiar form. See Fig. 2.2 below [2] for the charge distribution in a mature thundercloud. This creates a potential difference of 2×10^7 to 10^8 volts between the ground and the bottom of the cloud, the ground being at a higher potential. The resultant electric field is in the upward direction and has a value of 10^4 volts/meter to 3×10^4 volts/meter. Towards the end of each storm, when the electric field reaches such a high value, an electrical breakdown of the air occurs. The air gets ionized and can conduct large amount of negative charge along narrow pathways from the cloud to earth as mentioned before. This happens in bursts of small duration.

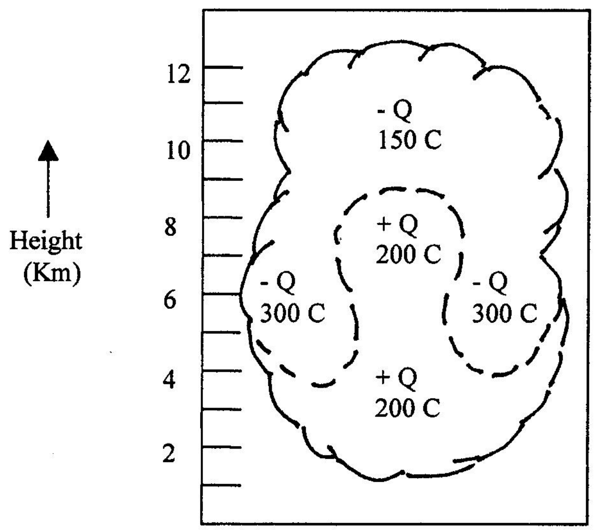


Fig. 2.2: Estimated charge distribution in a mature thundercloud

A typical lightning discharge starts with a leader stroke that is a downward movement of a negative charge in steps seeking areas of positive space charge. Each step of a leader advances its tip a distance 10 to 200 m in 40 to 100 μsec. Simultaneously, the point discharges from earth objects like towers, buildings and trees continue to move upwards towards the cloud. These two channels meet somewhere above ground (at about 70 m) at a point called a point of strike and a return stroke begins.

The return stroke can be regarded as an intense positive current from ground or as a lowering of negative charge to ground. Its purpose is to neutralize the opposite charges between the cloud and the earth. After the first return stroke it is usual for another region of the cloud to provide sufficient charge for a second stroke or several more, separated by intervals of 10 to 20 msec. This return discharge of one stroke or a succession of strokes is called a flash. The current in a stroke averages about 20 kA (100 kA in an intense storm). The average charge released per flash is about 20 coulomb. Hence, about 1000 to 2000 storms are required to occur (*and they do occur*) per day to maintain the energy balance in the atmosphere.

The return stroke current heats the path instantly to temperatures of 15,000 to 20,000^0 C, making the air luminous and causing the explosive air expansion that we hear as a thunder. Each return stroke is a unidirectional current pulse that rises to a crest value in a few microseconds and then decays over a period of several tens or hundreds of microseconds. Lightning strokes are commonly described by two figures such as 1.5x40 which means a current rise time of 1.5 μsec and a 40 μsec period for the current to fall to one half its crest value. Fig. 2.3 below [2] represents a typical shape of the return stroke current pulse. A current pulse exceeding 40 msec is sufficient to cause a forest fire.

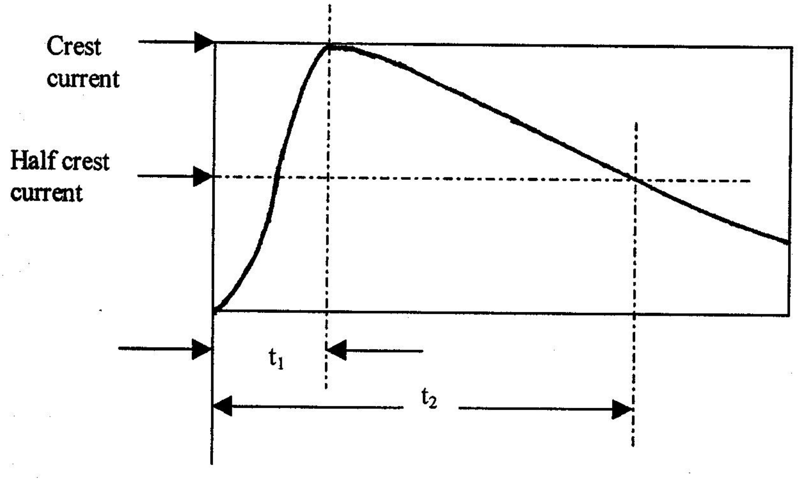


Fig. 2.3: Typical lightning current waveshape

After the first return stroke, there is usually enough charge in a higher region of the cloud to initiate another leader (called a dart leader) which may take the same path as a leader stroke. The dart leader starts after about 70 msec from the return stroke and reaches the earth within about 1 msec. This sequence of a return stroke followed by a dart leader repeats a few times till the charge on the cloud neutralizes.

Table 2.1 below [2] gives the typical parameters of various components of lightning.

Table 2.1: Quantitative aspects of lightning strokes

	Minimum	Representative	Maximum
Stepped leader			
Length of step (m)	3	50	200
Time interval between steps (μsec)	30	50	125
Average velocity of propulsion (m/sec)	1.0×10^5	1.5×10^5	2.6×10^6
Charge deposited on channel (C)	3	5	20
Dart leader			
Velocity of propulsion (m/sec)	1.0×10^6	2.0×10^6	2.1×10^7
Charge deposited on channel (C)	0.2	1	6
Return stroke			
Velocity of propulsion (m/sec)	2×10^7	5×10^7	1.4×10^8
Rate of current increase (kA/μsec)	1	10	80
Time to peak current (μsec)	1	2	30
Peak current (kA)		10-20	110
Time to fall to half peak current (μsec)	10	40	250
Charge transferred, excluding continuing current (C)	0.2	2.5	20
Channel length (km)	2	5	14
Lightning flash			
Number of strokes per flash	1	3-4	26
Interval between strokes in absence of continuing current (msec)	3	40	100
Duration of flash (sec)	10^{-2}	0.2	2
Charge transferred, including continuing current (C)	3	25	90

2.2 The nature of the danger from lightning

It is a common knowledge that lightning can cause injury and death. There is a greater risk of this in the equatorial latitudes, where thunderstorms occur with a greater frequency than at other latitudes. The degree of injury inflicted depends upon the value of the current passing through the human body, which in turn depends on the physical condition of the individual. Mostly the danger to human life is always from an indirect contact with the electric potential from a lightning stroke.

A Lightning striking a structure or tree can take a parallel path to earth through a person who happens to be close to the stricken object. The intense electric field from a stroke near a person can induce sufficient current in the body to cause death.

Lightning that terminates on the earth can set up a high potential gradient over the ground surface in an outward direction from the point or the object struck. A person near the point of strike standing on his feet is endangered by the potential drop between the points of contact made to earth at his two feet. The potential drop could also be developed in a vertical element carrying a lightning discharge, such as a wall, post or tree, and therefore across any person touching it at two separated points.

Thin conductors like those used in telephony can be melted by the temperature rise produced by the high lightning current. Furthermore, lightning hits on telephone lines cause arcing between the telephone junction box and other metal in the building and may produce a fire.

Power lines terminating at the building, if struck by a lightning, cause a burnout of the step-down transformer, damage to the switchgear or a fire.

In a coaxial cable struck by a lightning, a high potential on the outer conductor can produce flashes from it to other metallic elements that are at ground potential. Also a flash between the outer and the inner conductor can permanently damage the cable.

2.3 Protection from lightning

Lightning usually terminates on some vertical projection of a structure. In lightning protection one aims to protect only objects that are sufficiently isolated from higher objects to be vulnerable to a strike [2].

2.3.1 Lightning arresters for buildings

These are the long metal rods with pointed tips, which are mounted on the tall buildings to protect them from bolts of lightning. The pointed end (air terminal) of the conductor is connected to a long thick copper strip (down conductor), which runs down the building. The lower end of the copper strip is properly earthed or grounded by a buried earth electrode system. When a charged cloud comes near a building, an opposite charge is induced on the pointed end of the conductor. Due to discharging action of pointed tips, an opposite charge is sprayed to the surrounding air, which neutralizes the charge on the cloud. This spraying initiates and provides a pathway in the air along which the charge built up in the cloud can quickly travel and points to the earth. If the cloud discharges, it discharges through the conducting copper strip to the ground and the building is saved from a damage [5].

2.3.2 Protection of equipment

For the protection of electrical/electronic equipment and cables, surge suppressors are installed in the systems to be protected. Gas-filled spark gaps, solid state suppressors (Metal Oxide Varistors-MOVs) and quarter wavelength stub type surge suppressors shunt out lightning currents to ground once the incoming impulse voltage exceeds the breakdown voltage of the respective protection device.

3. Electrocution of a human body and its prevention

In a field station or a laboratory, a human operator may come in contact with a live voltage accidentally. This could be due to a faulty insulation of the live wire or a leaky ungrounded metallic chassis of an instrument. A current from this live point passes to the floor ground through the body of the operator who experiences an electrical shock. The intensity of this shock depends upon the live voltage, the resistance of the body of the operator and the floor resistance etc. Sometimes this contact could prove to be fatal and the utmost preventive care should be taken to avoid it in the first place. This chapter discusses the effects of an electrical shock, the safety measures and the first aid to be provided to a victim. These aspects have been extensively discussed in an Application Note from Protech Switchgears Limited, Vadodara [6].

3.1 Contact of a human body with electrical current

The human body is very sensitive to the passage of electric current. Just a small current passing through the chest can cause a serious harm.

At the standard power supply frequency of ***50 Hz***, the passage of an electric current through the human body may cause:

Muscular contraction, as a result of which the person concerned may remain stuck to the live part concerned, without having the strength to release himself.

Asphyxia: The muscles in the respiratory function ensure the rhythmical inhaling and exhaling of air by the lungs. If these muscles suffer contraction, the affected person may die of suffocation.

Cardiac fibrillation: The human heart is a pump that, with the coordinated and rhythmical contraction and expansion of its muscular fibers ensures circulation of blood throughout the body. When an electric current enters these fibers, the heart rate becomes irregular with increasingly uneven contractions which may cause total cardiac arrest.

If cardiac activity is stopped for more than 3 minutes the result is irreversible damage to the heart muscles and the brain tissue.

Sudden stoppage of the heart may occur due to the passage of strong electrical current through it. However, if the passage of the current is limited to an extremely short period, the heart may start again spontaneously without causing any damage.

Burns caused by electrocution due to strong currents may damage tissues, tearing of arteries and destruction of nervous centers etc.

The effects caused by the passage of an alternating current at standard frequencies through the human body for an unlimited period of time are described in the TABLE 3.1 below [6]:

Table 3.1

Magnitude of the Current	The effect on an adult (weight 68 Kg)
From 0 to 0.5 mA	no sensation
1 mA	threshold of perception
From 1 to 3mA	weak sensation
From 3 to 10 mA	painful sensation
10 mA	threshold of muscular contraction in the arms
30 mA	threshold of respiratory paralysis
75 mA to 100 mA	threshold of cardiac fibrillation (probability 0.5%)
250 mA	cardiac fibrillation with 99.5% probability (for an exposure time of 5 seconds)
4A	threshold of cardiac paralysis (sudden stoppage of the heart)
5A	burning of organic tissues

The amount of the electrical current passing through the human body depends on the resistance of the path through which it passes. The electrical resistance of the human body varies widely according to the age and sex of the individual.

It also depends on the factors listed below [6]:

- The condition of the skin area of electrical contact
- Contact voltage
- Type of insulation (shoes etc.)
- The mechanical pressure with which the contact is made
- Composition of the blood of the individual
- Percentage of alcohol in the blood

The magnitude of the applied voltage necessary to produce dangerous current values depends on the resistance of the body. This resistance varies between wide limits. Between hand and foot, for example, assuming good electrical contact, the resistance is about 500 Ω, excluding skin resistance. The skin resistance varies from about 1000 Ω/cm^2 for wet skin to about 3×10^5 Ω/cm^2 for dry skin and even higher values on hands toughened by manual work. However, at voltages above about 240 V the skin is punctured, often inflicting deep burns and leaving only the internal impedance of the body to limit the current.

For the protection purposes a value of 500 Ω is commonly assumed for the body resistance between major extremities and a figure of 1500 Ω for the resistance between the perspiring hands of a worker [2].

Publication No. 479, published in 1974, by the International Electro-technical Commission (I. E.C.) gives the following current-time curve (see Fig. 3.1 [6]) produced by the Medical Studies Group of UNIPEDE in close contact with Committee 64 (Electrical Equipment) of the I. E. C.

