BASIC PRINCIPLES OF LIGHTNING ROTECTION PERTAINING TO A FACTORY ENVIRONMENT

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Abstract

In the industrial and administrative environment the installed base of distributed controls, measurement devices, and data networks, that utilise sophisticated electronics, has increased greatly over the past decade. Factories have become more reliant on electronic instruments and controls for efficient operation. The equipment used is interconnected via a web of communication, control and power cables. These cables often radiate out to remote locations such as weighbridges and pump stations, and act as receptors of surges caused by indirect lightning strikes, thus endangering the control system. On the administration side, offices contain a plethora of equipment such as computers, printers, scanners and telephone systems, usually connected via copper cable networks. Although this equipment may not be in use in control functions, it plays a vital role in the operational system.

All electrical and electronic equipment is susceptible to disruption by lightning electromagnetic pulses, by electrostatic discharges, and by switching electromagnetic pulses. This paper describes how progressive protection can minimise lightning and other surges entering electronic systems, and the importance of choosing the right protection. The holistic view taken considers three areas of protection. These are the building, where practical, the co-ordination of surge protection devices within the building, and the correct earthing principles.

Keywords: lightning, surge, strike, earthing, grounding, arrestor

Introduction

A very high percentage of damage that occurs in electronic systems can be directly related to the effects of transient over-voltages (surges), over-currents and 'noise' originating from lightning, switching operations and other sources of electrical disturbance. These harmful effects are introduced into systems and equipment primarily in two ways, (i) via resistive, inductive or capacitive coupling, and (ii) through earth potential differences.

The first effect can be limited by protecting buildings where practical, combined with the use of commercially available surge arrestor devices. The second effect concerns earth potential differences, where remote equipment is electrically connected through data lines and referenced to various earth points. The solutions here are more complicated, and depend largely on the circumstances.

The consequences of surges and earthing problems are generally of a disruptive nature, and result in lost productivity and downtime rather than total equipment failure. The cost of the former usually far exceeds the latter.

How Lightning Behaves

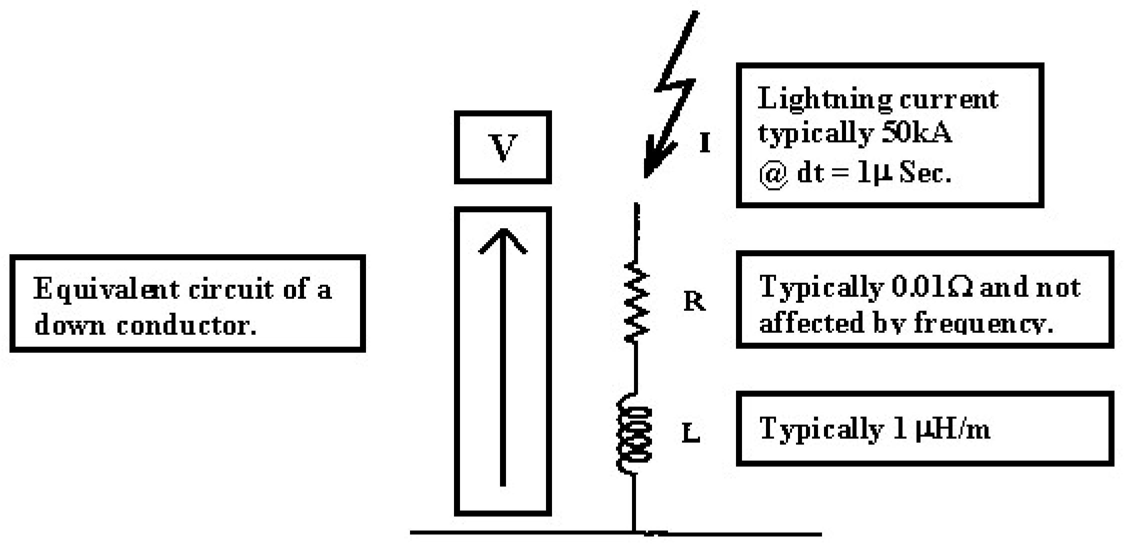
Essentially, lightning is a current source. A given stroke will contain a certain amount of energy that must be neutralised during the discharge process. If the lightning current is 50 kA/µS (values range from 5 to 250 kA (Anon, 1993)), that is the magnitude of current that will flow, whether it flows through one ohm or 1000 ohms. Achieving the lowest possible impedance (not just resistance) therefore serves to minimise the transient voltage that has developed across the path through which the current is flowing. It is this surge voltage, generated by the current flowing through the impedance over the conductor length, that induces secondary surges into adjacent cables or equipment and causes equipment failure.