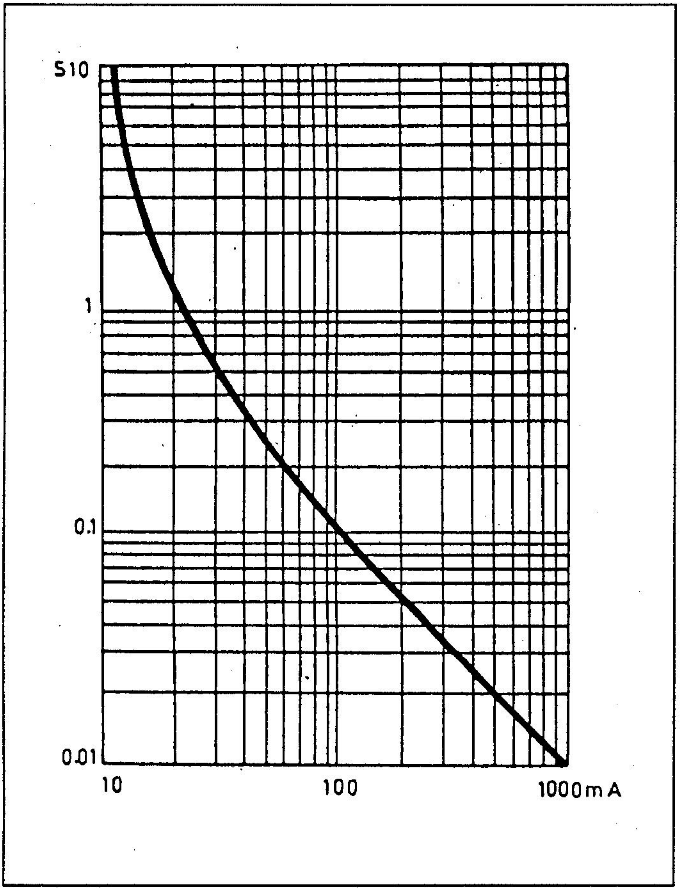


Fig. 3.1. Time/Current Characteristics

For all current/time values to the left of the curve, contact with a live part is so brief as to give rise to no harmful consequences, whilst all of the areas to the right of the curve indicate dangerous situations.

Effects of the current on the human body over a specific period of time are illustrated in the Fig. 3.2 [6] shown below.

The curves given here refer to the hand-foot electrical contact of individuals weighing at least 50 Kg.

This curve shows five areas, each with its properties listed as below:

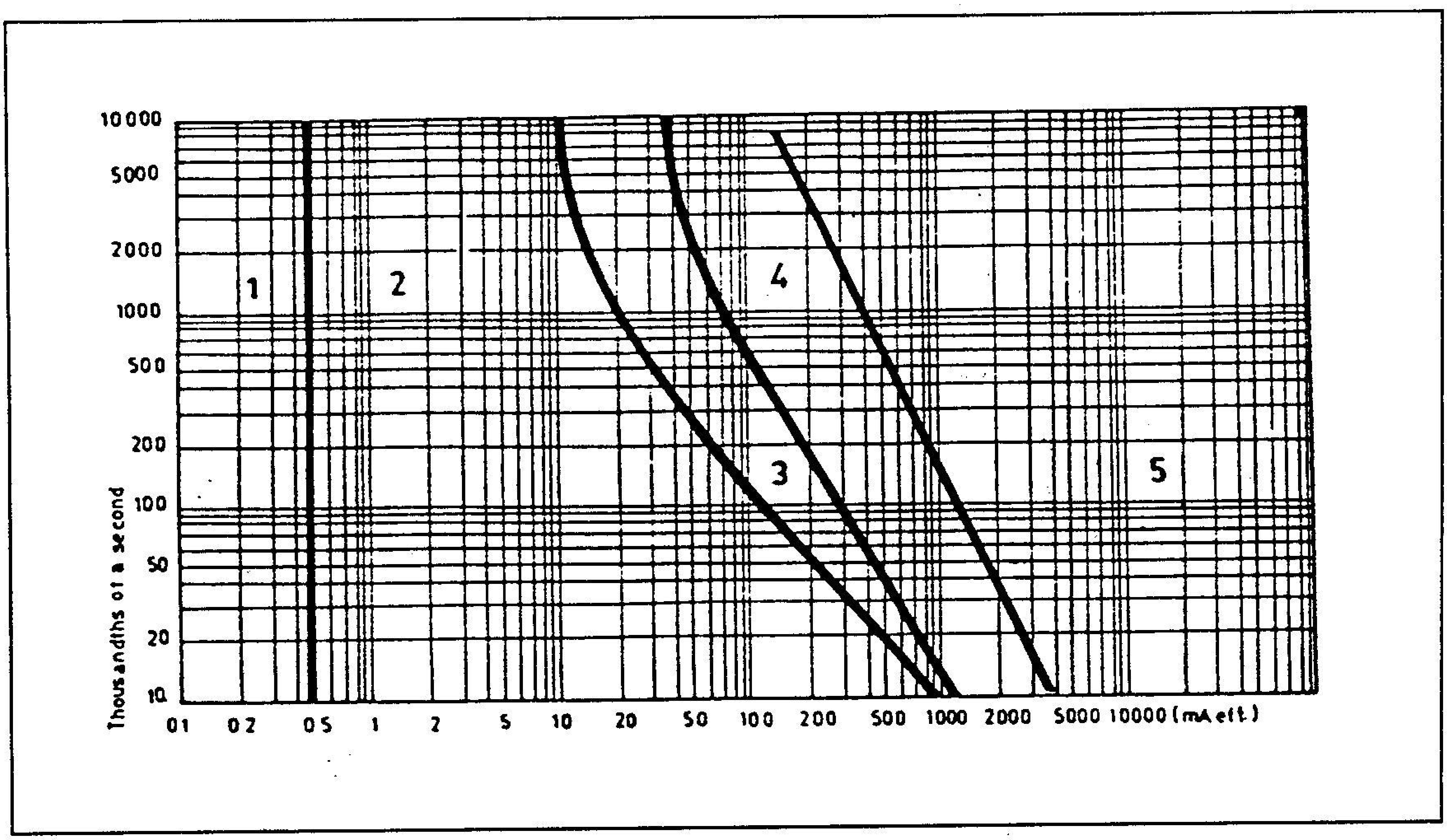


Fig. 3.2 Zonewise Time/Current Characteristics

Area 1:The individual shows no reaction to the passage of the current

Area 2:Passage of the current normally causes no dangerous physiological effect.

Area 3:Usually the individual runs no risk of fibrillation.

Area 4:Possibilities of fibrillation with probability up to 50%.

Area 5:Danger of fibrillation with probability above 50%.

At power frequency the impedance of the body is mainly resistive, but above 1000 Hz it exhibits reactance also due to the body's cellular structure and looks like a capacitance in parallel with a resistance. It is believed that very high frequencies, above 100 to 200 KHz, burns are the main effects produced.

3.2 General guidelines for safety while using electrical/electronic equipment

1. All metallic enclosures of the electrical/electronic equipments are connected to the ground conductor in the AC power outlet. This ground conductor is directly connected to the AC supply neutral at the secondary of the sub-station transformer where it is adequately grounded.

When a live to chassis (short circuit) fault occurs at the users premises, a heavy current flows through the ground conductor back to the AC supply neutral which ensures the tripping of the in-line fuses or a circuit breakers.

2. In addition to using the ground conductor of the AC mains supply, a buried earth electrode system at the user's premises may supplement the main system of power grounding. It will divert any leakage current in any equipment to the ground ensuring that any dangerous voltage does not appear on the metallic enclosure of the faulty equipment.

3. Earth Leakage Circuit Breaker (ELCB) may be installed at the AC supply entrance point of the equipment room. The ELCB monitors the leakage current flowing in any of the equipments in the room continuously and trips the AC mains supply in case the leakage current (difference between the phase current and its return current in the neutral) exceeds a few milliamps (typically between 5 to 30 mA) [2].

3.3 Human safety

When working in a field station, observing proper safety precautions is very important. The most common and serious hazard of the field station is an electrical shock. The severity of an electric shock varies somewhat with the age, sex and physical condition of the victim.

3.3.1 First aid for electric shock

The first step in aiding a victim of electric shock is to try and shut off the power to the conductor with which he is in contact. If the attempt is not successful and the victim is still receiving shock, pull the victim from the live conductor with the help of an insulator like a piece of dry wood, rope, cloth or leather.

If breathing has stopped and the individual is unconscious, start giving artificial respiration immediately. Do not stop until a medical authority pronounces the victim beyond further help. This may take up to eight hours [7].

3.3.2 Safety rules

Wolf [7] suggests following general-purpose safety rules that may be observed by the personnel working in a shop housing a variety of electrical equipment.

1. Never work alone. Be sure there are others in the field station to summon and provide aid in case of accidents.

2. Use only instruments and power tools provided with three-wire chords.

3. Always shut off power before handling wiring.

4. Check all power cords for sign of damage. Replace or repair damaged cords and leads.

5. Always wear shoes. Keep shoes dry. Avoid standing on metal or damp concrete. Do not wear metal rings etc.

6. Never handle electrical instruments when your skin is wet.

4. Protection Devices

The 3-ϕ substation transformer at the field station site provides electrical power to the field station building through an underground armored cable. Inside the field station, the electrical power is distributed through insulated cables to various rooms and equipment racks through distribution boards or wall sockets located at strategic points. A momentary direct contact with the ac supply voltage can cause an electrical shock or electrocution of a person if he touches an open wire, a damaged socket or a leaky instrument. The current flowing through the body of the operator depends upon the resistance of the path to the ground. Replacing an open wire or a damaged socket in time can prevent the danger of an accidental contact with it. A leakage on a metallic chassis of an instrument can be avoided by connecting it to a ground reference thus limiting the touch voltage to a very safe value.

Traditionally, the ac supply voltages are referred to the ground. The neutral wire of the substation transformer secondary is grounded or earthed near the transformer and a ground conductor (a thick copper strip or a wire) from this point is run along with the underground cable carrying the three phases and the neutral. The ground conductor is connected to the central grounding system of the field station. All the metallic enclosures of the electrical/electronic instruments in the station are also connected to the central grounding system. It provides a direct path for a current from an instrument to flow back to the neutral when a live wire in the faulty instrument directly touches its metallic enclosure (due to a breakdown of the insulation). This direct connection to the power neutral enables a prompt operation of the in-line circuit breakers installed upstream, thus eliminating the chances of a direct contact by the human operator. (See Fig. 6.2).

A short circuit at the load or a heavy leakage current flowing in a circuit for a long time can damage the wiring or the load equipment or can create fire and safety hazards at the installation and must be prevented by installing appropriate circuit breakers.

Electrical and electronic equipment in the field station also needs to be protected from power line surges and lightning strikes. Lightning surges also enter the field station via the overhead telephone line or the antenna and coaxial cable of the radio communication equipment. Direct lightning strikes on the field station building are diverted to ground via the lightning arresters mounted on the rooftop of the building.

The common protection devices usually used in a field station for the protection of the human operator, the wiring and the field station equipment are described below.

4.1 Fuses

A fuse is an intentionally inserted weakest series element in an electrical circuit. On many occasions a short circuit at the load, heavy leakage current due to a faulty insulation on the wires or coils or an overvoltage from the supply side can cause excessive current to flow in an electrical circuit. An abnormal overloading current flowing in a circuit for a long time can damage the wiring or the load equipment in addition to creating fire and safety hazards at the installation and needs to be prevented by using a fuse of a proper rating [8].

A fuse is a piece of a good conducting material (usually an alloy formed by the metals like silver, lead, copper, tin and zinc) wire or a strip which melts when excessive current flows through it. This action disconnects the load from the supply line before any damage occurs to the wiring or the load equipment. (Circuits should be installed with fuses on the hot side of the input power line unless both sides are fused. If the fuses were placed in series with the neutral side of the line, the load side would remain at the potential of the hot wire, even if the fuse were burnt out. Therefore the shock hazard would still exist.) In ordinary applications, the so-called *fast fuses* are used. In some of the special applications, delayed-action or *slow-blow fuses* may be used as the protective element. A slow-blow fuse resists melting if its current rating is exceeded for a short period of time. However, if the overload is too large or persists too long, such a fuse also eventually melts and opens [7].

Replacing the fuse without identifying or rectifying the cause of the overload may not help. At times, repeated blowing of the fuse may tempt the operator to erroneously use a fuse of higher current rating only at the cost of a higher risk to the installation.

For selecting a fuse of proper current rating for a given installation it is important to know a few terms used in this regard and they are listed below.

Current rating of a fuse is the maximum amount of current flowing through it for a long time without changing the shape or temperature of the fuse itself and its contacts with its holder. The current rating of the fuse depends on the properties of the fuse material, its size and the environments in which it is mounted.

Fusing current is the lowest amount of current which when flowing through the fuse causes it to melt and disconnect the load from the power supply. The fusing current also depends upon the properties of the fuse material and its size. It is directly proportional to the diameter of the fuse and inversely proportional to the length of the fuse. It also depends upon the size of the contact terminals and the environments in which it is mounted. The fusing current also depends upon the past history of the current flowing through the fuse and any increase in its temperature due to it.

Fusing factor is the ratio of the fusing current and its current rating. It is always greater than unity and usually lies between 2 and 3.

Prospective current or ***fault current*** depends on the parameters of the circuit in which the fuse is installed. It is a function of the circuit voltage and the total circuit impedance at the time of the fault. The maximum fault current flows during a short circuit in the current path.

Cut off current of a fuse is the maximum amount of current flowing through the fuse before it melts and is normally equal to or greater than the fusing current.

Breaking capacity or the ***rupturing capacity*** of the fuse is the highest amount of current that can flow through it without damaging the case or the holder in which it is mounted. This requires that the arc formed in it should be quenched in a very short time and within the body of the fuse itself. The rupturing capacity of the fuse should be more than the prospective fault current.

***Total operating time*:** Whenever a fault or a short circuit develops in a circuit, a heavy current flows through the fuse element and it melts down in a short duration. This is the total operating time and is the sum of the pre-arcing time and the arcing time.

A fuse works on the principle of electrical heating of the material and breaks the current path of a circuit in which it is installed, when the temperature of the fuse reaches its melting point. A fuse element has (a very small but finite) resistance R ohms, and whenever a current of I amperes flows through it for a time t seconds, I^2Rt joules of heat energy is produced in it. This heat is transferred to its surroundings through the process of conduction and radiation. The temperature of the fuse stabilizes at a point where the amount of heat generated and that lost to the surroundings is exactly balanced.

A (sudden or gradual) increase in the current increases the temperature of the fuse (even if some amount of heat is lost to the surrounding atmosphere). Due to the oxidation of the surface of the fuse element, the diameter of the fuse element starts reducing resulting in an increase in its resistance and consequently the increase in the amount of heat generated with the result. Simultaneously, the length of the fuse element starts increasing due to the heat produced. Eventually the temperature reaches the melting point of the fuse material and the fuse breaks in two or more pieces. The air between the pieces, however, helps in forming an arc between them. The oxygen molecules in the surrounding air sustain the arc. This further increases the temperature and subsequent melting of the adjacent areas of the fuse material. This continues till the gap between the two pieces widens to such an extent that the arc can no longer be maintained and the electrical circuit finally breaks and the current ceases to flow through it [8].

The Table 4.1 [9] shown below gives a typical current-time characteristic of a typical quick-acting type fuse used in general applications for multiple values of its rated current I_R of 1 Amp.

Table 4.1

I_R	1.5 I_R	2.1 I_R	2.75 I_R	4 I_R	10 I_R
-	> 1 hour	< 30 sec	100 millisec to 5 sec	20 millisec to 1 sec	< 50 millisec

The other specifications for the same fuse are as follows:

Rated voltage: 500 V ac max,
Breaking capacity: 10 kA @ 440 V ac, and
Voltage drop (typical): 300 millivolts.

The total operating time of the fuse should be as small as possible to avoid the safety and fire hazards. An overloading current if not tripped by the fuse in time, can damage the insulation on the wires and coils over a period of time resulting in heating of the circuit components and wires leading further damage to the insulation. This, if remained unnoticed, can cause a big damage to the total installation and heavy losses in the long run.

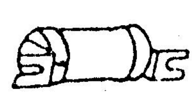
4.1.1 Classification of the fuses

Fuses can be classified by their current ratings, supply voltages in which they are recommended and their physical construction, the factors that are heavily dependent on each other. A few of them are listed below.

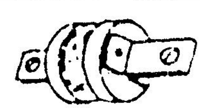
A. Semi-enclosed or rewirable type
B. Totally enclosed or cartridge type
C. Current limiting fuse link
D. High Rupturing Capacity (HRC) type
   1. Clip on type with offset tag
   2. Bolted type with offset tag
   3. Bolted type with central tag
   4. DIN type with blade contact

The figures below [10] shows the schematics of the HRC fuses mentioned above.

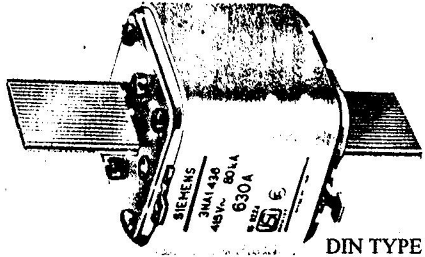
CLIP ON TYPE
WITH OFFSET TAG



BOLTED TYPE
WITH OFFSET TAG



BOLTED TYPE
WITH CENTRAL TAG



DIN TYPE WITH BLADE CONTACT

Fuses are available from many suppliers or manufacturers. A few of them are:

- The English Electric Company of India Ltd., Hosur.
- Siemens Ltd., Bombay.
- Larsen & Toubro Limited, Bombay.
- Protectron Electromech (P) Ltd, Bangalore.

Raychem RPG Limited, Bangalore, supplies *resettable* fuses from Raychem Corporation, USA.

4.2 Miniature Circuit Breakers (MCB)

A Miniature Circuit Breaker (MCB) protects wires and cables automatically against overheating arising out of excess currents due to sustained overloads and short circuits in domestic, industrial and laboratory installations.

In systems where proper earthing is provided the MCB provides additional protection by instantaneous interruption of the fault current thereby eliminating the possibility of excessive touch voltages.

MCBs can be used in place of wire fuses, cartridge fuses or HRC fuses in any installations and are more safe and dependable than all these types. They can be used for individual electrical appliances also. They are suitable for mounting in consumer units, distribution boards and switchgear panels. The Figure 4.1 below shows a typical single-phase (230-volt ac) and a three-phase (400-volt ac) MCB used in domestic or laboratory applications.

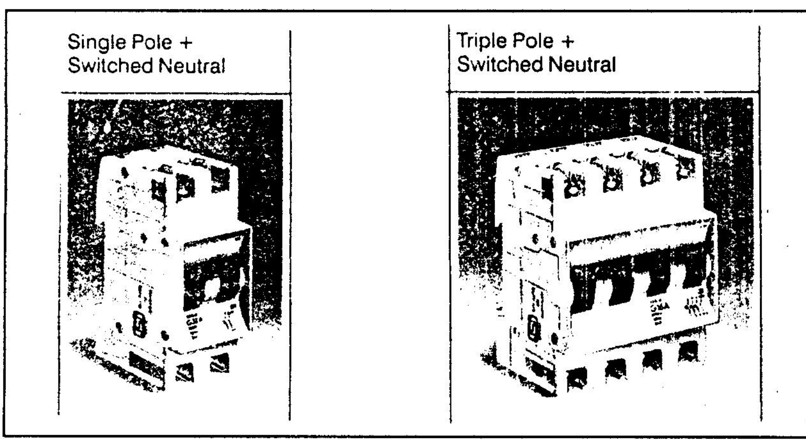


Fig.4.1: A Miniature Circuit Breaker (MCB)

The MCBs have a thermal (bimetal) release and an electromagnetic release. The thermal release trips on overloads and the electromagnetic release trips instantaneously on short circuits and excessive overloads. The electromagnetic trip is undelayed as against the thermal trip, which is inverse time delayed [11].

Typical MCB characteristics for tripping time against its rated current are shown in the Figure 4.2 [12] below.

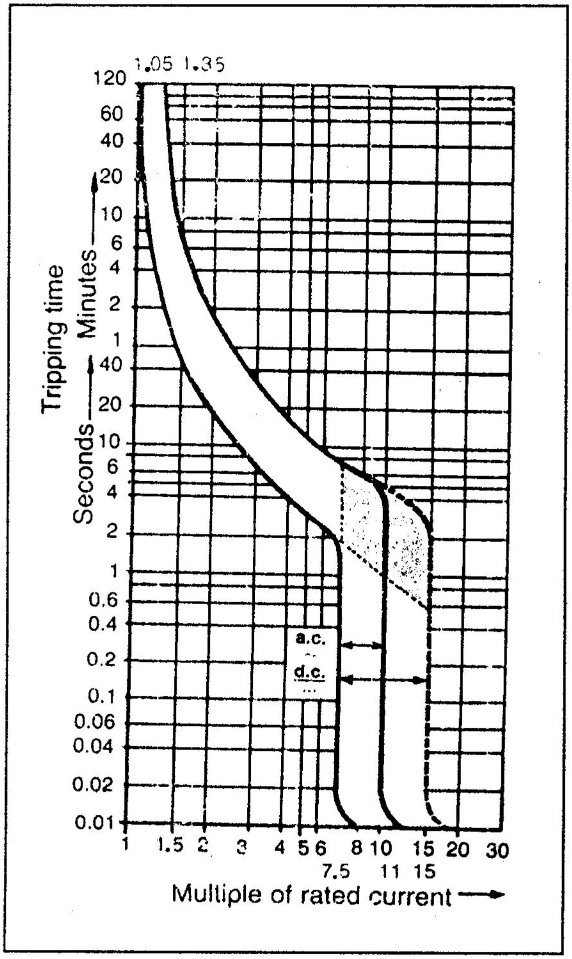


Fig.4.2: The tripping time Vs rated current of a typical MCB model

Under overload conditions, tripping is achieved with the aid of a bi-metal element, which deflects when heated by the over-current flowing through it. This deflection actuates a latch support that releases the latch mechanism, forcing the contacts to open under a positive spring force.

Under short circuit conditions, tripping is achieved instantaneously, by the action of a push-pull solenoid. Armature movement in this mechanism pushes the latch support to release the latch mechanism and simultaneously also pulls the moving contact to off position [13].

The current limiting MCB model (e.g. MDS make) has an arc chamber (chute) in it to extinguish an arc formed in it. Under a short circuit condition, as the current builds up, at a set value of the limit current, the magnetic trip takes over and the solenoid plunger – or hammer – forcibly separates the contact and establishes the arc within 1 millisecond. The arc is then moved into the arc chamber due to which the arc voltage rapidly rises and the short circuit current is killed in 4 to 5 milliseconds. To ensure quick arc quenching, a special arc chamber with a number of arcing plates (about 14) is provided. The arc is broken down into partial arcs, thus increasing the arc resistance and the voltage required to maintain it [12].

It is recommended that a 2 pole MCB should be used for a single-phase wiring and a 4 pole MCB should be used for three-phase wiring. This ensures that all the wire conductors are disconnected from the faulty loads when an MCB trips due to an overload or a short circuit on the load side. Models for rated current up to 60 amps are available in the market and can be easily installed on a main switchboard on the wall. Alternately, they can be installed on a DIN rails by a simple snap action. The multi-pole toggle switch on the MCB has to be manually reset to ON position after it trips due to an overload (or a short circuit). If the fault on the load side persists, the MCB trips repeatedly till the fault is cleared. The latest MCB models (e.g. Siemens make) incorporate a special trip-free mechanism. This MCB automatically interrupts all poles in the event of an overcurrent or a short circuit, even if the MCB toggle switch is held in ON position [11].

MCBs with 'L' characteristic have a low magnetic response limit (non-trip – 4 A, positive trip – 7A) and are most suited for lighting circuits and for protection of conductors.

MCBs with 'G' characteristic have relatively high magnetic response limit (non-trip - 7 A, positive trip – 10 A) and are most suited for installations with high in-rush currents including loads such as motors, air conditioners, fluorescent lamps, machine tools etc. These are the so-called motor-duty MCBs [13].

The MCB contact tips are made of special silver tungsten and silver graphite alloy, ensuring higher life and maximum safety against contact welding. These contacts have low contact resistance resulting in reduced voltage drop and very low watt loss leading to energy saving.

The MCB models with auxiliary contacts and for systems with DC voltages are also available.

In the majority of electrical installations the fault currents (of approx. 3000 amp) are considerably lower than the breaking capacity of the MCB. Therefore the MCB itself will clear the fault without the line side fuse blowing up. If the prospective fault level exceeds the rated breaking capacity of the MCB, back up protection from a line-side fuse is required. An HRC fuse of appropriate rating should be used before the MCB for additional protection [11].