Equation for transient voltage:

$$V = IR + L^{di}/_{dt} \qquad (1)$$

where V = voltage generated over the down-conductor
- I = lightning current
- R = resistance in ohms
- L = inductance in micro-Henrys
- di = instantaneous lightning current
- dt = rise time of the lightning current.

Consider a lightning conductor connected to an earth mat via a 10 metre down-conductor that has a typical inductance of 1 µH/m, and resistance of 0,01 ohm. Figure 1 shows that the impedance values are more important than the resistance values of a conductor.



V is the voltage generated over a 10 m long conductor when the resistance is defined as R and the impedance as $L^{di}/_{dt}$.
Lightning current I = 50 kA, R = 0.01 Ω, Inductance = 1 µH/m and t = 1 µS.
From the equation $V = IR + L^{di}/_{dt}$
$V = (50 \times 10^3 \times 0.01) + (10 \times 10^{-6} \times 50 \times 10^3 \times 10^6)$
$V = (500) + (500 \times 10^3)$
V = (500) + (500 000)
V = 500 500
The ohmic resistance generates a voltage of 500 V, whereas the impedance generates a voltage of 500 000 V.

Figure 1. Example of how the inductive reactance (impedance) of a conductor is far more important than its ohmic resistance.

Lightning protection properties of buildings

Factories are usually constructed with steel joists or reinforced concrete. These structures serve as partial Faraday cages and are good in conducting lightning currents to earth. However, this alone will not protect equipment or people inside the structure, due to secondary surge coupling and flash-overs between conductors.

Inductive, magnetic and capacitive coupling from the steelwork carrying the lightning current will result in significant surges being transferred to adjacent power and data conductors forming the network between equipment. Unfortunately, administration and weighbridge buildings (among others) are not constructed in the same manner as the factory; and consequently exterior protection is often warranted. This can take the form of cones of protection provided by existing masts that are higher than and fairly close to the building. Adding earthed catenary wires between the masts effectively creates an envelope of protection; however, there are problems associated with this type of arrangement. Lightning is attracted to the mast from an area approximately four times greater than the height of the mast (Calboutin, 1989), and heavy currents will be dumped into the ground, causing the surrounding area to be saturated and lifted in potential. It is therefore very important that the mast is properly grounded and bonded to the equipotential earth to prevent a flash-over to adjacent buildings, services or cables.

Although the factory and other buildings may provide a degree of Faraday protection, surges will nevertheless penetrate building walls via cables and other services. The surges may emanate from an adjacent building that has been struck, or they may be ‘collected’ by cables or services that radiate outwards by up to 100 m from the building.

Bonding and Equipotential Platforms

These structures are discussed by Calboutin (1991). Bonding assures that unrelated conductive objects are all at the same electrical potential. Without bonding, lightning protection will not work. All metallic conductors entering structures should be electrically bonded to the same point, usually an earth bar. The bonding of earth connectors should be of the highest quality, making use of welding, brazing and soldering to replace as many mechanical joints as possible, the reason being that mechanical joints are prone to corrosion and physical damage.

Equipotential earthing is achieved when all the equipment within a room or structure is connected to an earth bar that in turn is bonded to the external earthing system. There may be a problem where earth loops occur between equipment located in different parts of the plant; however, this can be avoided by using low voltage spark gaps between the cable screen and the earth bar. Differential voltage can be avoided by connecting an earth cable between the cabinets housing the equipment, thus reducing the risk of lightning current flowing through the signal cables.