The technical data of a typical MCB device available in the Indian market is shown in the Table 4.2 [13] below:

TABLE 4.2: Technical Data of an MCB

Specifications	Conform to IS:8828-1978, BS 3871
Rated Voltage	240/415 V AC
Rated Frequency	50 Hz
Current Ratings	2, 4, 6, 10, 16, 20, 25, 32, 40 A
No. of poles	1, 1+N, 2, 3, 3+N
Mounting	Quick mounting on 35 mm DIN channel
Short circuit breaking capacity	9kA
Electrical life at rated current	50,000 operations
Service life	1,00,000 mechanical operations
Protection Class	IP 20 as per IS 2147 – 1962
Max. cross section of conductor	16 mm^2

The MCBs are available from many sources and a few of them are listed below:

- Siemens Ltd., Bombay
- MDS Switchgear Ltd., Bombay
- Electric Control Gear (India) Ltd., Bombay
- Standard Switchgear Ltd., Ahmedabad.

4.3 Earth Leakage Circuit Breakers (ELCB)

A human operator may come in a direct contact with a live wire or he may touch a metal-case of a leaky instrument. In either case, a current flows through the body of the operator to the earth. The amount of this current depends on the touch voltage and the human body resistance, which is a variable. A current exceeding a few tens of milliamperes through the body may prove to be fatal if permitted to do so for a long time. The Earth Leakage Circuit Breaker (ELCB) when installed in the electrical wiring protects the operator from such hazards. The ELCB is a safety device, which operates on low earth leakage current flowing in an electrical system. At such small currents, fuses or circuit breakers do not provide any protection, as they cannot operate till very high current flows in the wiring [6].

In USA and Canada, the same device (ELCB) is known as a Ground Fault Circuit Interrupter (GFCI) and in Europe it is called a Residual Current Circuit Breaker (RCCB). All these devices (ELCB, GFCI and RCCB) operate on the same principle [14].

In a typical wiring arrangement of an ELCB installation shown below (see Fig. 4.3 [6]), the live and neutral wires are passed through a magnetic core. Under the normal conditions, because the current in both conductors is equal and opposite, there is no flux in the core and the relay coil is de-energized. The electrical supply to the load equipment is not interrupted.

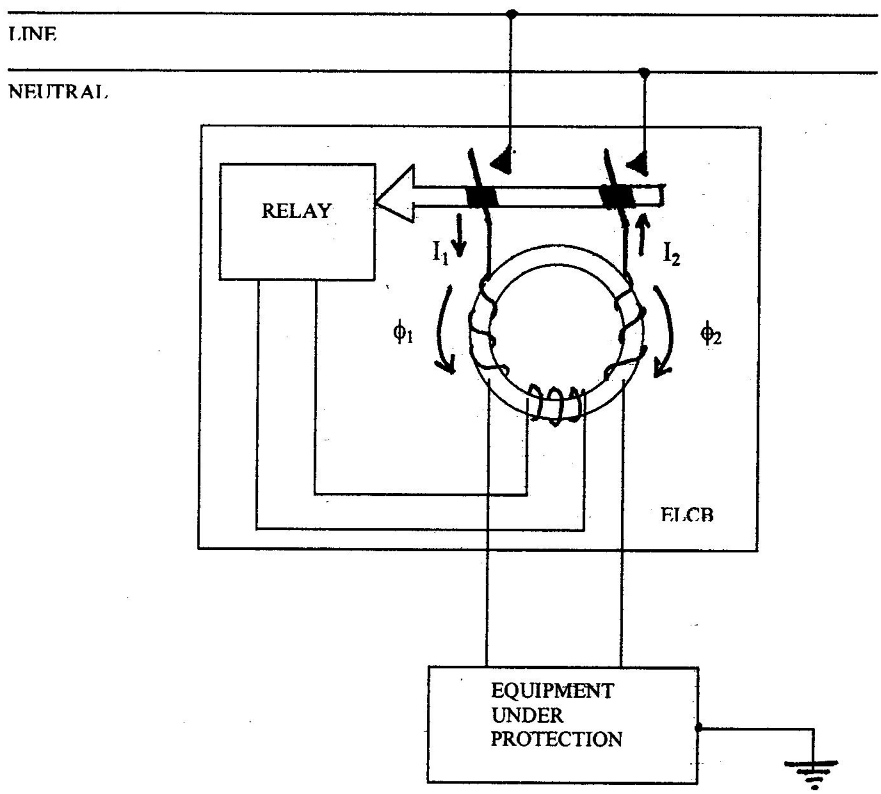


Fig.4.3: An Earth Leakage Circuit Breaker (ELCB) installation

Under certain fault conditions (e. g. leakage due to a faulty insulation), the current in the live wire can exceed the neutral wire. This produces flux in the core. The secondary winding on the same core produces a voltage, which is amplified and applied to a relay coil. The relay operates and interrupts the live and neutral conductor. The earth leakage trip current can be pre-adjusted between 5 mA to 30 mA depending on the application in which it is used.

A typical ELCB is built into a 230-volt circuit breaker and is located in the panel board. A reset lever is provided on the ELCB to reset it after the cause of the leakage is detected and removed. A test button, if provided on an ELCB, can be pushed to check the functioning of the device as this action simulates an imbalance in the live and the neutral wire.

In the three-phase ELCB variety, the vector sum of the currents in the three lines and the neutral is continuously monitored. A nonzero current indicates a leakage in the wiring and the ELCB operates and disconnects all the supply conductors of the equipment [15].

The technical data of a typical ELCB device available in the Indian market is shown in the Table 4.3 [15] below:

Table 4.3: Technical Data of an ELCB

Specifications	BS 4293 – 1983/IS12640 – 1988	
Sensitivities	High (30 mA)	
	Medium (100 mA)	
	Low (300 mA) Optional	
Normal Voltage	2Pole 240 VAC 50 Hz	
	4 Pole 240/415 VAC 50 Hz	
Electrical Life	4000 operations	
Mechanical Life	20,000	
Connection Capacity	25/40 A – 16 sq. mm	
	63/80 A – 25 sq. mm	
	100 A – 35 sq. mm	
Ambient Temperature Range	5^0C to 40^0 C	
Degree of Protection	IP 30	
Recommended Back-up HRC fuses	for 25 A & 40 A	80 A
	for 63 A, 80 A & 100 A	100A

Installation of an ELCB for a domestic environment and that for a number of equipment that performs a variety of unrelated functions in a field station can differ considerably. A tripping of a single ELCB need not bring to a halt the operation of the entire field station till the cause of the trip is located and rectified. For this, the equipment in the field station is divided in clusters and a separate ELCB is installed for each of them. This allows a majority of operations in a field station to continue in case an ELCB trips the supply to a group of equipment in a cluster.

ELCBs are available from following suppliers:

- Siemens Ltd., Bombay
- MDS Switchgear Ltd., Bombay
- Protech Switchgears Ltd., Vadodara.

4.4 Surge Protection Devices (SPD)

The equipment in a field station requires protection from power line surges and lightning strikes. In a field station, the overhead transmission line voltage (11KV) is stepped down by the substation transformer and on the secondary side of this transformer, a 4 core (3 phase and neutral) armored cable is laid underground up to the station building to power the station equipment. (See Fig. 6.2)

The substation transformer, the poles and the incoming overhead wires are protected from lightning and other surges by heavy-duty rod-gap, sphere-gap or horn-gap type arresters [8]. These are usually installed and maintained by the utility services like the state electricity board. The underground armored cable carrying a well-grounded neutral wire from the substation transformer is less likely to be damaged by a direct lightning strike. The overhead telephone lines and the radio link equipment, however, are more vulnerable to the lightning strikes and need protection against them. Inside the field station, surges may appear on the AC power line conductors due to power-line switching, switching on and off of large motors or from other equipment's operated in the field station [2].

Using surge or transient suppressors at the critical points in the station wiring helps in protecting the sensitive electronic equipment in the field station. In general, spikes, surges and transients are short duration pulses but their duration boundaries are not well defined. The protection devices used against them are industrially known as Surge Protection Devices (SPD). The SPDs divert and dissipate surges superimposed on the normal sine wave of the ac power source [16].

Surges are the high amplitude pulses of a few microseconds or milliseconds duration. When they appear on a power line, they cause system crashes, interruptions and occasionally damage to sensitive electronic devices and equipment. Surges can occur anywhere on the power sine wave, both in a negative and positive direction.

As stated above, the surges are caused by many natural or manmade events, for example, lightning strikes on the power line (direct or induced), power line switching, switching on or off of reactive loads, ground faults on the power lines etc. They can also originate from other electronic equipment like Xerox machines and printers operating on the same power line. The power line surges can have 5 to 6 kV amplitude but have no definite frequency and appear randomly due to the unpredictable nature of their origin. In addition to interruption and damage to equipment, power line surges can cause breakdown in the electrical insulators, can erode electro-mechanical contacts and generate noise on the line. Surges are too fast for the mechanical devices and circuit breakers or fuses to respond [16,17,19].

Surge suppressors or surge protection devices are the components that divert and/or dissipate the high voltage transients on a power line, telephone line, computer data line or a coaxial cable line connecting an antenna to a radio transmitter or a receiver. It needs to be ensured that the surge suppressors protect all the wire combinations (i. e. normal mode and common mode) reaching the circuit to be protected.

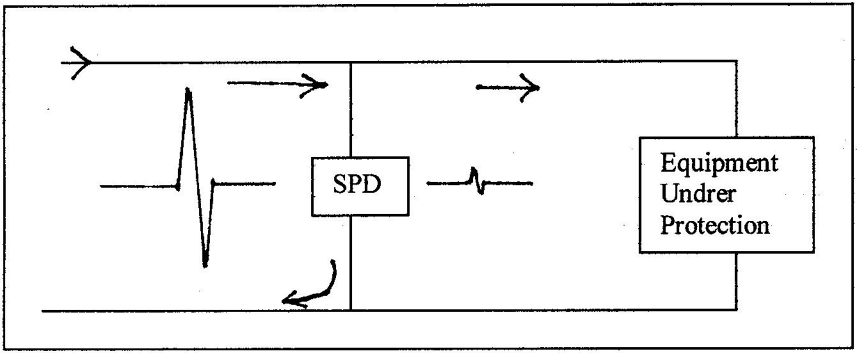


Fig. 4.4 Functioning of an SPD

A variety of surge protection devices like MOVs, spark gaps, Tranzorbs, Transient Voltage Suppressors (TVS) and coaxial line arresters are available in the market for various applications and a few of them are described below.

Guidelines for selection of surge protectors for specific applications [19]:

1. Determine the maximum steady state working voltage (AC or DC) of the circuit.
2. Establish the transient energy to be absorbed by the surge suppressor.
3. Calculate the peak transient current through the suppressor.
4. Select the surge suppressor type and model from the product catalog for the required maximum clamping voltage/current acceptable for a given application.

4.4.1 Metal Oxide Varistors (MOV)

Metal oxide varistors (Fig. 4.5) are voltage dependent non-linear devices. These are bilateral and have symmetrical V-I characteristics and have large peak current capability (of the order of a few kilo-amperes). They are used for absorption of transient voltages, suppression of pulse noise and circuit voltage stabilization [18].

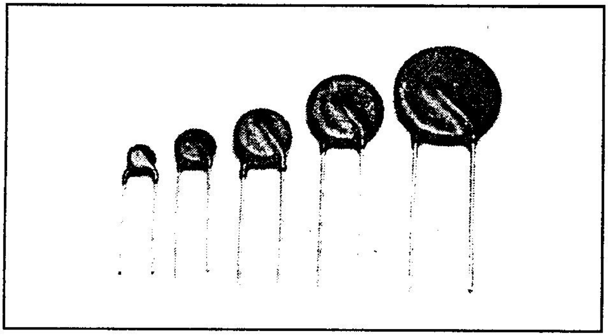


Fig.4.5: Metal Oxide Varistors

MOVs are manufactured using a semiconducting metal-oxide, mostly Zinc oxide (ZnO). At low and normal operating voltages, a Zinc oxide varistor provides a very high resistance and draws a very small current (a few hundreds of microamperes). As a high voltage spike exceeding the breakdown voltage of the varistor arrives, its resistance becomes very low and it clamps the incoming voltage to a fixed value till the surge is over. The V-I characteristics of a varistor beyond the breakdown is non-linear and is given by the equation, $I = kV^{\beta}$, where β is the slope of the V-I curve of the varistor. During the breakdown period, the varistor draws heavy current and consumes most of the surge energy; thus saving the equipment or device before the surge can cause any damage to it [17,19]. A typical application circuit employing MOVs is shown below in Fig. 4.6.

MOVs are now widely used surge protection devices in

- Consumer electronics
- Industrial electronics
- Telephone and telecommunication systems
- Relays and contacts (for absorption of switching surges)
- Electronic ballasts and
- Power supplies.

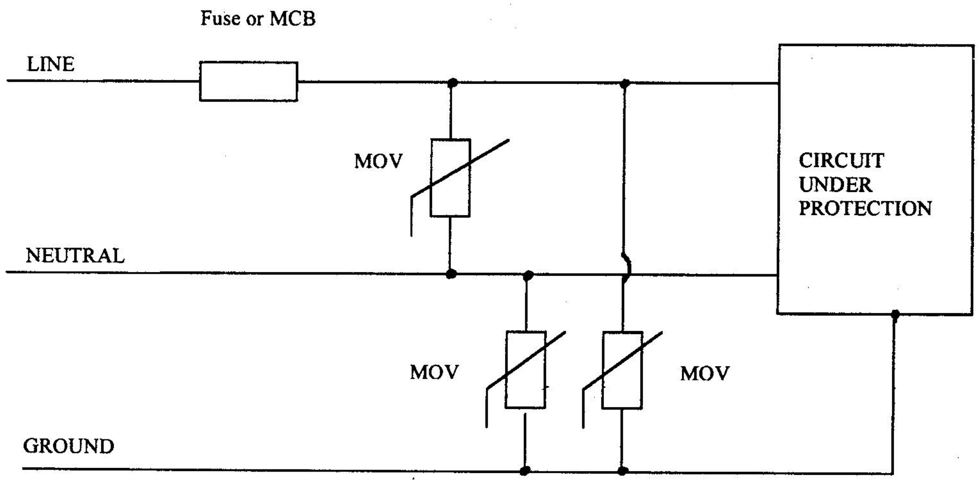


Fig.4.6: Circuit Protection using MOVs

A fuse (or MCB) should be connected before the MOV protection. It provides additional safety for the circuit in case of a fault in any of the MOVs.

In the circuit shown above, a 300-volt MOV will draw a negligible current in a normal operation of the circuit under protection. However, when a surge (of a few kV) appears on the power line, the MOV will clamp its output at a voltage slightly higher than 300 volts and will save the circuit from any damage from the surge. It dissipates almost all the energy in the surge. The transient energy consumed by the MOV during the surge can be given by the expression V_{clamp} x I_{pulse} x pulse duration and should not exceed the rating of the chosen MOV [18].

An MOV can absorb transients and surge voltages only. If it is subjected to a high voltage continuously, the MOV will heat up and fail.

The MOV chosen for a circuit protection will operate successfully only for a certain number of surges (depending upon the peak current and pulse duration). Afterwards there will be performance degradation in it resulting in higher leakage current or change in its V-I characteristics. The MOV is chosen for a particular circuit and environment so that it successfully operates for more than 100 times before it is replaced [17,19].

MOVs can be obtained from:

- M/s C P Clare Corporation, Beverly, USA
- M/s Gujarat Mulco Electronics LTD., Umargam (Valsad)
- M/s Keltron, Trivandrum
- Philips India Ltd., Bangalore.

4.4.2 Gas-filled spark gaps

A basic form of gas-filled spark gap consists of two spaced electrodes sealed in a glass or ceramic capsule containing gas. The threshold voltage, also called striking or spark-over voltage is determined by the electrode spacing, the kind of gas mixture and the gas pressure. The gas filled gaps are now available for a wide range of spark-over voltages (from 200 to 5000 volts), current (up to 50 kamp) and energy ratings (50 kjoules) to protect various kinds of circuits. The arc resistance of these spark gaps is typically of the order of 10-20 milliohms [20].

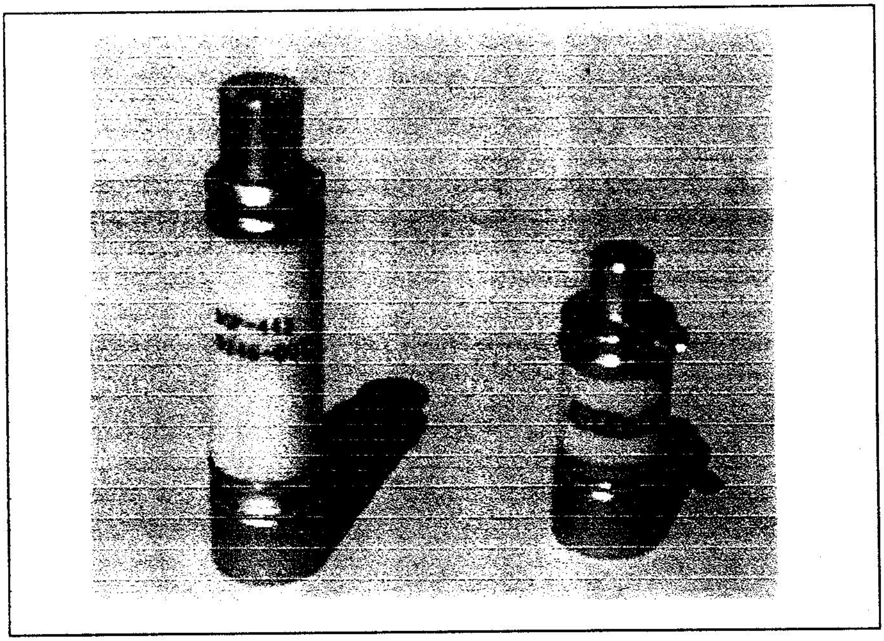


Fig 4.7: Spark GapsFrom E G & G Inc. (USA)

For example, a small model using two electrodes of 16 gauge (0.13-cm diameter) tungsten metal will carry a current of 80 kamp for a few microseconds, after which the wire ends will vaporize, thus widening the gap so as to extinguish the arc. In order to preserve the gap for repeated operations under sustained current, a current-limiting resistor and inductance is added in series with it. Occasionally, a fuse is also added in series with the gap.

A typical circuit where such gaps are used between each conductor of the telephone line and the ground is shown below in Fig. 4.8.

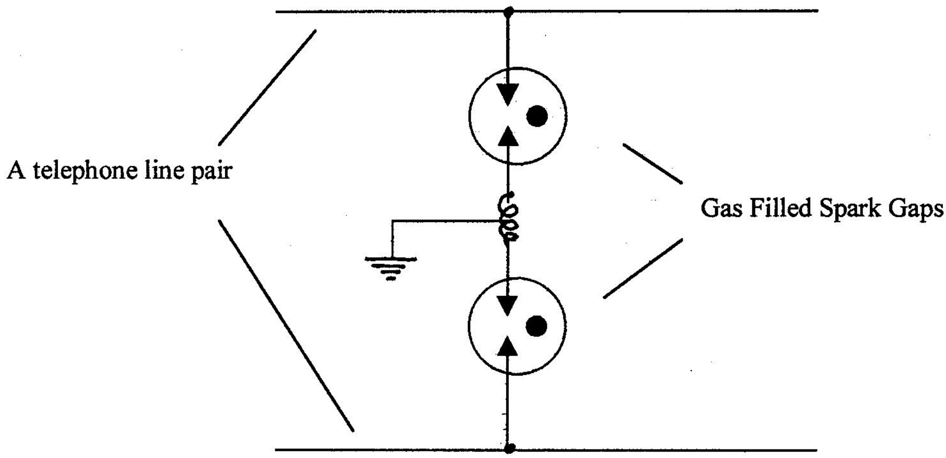


Fig.4.8: A Telephone Line Protection with two Spark Gaps

The circuit above tends to make both arresters strike at the same time and retain the circuit in balanced and operating condition even though the protective gap is operated.

Three element gaps in a single capsule is also available for protecting both sides of a balanced circuit to ground.

The striking voltage of arresters is dependent on the waveshape of the overvoltage. The waveshapes of surges due to lightning and other causes vary with each occurrence. This information and the rate of repetition of these surges is also not predictable with any precision and hence must be predicted on the basis of the past experiences [2,20].

4.4.3 Coaxial line arresters

For the protection of radio transmitters and receivers coaxial line type arresters are recommended. These type of high energy surge and lightning arresters have a wide bandwidth, low VSWR (1.1:1) and low insertion loss making them suitable for a wide variety of applications that include telemetry, fixed/mobile transmitters and receivers. These devices have an M5 stud on the base so that they can be chassis mounted. Alternately they can be mounted on a mounting bracket.

These are available in N, BNC and UHF types with female connectors as shown below in Fig.4.9 [21]. Maximum transmitted power through these is 150 watt at 50 Ω. The protective element is either a low capacitance gas arrester or of solid state type

(MOV). A superior method of protecting rf transmitters and receivers is a quarter wavelength (λ/4) stub [22] which shunts lightning currents to ground. The λ/4 stub suppressor acts as a short circuit for frequencies operating below the intentional passband and has low rf loss for the transmitted signal.

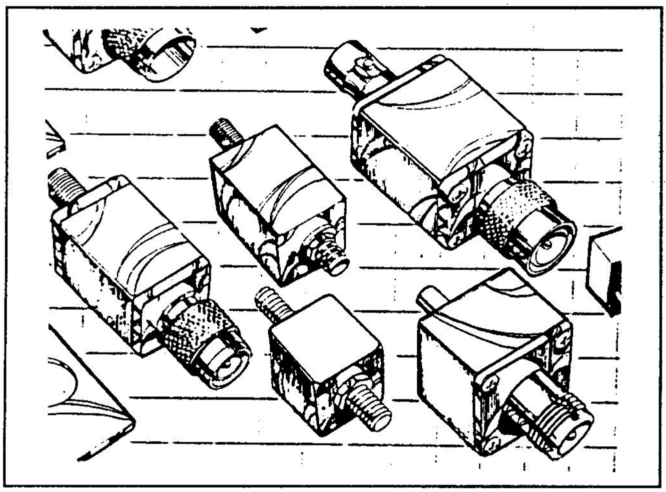


Fig.4.9 Coaxial Line Arresters
(from Fischer Custom Communications Inc., USA).

The low loss in the passband frequencies occurs because the intentional signal at the junction of the λ/4 stub

-is diverted along the λ/4 stub for a phase angle rotation of 90^0,
-is reflected 180^0 at the short circuit of the λ/4 stub, and
-travels back to the junction of the coaxial cable with an additional 90^0 of rotation. The incident and reflected signals are in phase and the intentional signal does not encounter a short circuit.

Transients and other signals that have a longer wavelength, like lightning, encounter the short circuit and are diverted to ground, preventing them from damaging the transmitter or receiver.

The limitation of this type of suppressor is bandwidth and that the coaxial cable cannot simultaneously carry Dc current to power an amplifier or receiver located adjacent to the antenna.

5. Noise suppression techniques in a field station

A modern field station houses very sensitive electronics data acquisition, processing and control instruments. For the distributed functions in the entire field station, a cluster of interconnected computers and instruments is installed and operated continuously for long duration of time. These instruments operate at high data rates and hence have large bandwidths. The long interconnecting cables and wires carrying these signals between any two instruments in the field station create disturbances in nearby circuits and systems.

In addition, noise voltages and currents arise from external sources like power lines, telephones, radio, TV, air-conditioners and similar gadgets and create disturbances in the field station circuits.

A few common techniques and devices used in a field station for minimizing the noise voltages at various circuit points are described below.

5.1 Zero potential reference and voltage equalization for the noise control

Connecting the metallic frames of all electronic modules in a field station as well as the shields of interconnecting cables between them to a common point that is grounded is intended to bring them all to the same potential. This is done for eliminating voltage differences between various grounded parts in the system. This in turn helps in breaking the ground loops that are likely formed and the noise interference arising due to them.

In practice, however, connecting all metallic enclosures in a system to a common grounded point is not achieved without difficulties.

The inductance of a long wire or a strip between a metallic enclosure and the ground point is not negligibly small. Even at the supply frequency of 50 Hz, the inductive reactance of a long wire (or a metal strip) is comparable to its resistance. For any wide-band noise, the impedance of a ground wire becomes too high to be effective for a potential equalization of two end points.

Figures 5.1 and 5.2 below [23] show typical curves for power source impedance and ground wire impedance.