Earthing

The earthing system must be designed to offer a low impedance, as well as a low resistance, path to earth. A considerable portion of the current responds horizontally when lightning strikes the ground, and it is estimated that less than 15% penetrates the earth. As a result, low resistance values are less important than the impedance efficiencies of an earth electrode system.

A lightning pulse has a tremendous effect on the voltage generated when combined with the impedance properties of a conductor, whether it is used as a lightning rod, down-conductor, earth rod or earth mat.

The very fast rise time of a 1 µS lightning pulse generates a high voltage in comparison to the relatively slow 50Hz waveform, shown in (Figure 2).

Where there is a problem with earthing, such as a radio mast installed on a rocky mountain top, the use of radial techniques in the form of a 'crow's foot' can lower impedance by allowing lightning energy to diverge as each conductor shares the voltage gradients. Earth or guard rings around a building are used to dissipate currents from protective masts and the equipotential system to earth, as well as being useful in preventing voltage gradients from nearby lightning strikes spreading across a building.

The use of reinforcing, foundations and concrete footings when new structures or extensions to buildings are considered, will greatly increase the number of conductivity paths and will consequently reduce impedance to lightning currents.

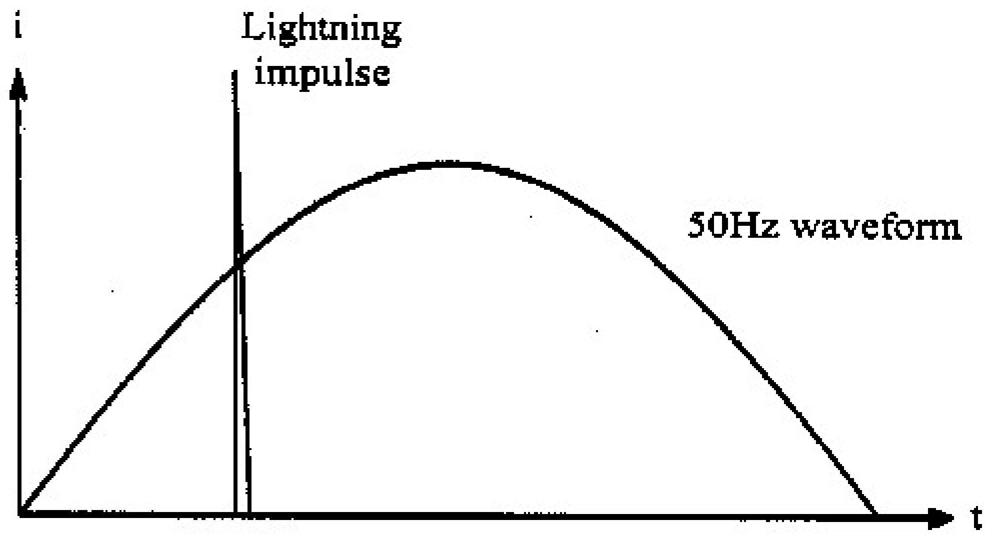


Figure 2. Comparison of waveform rise times.

Corrosion

Dissimilar metals that are in contact with or in close proximity to one another may undergo electrolytic corrosion. This can occur when an electrically conducting path is made, through a liquid, damp soil or exposed to air. The degree of corrosion depends on the electrolyte, the type of metal, and where it is used (Table 1).

Table 1. Guide to the use of materials to minimise corrosion. (Anon, 1993).

Material	Where to use it		
	Open air	In soil	In concrete
Copper	√	√	×
Hot galvanised steel	√	√	√
Stainless steel	√	√	×
Aluminium	√	×	×
Lead	√	√	×

A common mistake when installing lightning protection is the use of incompatible materials at joints. joining aluminium down-conductors with copper ground wires is a typical mistake.