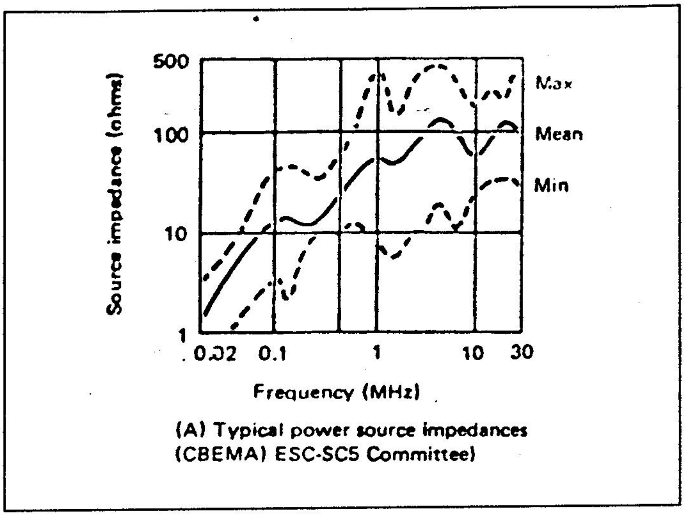


Fig. 5.1: Typical power source impedance

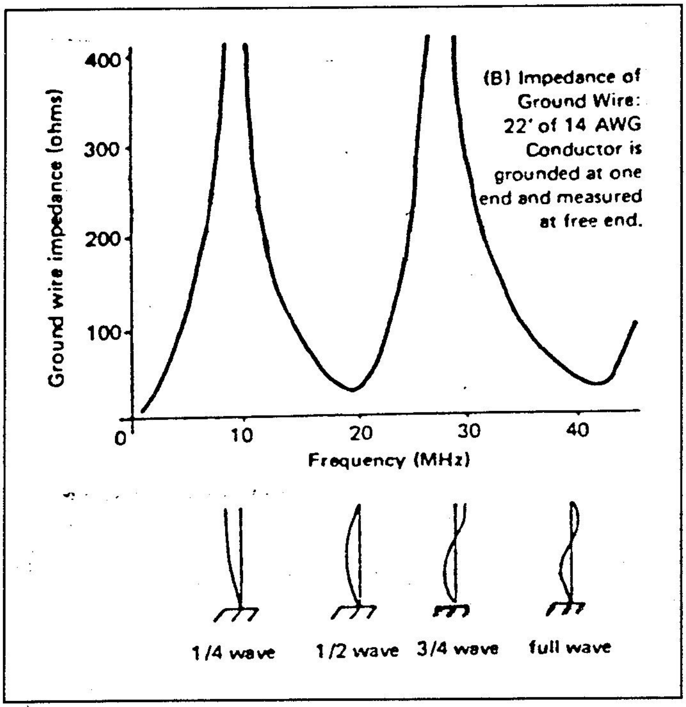


Fig. 5.2: Ground wire impedance for a fixed length

If the field station is spread over a significant area with distances of 30 ft or more with many instruments interconnected by high data rate cables, it may be provided with a 'signal reference grid'. This grid is a sheet of copper foil, a mesh of bonded copper wires or a suitably bonded supporting steel structure. All metallic enclosures are bonded to this 'signal reference grid' and also to a building ground point. See Fig. 5.3A [23] below.

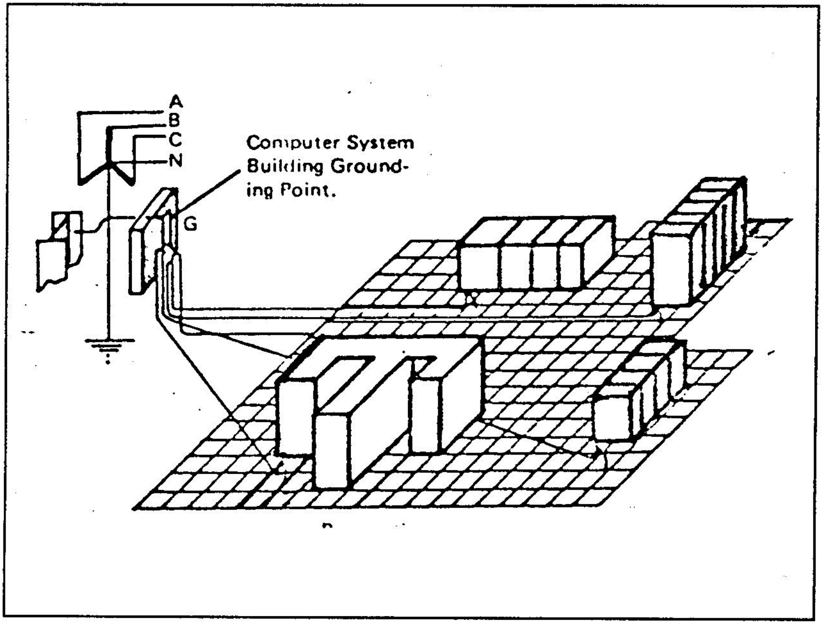


Fig. 5.3A: Star-connected green-wire grounding with supplementary broadband reference grid connected in parallel with safety grounding

The impedance of the foil or grid at high frequencies is much lower than single conductors and has fewer resonant frequencies in the desired signal frequency range (see Fig. 5.3B [23] below).

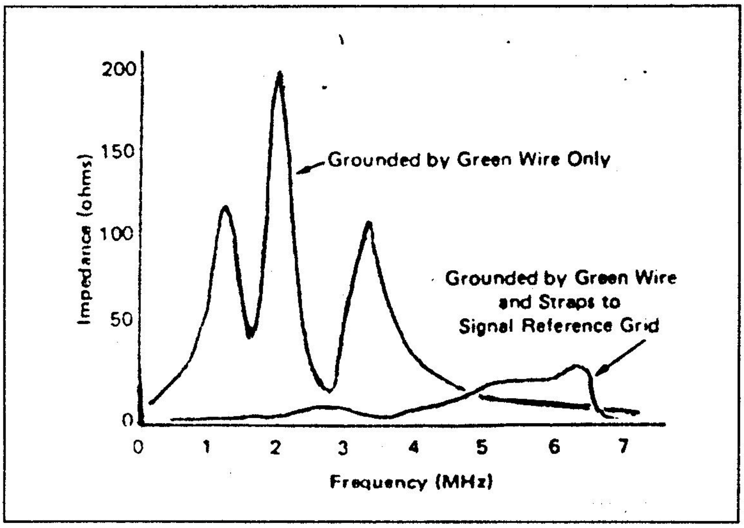


Fig. 5.3B: Cabinet-to-ground impedance plotted as a function of frequency

5.2 Proper layout of high data rate cables

At high frequencies, the distributed parameters of the transmission lines play a major role. A voltage impulse has high frequency components in it and when applied anywhere on a conductor cannot reach the ends of the conductor instantly. Depending on the geometry and the insulation dielectric between the conductor and the return path, electrostatic and magnetic fields are created as the voltage wave moves towards the ends.

The distributed inductance and stray capacitance of a transmission line governs the propagation velocity of a travelling voltage and current wave, typical velocity being 0.9 x speed of light. In addition, travelling voltage and current waves reflect from the ends of the conductors if the impedances are not properly matched. At specific frequencies, resonances occur and the impedance of the conductors reaches infinity. Another source of a disturbance is the common mode noise. It is the noise voltage that appears equally on both the signal conductors of a pair with the ground. Common mode noise may be caused by one of the following two factors:

- Electrostatic induction: With equal capacitance between each of the signal wire and surroundings, the noise voltages and currents developed will be the same in both the signal wires.
- Electromagnetic induction: With magnetic fields linking both the wires equally the noise signals developed in each wire will be the same.

In practice, there is rarely a pure, perfectly balanced common mode noise or signal. The common mode and the normal mode noise voltages are simultaneously present on the conductor pairs. Unless the circuits are extraordinarily well balanced, the common and normal mode signals exchange some energy with each other.

At high data rate, a balun is used for this purpose. It is a longitudinal transformer that absorbs the voltage difference and reduces the longitudinal current while preserving the normal mode signal relationships between the wire pair and between the pair and a shield. It increases the common mode impedance between the ends of the line. A shunt path for ground current to flow between the two grounded systems is needed to help equalize their voltage difference and reduce the noise current which otherwise may flow through the signal cable. While interconnecting signal cables between two separated systems, one balun per line is installed. For a longer separation between the systems one balun is installed at each of the end of a signal line.

A few standard practices for laying the data cables in a field station are listed below.

- Make a practice of pairing conductors so that circuit wire and its return path will always be together. This minimizes the area between the conductors and the magnetic field that it either creates or intercepts to pick up noise. A ground conductor should also be used with a balanced line for the same reason.

- Signal wire cables lying upon tables and floor in a field station can pick up noise voltages by capacitive or inductive coupling with other surrounding structural steel and conductors. Hence, at the system central grounding point, a connection should be made with the building steel.

- Avoid parallel nearby runs in which both electromagnetic and capacitive coupling will occur. The two sets of conductors should cross at right angles to each other to minimize their possible inter-coupling [23].

5.3 Use of power-line (EMI/RFI) filters

The mains, or powerline, filter is the key element in eliminating mains-borne interference. They are available in the market under various brand names and usually come in two forms: chassis mount types and PCB-mount types. In general, chassis mount filters provide a higher performance solution, in metal cases for optimum connection to earth and good high frequency performance. They are available for a wide range of power levels- from 1 A to 55 A. The PCB type filters on the other hand are designed for compactness and ease of assembly. They can handle lesser power levels up to 6 to 7 A. This topic has been discussed exhaustively in an Application Note from Schaffener Electronics Ltd., Lutarbach [24].

5.3.1 Interference sources and spectrums

The most common sources of conducted EMI are power electronic products such as switched mode power supplies (SMPS), pulse width modulated (PWM) frequency converters or motor drives, and phase angle controllers (thyristor drives etc.)

The emission spectrum of such a source typically starts off very large at low frequency and rolls off as frequency increases. The point at which the noise falls below the permitted limits depends on several factors, the most important being the frequency of operation and the rise time of the semicondctor devices. Interference spectrum generated can be either continuous, as in the case of phase angle controllers or discrete which is typical of an SMPS.

5.3.2 Interference propagation

EMI can propagate by two means:

By radiation – where the energy can be coupled either through magnetic or electric field, or as an electromagnetic wave between the source and the victim

By conduction – where the EMI energy will propagate along power supply lines and data cables.

5.3.3 Interference types

To understand the problems associated with conducted EMI it is first necessary to understand the two modes of conducted noise; differential mode (or symmetrical mode) and common mode (or asymmetrical mode). Differential mode interference creates a voltage between the phases of the system and is independent of earth; the differential mode currents flow along one phase and returns along another phase. (See Fig. 5.4 below)

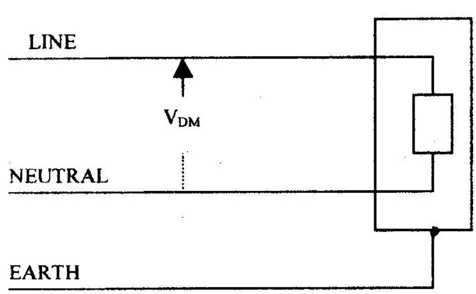


Fig.5.4: Differential Mode Interference

Common mode noise creates a voltage between each phase and the earth. The common mode currents flow from the noise source to the earth (usually via a parasitic capacitance) along the earth path and returns along the phases. The power line filter must be designed to attenuate both common mode and differential mode interference. See Fig. 5.5 below)

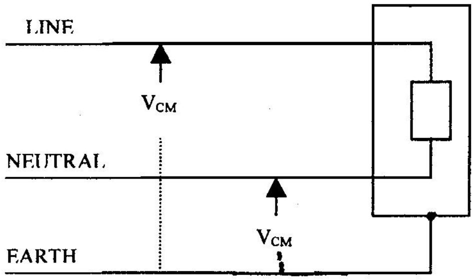


Fig.5.5: Common Mode Interference

5.3.4 Mains Filters

Maximum power transfer occurs when source and load impedances are matched. A power line filter is an inductor-capacitor network that aims to cause maximum mismatch between impedances, and therefore reduces the amount of EMI power to be transferred from the noise source onto the power line cable. Fig. 5.6 below shows a typical single-phase power line filter.

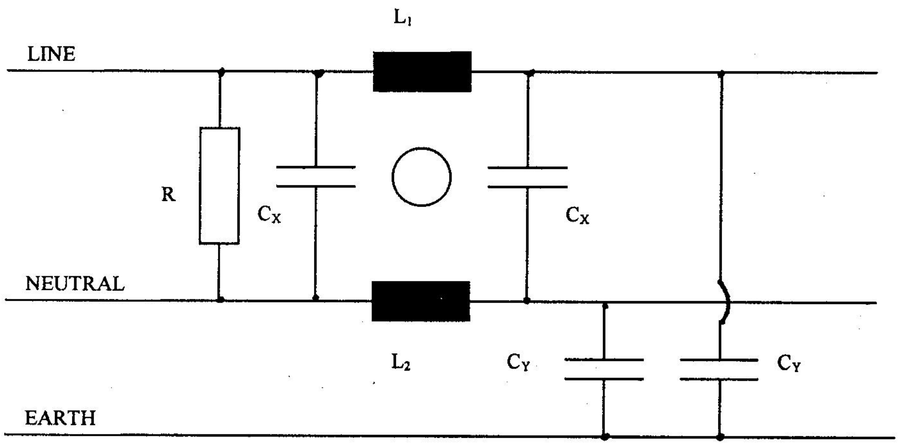


Fig.5.6: A typical single-phase power-line filter

The inductors L1 and L2 are usually wound - in a current compensated fashion – on a toroidal core. This winding method allows flux due to differential mode currents and mains currents to cancel each other, while common mode currents will be added together. This gives large inductance to common mode currents and ensures that the inductor will not be saturated by the large magnetic flux produced by the mains current.

The capacitors placed between the phases, known as "X" class capacitors must offer a high pulse voltage rating and are used to attenuate differential mode interference. The capacitors between the phase lines and earth, known as "Y" class capacitors must have a more stringent rating and are used to attenuate common mode interference. The permissible leakage current allowed restricts the value of the Y capacitor. The maximum leakage current is governed by standards and regulations and depends upon the type of equipment. The leakage current is given by

$$I_L = 2\pi . U . f . c$$

where I_L is the leakage current; U the voltage across the capacitor; f the frequency of the mains voltage across the capacitor, and c is the capacitance.

Mains filters should be mounted as close as possible to power entry so that high frequency interference do not bypass the filter. To achieve higher attenuation or an increase in the effective working frequency range more complex filters can be made using more common mode or differential mode inductors and capacitors.

A typical data sheet of a power-line filter gives information on the following parameters:

- Insertion loss
- Current ratings
- Voltage ratings
- Leakage current and
- Environmental properties.

Power-line filters for special applications are also manufactured and are popular. Some of these applications are described below.

5.3.5 Filters with earth line chokes

It is possible to get interference induced on all conductors of a cable including the earth conductor simultaneously. In this case the same noise will also be induced onto the earth conductor. To reduce this interference, earth line chokes are fitted into the filter. This will also provide extra attenuation for normal common mode currents. Care must be taken not to bypass earth line chokes in the system when sharing the same ac supply with other equipment having data interconnections.

5.3.6 Filters for medical equipment

For enhanced safety in medical applications, filters having lower leakage current (3 μA typical) and a discharge resistor are used. (See Fig. 5.7 below)

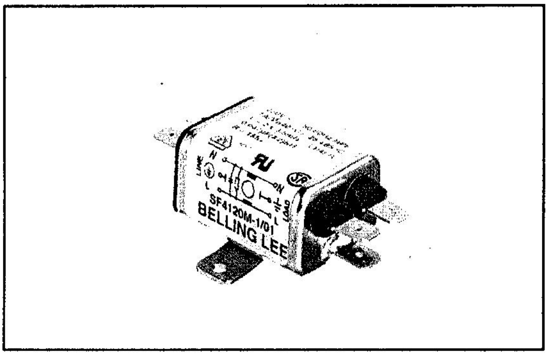


Fig.5.7: EMI/RFI filter for medical applications

5.3.7 Filters with surge suppressors

In this type of filters surge protection devices like varistors, gas discharge tubes and suppressor diodes are mounted between the power lines and between the lines and earth.

Powerline EMI/RFI filters are available from

- Sakura Industries, Bombay
- Elcom Filters, Bombay
- M/s Alpha Products Co., New Delhi
- Corcom, Barbados.

5.4 Use of an isolation transformer

Disruptive effects of power line noise hamper a smooth operation of sensitive electronic equipment. Devices such as air conditioners, heaters, elevators, copiers, laser printers etc. cause high levels of spikes and transients on the power line on which they are connected. If such a 'dirty' electrical power is fed to sensitive equipment like a computer, malfunctions and disc crashes can bring the computer installation to a complete halt resulting in heavy losses. Poor performance and data distortion can occur. Transients and spikes on the line, both from internal and external sources, can even damage sensitive equipment [25].

To reduce these effects, any computer equipment normally derives its AC mains power from an "isolation transformer" connected between the building mains and the computer load. An isolation transformer reduces the common mode and normal mode electrical noise on a power line and thus isolates a load from the source. An ultra-isolation transformer with proper shielding and grounding could provide up to 140 dB common mode noise attenuation at 1 MHz [26].

5.4.1 Connecting a load through an isolation transformer

An isolation transformer differs in construction from an ordinary power transformer. An ordinary transformer is generally constructed with a primary and secondary winding closely wrapped about the same ferrous core. The AC mains power at 50 Hz is transferred from the primary winding to the secondary through the process of mutual inductance due to the magnetic flux set up in the core. The electrical coupling of the wide-band noise, however, occurs due to the inter-winding capacitance between the primary and the secondary winding without any difficulty. An isolation transformer is designed to specifically address the problems associated with this wide-band electrical noise. An isolation transformer is constructed with two isolated Faraday shields between the primary and secondary windings. The use of two shields diverts high frequency noise, which would normally be coupled across the transformer to the ground. Increasing the separation between the two Faraday shields minimizes the capacitance between the two and hence, the coupling of noise between the two [27].

The Fig. 5.8 [26] below shows the construction and grounding scheme envisaged for an isolation transformer. In this, the primary and secondary windings are separately shielded in boxes, which totally surround the windings, thereby limiting the inter-winding capacitance to less than 0.0005 picofarads. The figure also shows the grounding method and the noise current loops (P_1 to P_4), showing that any noise that penetrates the shield gets shunted through its own path to ground. Generally a conductive foil completely enclosing the windings provide a ground path for circuit noise.

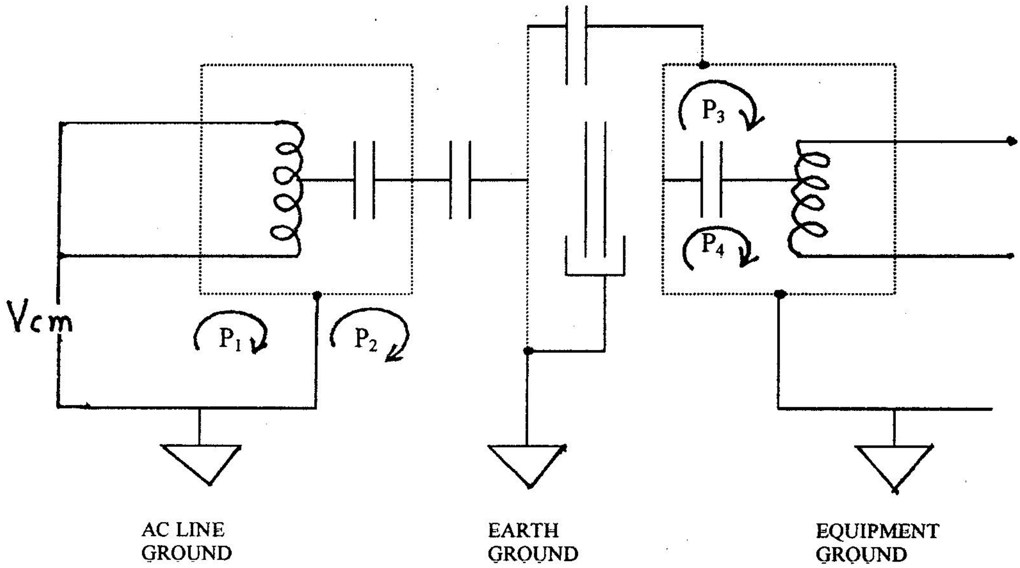


Fig.5.8: An ideal shield grounding in an isolation transformer

The isolation transformer reduces the common mode noise by bonding the secondary neutral to the ground. Normally, by the proper selection of core loss versus primary winding inductance, a well-designed isolation transformer eliminates the transverse mode noise. The shield, if grounded properly, does not reradiate the noise signal thus reducing the electromagnetic noise reduction.

The circuit below (Fig. 5.9) shows the standard method of connecting a load through an isolation transformer.

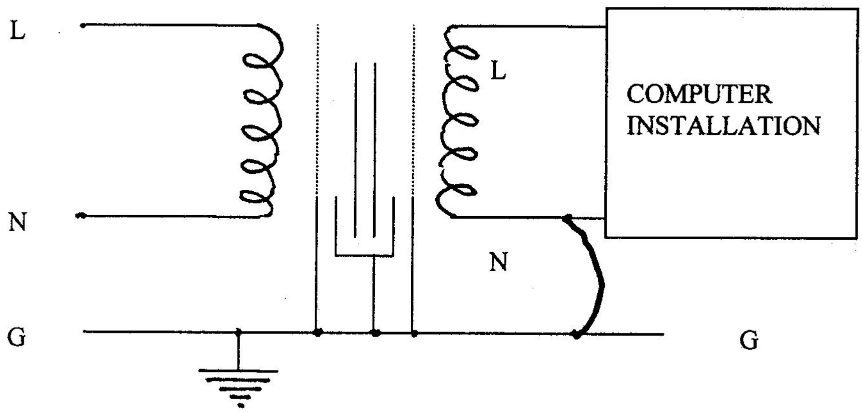


Fig.5.9: Connecting a load through an isolation transformer

Isolated ground schemes, where the signal reference plane is isolated from the equipment ground but connected to an isolated electrode in the earth, do not work and are unsafe. The isolated earth ground is not a clean ground as it may appear and believed by many. There is always some resistance (a few ohms) between the equipment ground and the isolated ground and that becomes a noise-coupling path as well as a source of a large (a few thousand volts) differential voltage between the two grounds in case of a lightning strike [1].

Isolation transformers of various power ratings (500 VA to 10KVA) are available in the market. Models for 3-phase isolation are also available. A few suppliers of these are listed below.

- M/s Suvik Electronics Pvt. Ltd., Gandhinagar
- Automatic Electric Ltd., Bombay
- Keprej Electronics, Gandhinagar
- Intel Micro Electronics Pvt. Ltd., Ahmedabad.

5.4.2 Line power conditioners

By combining an isolation transformer, a surge suppressor, a power line filter and lightning arrester, one can make a multifunction noise suppressor. A typical arrangement is shown in Fig. 5.10 [26] below.

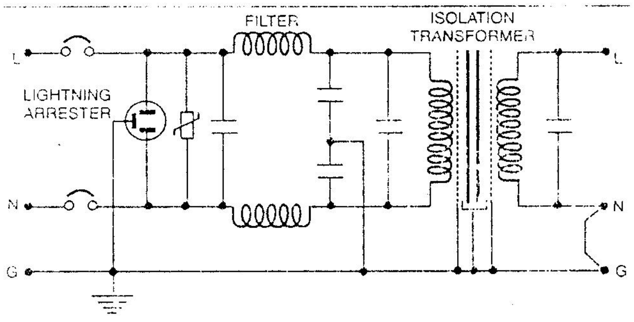


Fig. 5.10: Line Power Conditioner

5.5 Shielding

Grounded metallic enclosures, conduits and flexible metal wire braid surrounding conductors and electronic components and circuits shield them from external fields.

Shielding effectiveness varies with frequency, metal thickness, conductivity and above all the geometry of the system. Shielding performs its functions in three major modes [23].

First, it serves as a terminal for electrostatic coupling with another conducting body at a different potential.

When interposed between the external body and the circuits under protection, the ac currents induced through stray capacitance into the shield flow through the shield rather than through the protected circuits. This is effective at intermediate and low frequencies.

Second, electromagnetic fields induce currents in any conducting material but the induced currents tend to remain on the surface of the conducting body and are exponentially attenuated beyond a few millimeters deep inside the metal of the box and perpendicular to the external surface of the box. By choosing correct thickness of the shielding box for a given minimum interfering radiation frequency and the box material, the circuits inside the shielded box are protected from the external electromagnetic radiation.

Third, magnetic fields can be steered around circuits by magnetic materials in the form of shields: electrical steel, permaloy, ferrite etc.

Grounded shields also avoid the shock hazards by providing a touch voltage safety to the users.

5.6 Control of electrostatic potentials in a field station

Ungrounded metallic frames may have high reactive voltages on them that could affect circuits inside. Connecting the frames together prevents any build-up of reactive or electrostatic potentials between them.

To control the static electricity in a field station the following preventive measures may help [23]:

- Keep relative humidity above 40%.
- Specify hard surface floor coverings with not greater than 10^9 ohms to a grounded supporting structure. Pressure laminates are useful for this purpose.
- Avoid using carpets in a field station.
- Insist use of footwear and clothing that generates less static when walking on a floor.
- Avoid furniture with plastic upholstery to reduce static problems.
- Use anti-static mats with a ground conductor.

6. An earthing system for a modern field station

A practical earthing system for a field station is to form a 'cage' of a number of pipe-type or plate-type earth electrodes around it (see Fig. 6.1). These vertical electrodes are joined by a horizontal run of an insulated cable. This forms a system of parallel earth electrodes to reduce the overall earth resistance. Alternately, the electrodes are joined together by a horizontal run of a buried bare copper wire or strip. The earth resistance of such a cage can be estimated if the specific resistance of the soil is known and the electrodes are sufficiently far apart from each other.