Inspection and Maintenance

Regular physical inspection of all the related lightning protection measures and installations should be an integral part of the maintenance programme. Testing of the earth mat for resistivity should be done annually. Any protection measures that are removed during maintenance operations should be restored to their original condition.

All surge protection devices (SPDs) should be checked to see whether they are functional. This is normally indicated by a light emitting diode (LED) mounted in the unit. Some devices revert to a fail-safe mode after they are destroyed by a surge, allowing the 'protected' equipment to carry on operating, but without protection. These devices normally have LED indicators and/or contacts that can be set to generate an alarm when they fail.

Failure to maintain any piece of equipment will eventually render it useless. This pertains in particular to lightning protection devices, and the equipment they are designed to protect.

Transients and Surges

An uninterruptible power supply (UPS) is designed to act as a temporary power back-up. However, these are often regarded as the answer to all lightning and surge problems coming through the power supply. They are not designed for this and should not be used as replacements for SPDs.

The correct installation would be: power from an outlet, into a surge device, then through the UPS to the equipment. Ordinary fuses and circuit breakers are not capable of dealing with lightning or any other type of transient induced surges. SPDs are designed to shunt currents, clamp voltage levels and prevent energy from travelling through the power and data lines of a system.

Single task SPD modules are available that will shunt very high level currents to earth. These are normally installed at the incoming power distribution panel. Other modules are designed to clamp the high, secondary voltages to safe levels. Integrated modules are available that perform both the above functions without the user having to co-ordinate the characteristics of separate modules and the associated interconnecting cable between them that acts as a current limiting inductance.

Zones of protection
Considering that surges can originate from both internal and external sources, SPDs should be installed where they will provide maximum protection, regardless of the source location. For this reason, a 'zone of protection' approach is necessary. The most vulnerable area is known as the lightning protection 'zone 0_A', which is the outside of any structure that can be struck directly by lightning. Zone 0_B can also be outside, but protected from a direct strike. Zones 1, 2 and 3 are determined by the SPD installed at the entry point of a building on the power lines, data lines and services entering from the outside.

Figure 3 shows the correct configuration of the protection zones. Each of the zones is co-ordinated to gradually reduce the surge to an acceptable level that can be handled by the equipment being protected. The preferred approach is to protect the AC power main panel, all relevant secondary distribution panels over 50 metres away, and all critical plug-in devices such as process control instrumentation, computers, peripherals and fire alarms.

For the protection of incoming/outgoing data, signal lines on local area networks (LANs) and modems, SPDs must be installed exactly as per supplier instructions, with short leads and the correct size of cabling to reduce high speed surge voltages.