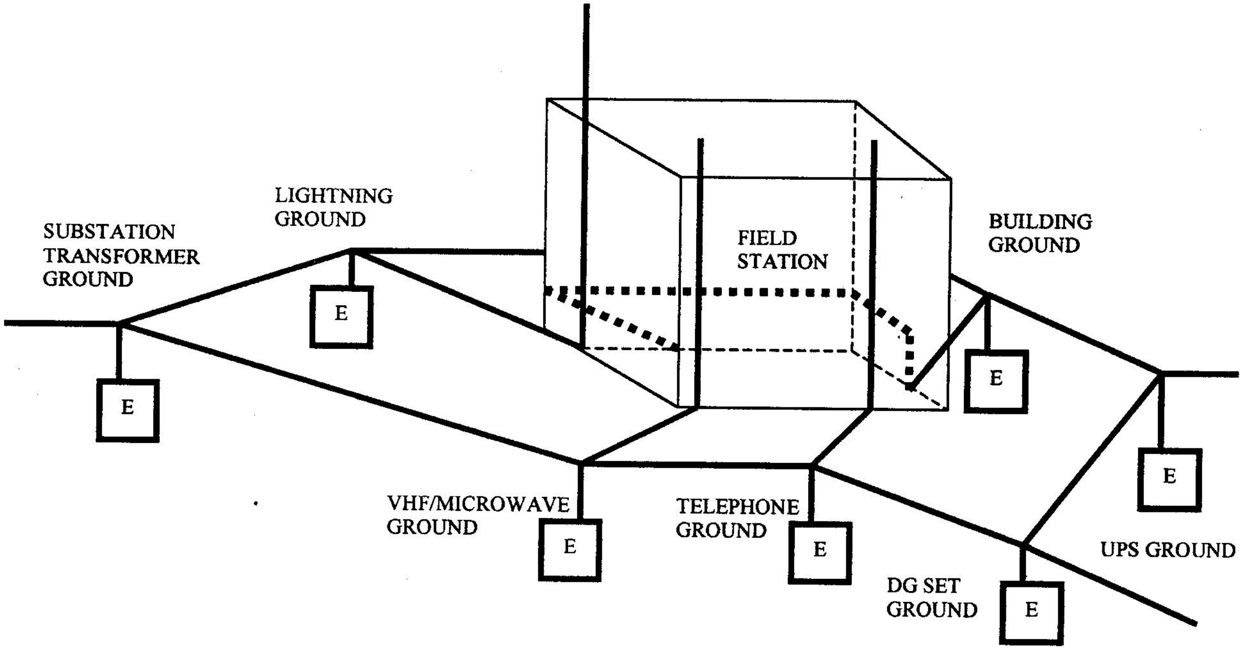


Fig 6.1: A practical earthing network system for a field station

The 3φ, 11 kV overhead power line, after reaching the field station, is fed to a delta-star transformer. (The Electricity Board provides the appropriate lightning arresters on the pole for the 3 overhead wires that feed power to the substation transformer). The secondary of this transformer supplies 400 V AC power to the field station. The R, Y, B phase wires and the neutral wire are carried separately in an underground armored cable. The neutral of the secondary winding of the substation transformer is connected to the same common earthing system of the field station. During installation, efforts are made to distribute the electrical load in the field station evenly on the 3 phases to maintain the neutral to a near-zero potential. The outer armor of this cable is connected to the same earth electrode that grounds the secondary neutral of the substation transformer as shown in Fig. 6.2 below.

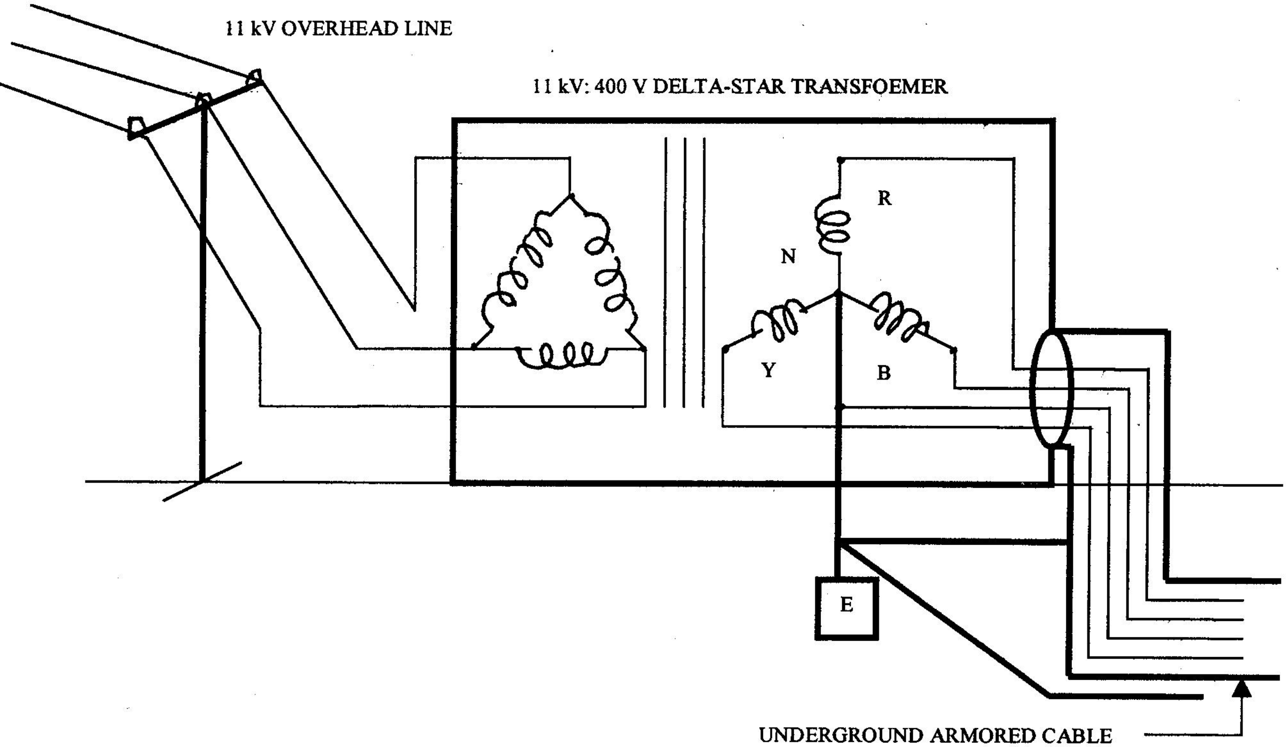


Fig 6.2: The substation transformer

The field station may have optional standby ac power source like a diesel generator, a wind turbine or a battery-inverter system charged by the solar power and must ground its neutral to the field station ground.

Utmost care is needed when a UPS powering a total or partial electrical load of the field station has an isolation transformer at its output. The secondary neutral of the isolation transformer is grounded to reduce the common mode interference and contrary to earlier belief and practice, *should not have* an isolated ground from the common field station ground. If provided, the separate ground connection makes the load powered by the UPS vulnerable to a damage due to a lightning strike. The transient lightning current (of about 2,000-10,000 A) if passed through the finite earth resistance (5-10Ω) between the system ground and the so called *isolated ground* develops about a million volts on the UPS with respect to the field station ground and could result in equipment damage and personal hazard.

Moreover, there is no reduction in the noise in the isolated system as *there is no such thing as an isolated ground for noise voltages.* Since electrical resistance between two unconnected earth electrodes is never zero, a broad frequency spectrum of electrical noise exists between any two earth electrodes. Whenever a current flows from one earth electrode to the ground, it has to return from *somewhere* as electricity always flows in complete circuit and this *somewhere* matters a lot in noise coupling in any grounded system [1].

The telephone wires and equipment, the communication antenna and cable, and the field station lightning protector are connected with suitable protection gaps, gas filled spark-gaps, MOVs and arresters etc. and use the same field station ground.

Inside the field station building, a 1 or 1.5 in. wide continuous copper strip is fixed on the walls of all the equipment rooms at a height of 1 or 2 ft. above the floor to form a building ground bus. (See Fig. 6.3) All the equipment racks and metal cabinets are bonded to this bus by short runs of No. 6 AWG (0.4-cm dia.) wire. Bonding together of equipment panels, cabinets and other building steel structure and connecting it to the common building ground bus prevents potentials arising between these components. The building ground bus is brought out to the main terminal box at the building entrance and linked to it. Here, a connection is made to the buried earth ground system of the field station building [2].

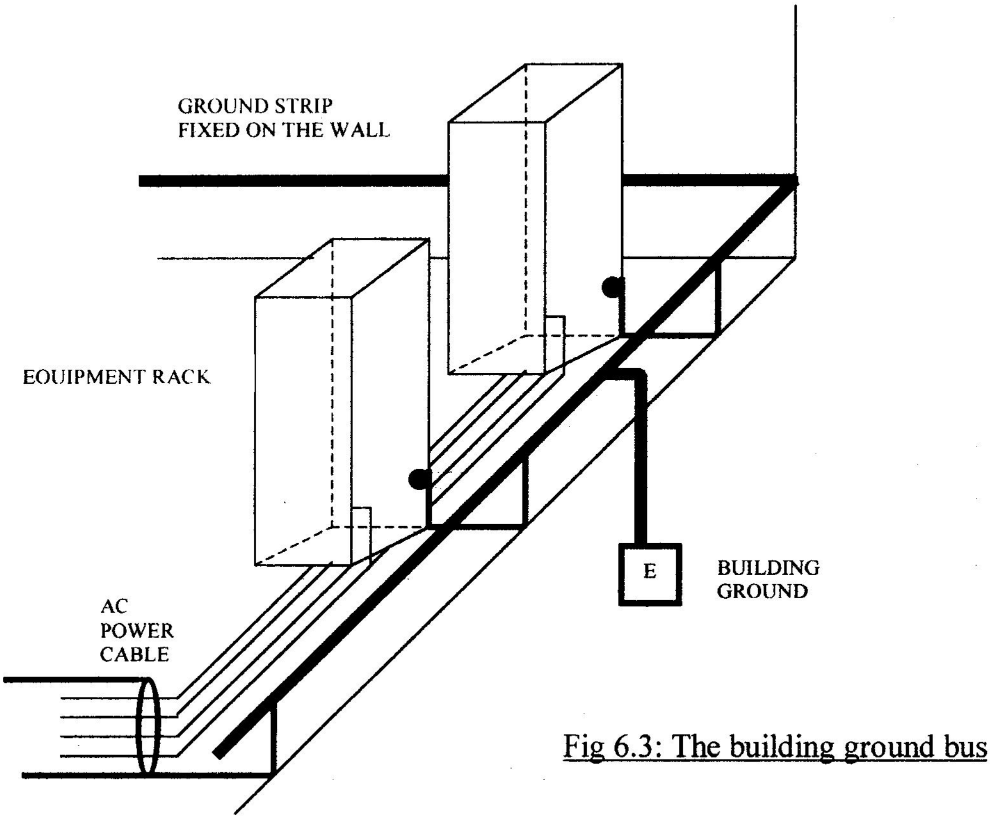


Fig 6.3: The building ground bus

In a field station, redundancy is provided at every step for connections to the ground system to ensure a standby protection in case of an accidental break in a ground connection that may remain unattended for a period between any two routine maintenance schedules. In the modern field station systems, very rarely the earth is used as an intentional current carrying path for fault currents or short circuit currents to flow.

Short circuit current flows in a circuit due to an accidental contact of phase to phase or phase with neutral or phase with earth wire either at the distribution point or at the load end. It may also flow due to an insulation failure of a power cable caused by aging of the PVC coatings on the cable or snapping of cables/connectors.

Conclusions

In all, the installation of earthing network in a field station is quite an involved operation. The human safety is of paramount importance. The field station equipment protection from lightning and high voltage power lines comes next to it. A modern field station housing computers and other sophisticated equipment needs to be freed from wide-band electrical noise and the grounding plays a very important role in it. As discussed in this document a grounding bus at ac supply frequency of 50 Hz is not adequate for minimizing high frequency and wide-band noise in a field station. For this, an elaborate ground plane is required to be prepared. All the hardware like each of the earth electrodes, the copper strip of the ground bus and the copper mesh ground plane needs to be periodically inspected for any corrosion and checked for any deterioration in its continuity. The soil around the field station needs to be kept moist particularly in the hot summer. Creating an *equi-potantial zone* over the entire field station is a key to the success.

Acknowledgements

Most of the field tests were carried out at the IR Observatory (Gurushikhar, Mt. Abu) and the Thaltej Field Station of the Laboratory. We acknowledge all the staff members working in both the field stations, who, from time to time, complained (?) about the *poor grounding* at both the sites. These *unending complaints* prompted us to undertake the job of studying the problem at its root level and take all possible steps to get the things going. The positive results of our efforts in this encouraged us to bring out this reference document on earthig and grounding covering all related matters of common interest for the benefit of all those who face similar problems in the field stations.

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