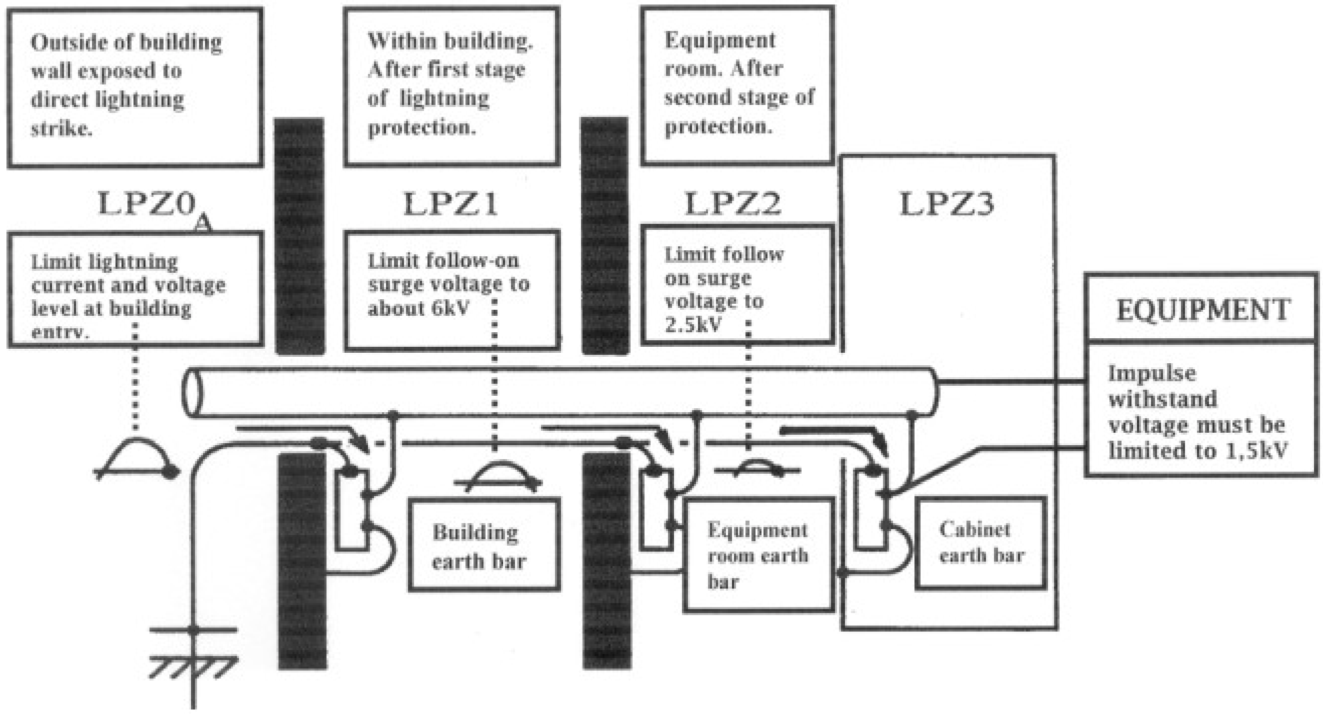


Figure 3. Systematic protection using the building shielding and co-ordinated surge protection devices to limit the level of surge voltages penetrating into equipment.

Instrument cable screening and earthing

Cables used in instrumentation are normally fairly specialised and are manufactured to address problems that are inherent in the industrial environment. A typical cable will have wires twisted in pairs to reduce inductive coupling, a signal reference (usually 0v), a screen wire to reduce capacitive coupling, and a drain wire.

Instrument suppliers usually prescribe in an installation manual the way in which their system should be earthed and screened, often specifying that the screen wire of a cable must be earthed at one end only, a practice that prevents earth loops that could interfere with the signals being received by the instrument. This negates all and any protection that may have been installed between zones, as a surge will be able to couple with adjacent cables and reach the innermost sensitive zone, as the screened cable will not have been earthed at each zone entry point (see Figure 3).

Another established practice that can lead to problems is that of multiple earth bars mounted in a control room. When there is an earth bar for the 0v signal reference line, one for the cable screen and one for the chassis earth, and each bar has its own down-conductor to the earth mat, there is the possibility of high potential differences between the earth bars. A current surge, the majority of which is conducted away in the screen of a cable, will 'equalise' between all the cable screens at the equipotential bar. However, when the surge travels through the down-conductor to the earth mat, it will cause a high differential voltage between itself and the other earth bars, and will have a high probability of causing damage.

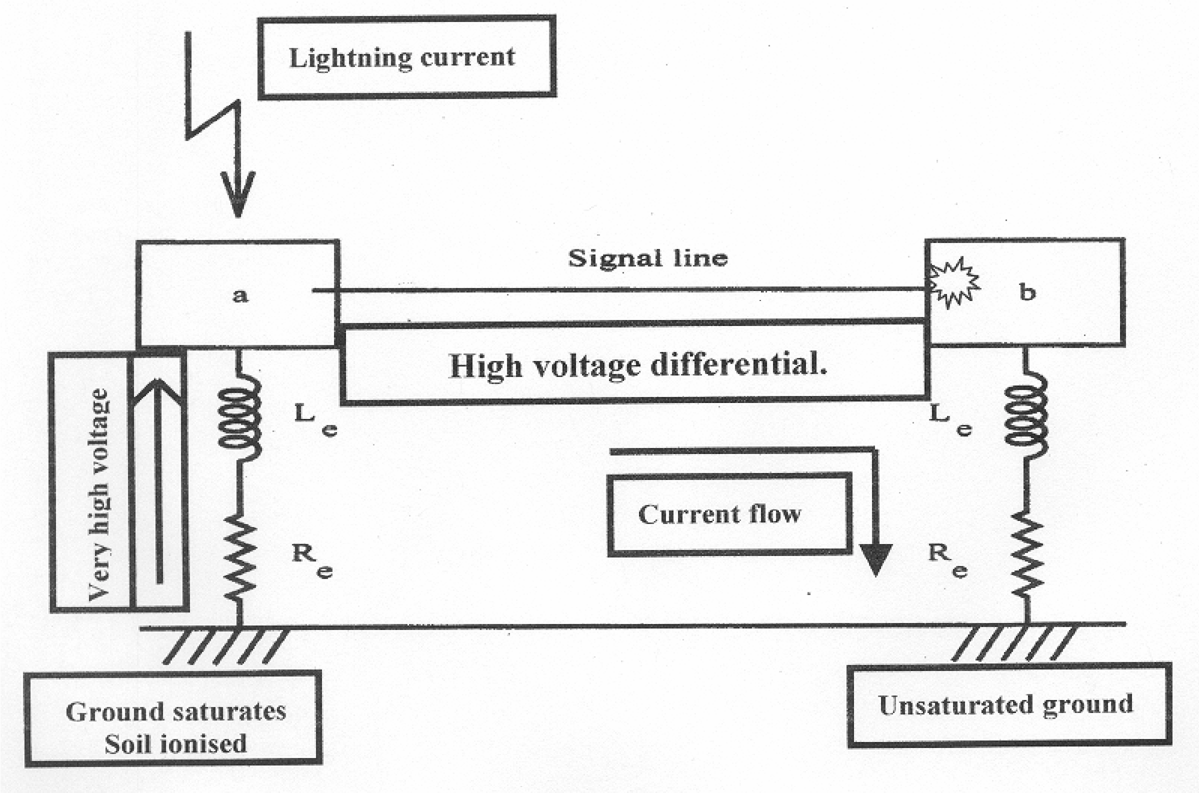


Figure 4. High differential voltages being generated over separate earth lines.

Figure 4 shows potential problems that can be caused by high differential voltages being generated over separate earth lines.

Very high voltage in equipment 'a' can cause a flash-over on the signal line, allowing current to flow via equipment 'b' to the unsaturated ground level. This may cause equipment damage or could trigger an explosion in a hazardous area.

Selection of SPD Devices

In all instances, the use of high quality, high speed, self-diagnosing SPD components is suggested. SPDs are constructed with high technology components designed for the purpose and include spark gaps, metal oxide varistors, gas tubes and silicon avalanche diodes. There is a device for each application, e.g. zone one may require a high current shunt, and zone two a voltage-clamping device. Should these devices be reversed, they will serve very little purpose, and installing them in the wrong location will be worse than having no protection at all, as there will be the false impression of being provided with protection where in reality none exists.

Although there are various international bodies that test SPDs, they do not all use the same parameters. The standards of the Institute of Electrical and Electronic Engineers and of Underwriters Limited uses an 8 x 20 μs rise and decay time waveform, whereas the European standard uses a 10 x 100 μs rise and decay time waveform, which is a far more stringent test. For this reason, it is recommended that only SPDs that conform to the specifications of the European standard be used.

While it is necessary to consider the power supply aspect, it is equally important to take into account the data line aspect, where co-ordinated surge protection levels should be applied.

Summary

To mitigate the hazard of lightning damage, attention to the following details is recommended:

- Protection should start by utilising the building structure, or external conductors, such as lightning conductor poles adjacent to the structure.
- Low structures such as a weighbridge can have a conductor along the apex of the roof attached to down-conductors. This has the advantage of *not attracting* lightning over a larger area.
- An equipotential earth bar should be provided in a central position so that all the individual earth connections from instruments, computers, power distribution board, building structure and external lightning protection can be connected. This in turn would be connected to an earth mat or guard ring.
- To minimise corrosion, care should be taken when choosing materials that will require bonding together, whether above or below ground.
- The provision of an adequate earthing system will enable the protection system to dissipate lightning currents efficiently.
- Use SPDs in a co-ordinated manner on the power and data lines, particularly where cables enter and exit a building.
- Maintenance of the system must be viewed as a whole, by preventing corrosion, checking earth mat integrity, checking for SPD component functionality, and by making visual inspections.

Conclusions

Lightning has its own agenda, and may cause damage despite preventative measures being taken. Any comprehensive approach to protection should be site-specific to attain the best overall result.

Most damage to equipment is caused by indirect lightning strikes, and falls into four main categories:

- Firstly there is disruption at the work station, which may involve just one individual or may affect everyone. Although there is no visible physical damage, surges cause loss of data, corruption of software and system faults.
- Secondly there is degradation, which can be a somewhat more serious problem, as long term exposure to surges degrades electronic components and reduces their reliability and lifespan.
- Thirdly there is the physical damage to components caused by large surges. Sometimes this is spectacular, and at other times less apparent. This damage is the easiest to identify and thus to rectify; however, it is downtime that becomes the critical factor.
- Fourthly there is the situation where staff are unable to work normally. Senior managers and technical specialists get tied up in problem solving, with a resultant loss in productivity and at a later stage having to work abnormal hours to compensate for this loss.

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APPENDIX
Glossary of Terms

Arrestor is a device that limits current or voltage to an acceptable level when installed on power or data lines. Arrestors need to be installed correctly and co-ordinated to give effective protection at each level (see Figure 3).
Bonding is the connection made between 'conductive' parts of a system or circuit, so that they are at a common voltage, usually earth potential.
Differential voltage is the difference between a piece of cable or equipment that has been raised in voltage potential with respect to earth, and one that has not.
Down-conductor is a cable or flat bar connected between a protection system, usually mounted on the apex of a structure and the earth mat.
Earth mat is a collection of copper coated steel rods forced into soil and coupled together with a bare copper cable to form a low impedance current path to earth.
Earth potential difference is when a large current flows through a structure or cable and electrically saturates the earth surrounding it, causing a high voltage to be generated. Where two pieces of equipment are attached by a signal cable, this voltage will break down the insulation of a cable or circuit board that is connected to an earth which is not saturated and is subsequently at a lower potential, thus allowing current to flow and damage the equipment.
Earth rod or electrode is a single rod forced into the earth and connected to a down-conductor.
Equipotential bar (of equal potential) is a single copper or similar bar mounted near equipment requiring protection. All equipment earth wires are connected to the bar, which is in turn connected via a single cable to earth, or to an adjacent bar and then to earth (see Figure 3).
Faraday cage is a metallic structure that surrounds a person or device to be protected from electrical discharges. Sitting inside a car during a storm is a good example, as a lightning strike would take the path of least impedance around the outside shell to earth. The rubber tyres do not present a barrier to a very high voltage surge.
Flash-over is a temporary breakdown of insulation that allows a spark or discharge between conductors.
Grounding is an American term that is interchanged with earthing, both of which refer to the connecting of equipment to a ground/earth point.
Guard ring is a bare copper cable buried approximately 500 mm deep around the periphery of a building, with earth rods bonded along its length.
Lightning. A lightning strike usually consists of multiple strokes of current that flow from a cloud formation to points on the earth. These are complemented by an equal number of 'return' strokes from the earth to the cloud. The flash is a result of the current flowing in the ionised path of air. Thunder is caused by the rapid expansion of the air particles due to the heating effect of the current flow.
Strike is when lightning of a very high voltage hits a structure or the earth. This strike is then transformed from a voltage strike to a current stroke due to the presence of resistance.
Stroke is the movement of lightning current between the clouds and the earth, and *vice versa*.
Surge is a common alternative description for an over-voltage transient.