BSC Associates Ltd

Consultants on radio systems and antennas

Technical Memorandum

The protection of radio installations against damage by lightning

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Contents

Note on Terminology:

The terms *ground/grounding* and *earth/earthing* are regarded as synonymous and are used interchangeably. The term *tower* is always used to indicate a self supporting structure and *mast* to indicate a stayed/guyed structure.

Feeder is used to refer to lengths of coaxial cable or waveguide between antennas and the equipment connected to them.

1. Introduction

Most operators of broadcasting and telecommunications facilities are familiar with the occasional disruption of their systems that occur during electrical storms. This document describes how the risk of danger to personnel and the chance of equipment failure can be minimised. It is not suggested that the methods described are novel or original, but they reflect good current practice.

The effects of lightning on communications systems can be divided into four classes:

1. Danger to personnel operating or maintaining the equipment;
2. Permanent physical damage. This may include damage to -

   Antennas and feeders,
   Radio equipment,
   Incoming line or link equipment,
   AC power supply equipment

3. Corruption of the information being transmitted;
4. Corruption of data that controls or monitors the equipment -

   Control status,
   Improper reversion to standby modes or non-permitted configurations,
   Control signals to other related equipment, perhaps at other locations,
   BITE status.

The present generation of high power transmitters with semiconductor final amplifiers is more vulnerable to damage by transient voltage spikes than earlier vacuum-tube designs, and the reliance on computer control of complex systems has increased the vulnerability of equipment at the level of system control.

The general principal which will be followed in this paper is that of providing progressive control of surges at different levels of the system; the cost of effective control may appear high, but is much less than the cost of repairing failures and suffering system outages.

Protection against data corruption is outside the scope of the memorandum, but awareness of the risk of corrupt data in control and monitoring systems is most important. Built-in data validation, whether by parity checking or other means is essential for reliable operation. Always design systems to be fail-safe, so no dangerous incident can occur by the malfunction of an executive control system. The corruption of data traffic generally causes less trouble, as communications systems are usually designed to handle errors

To facilitate further reading, an extensive bibliography is provided at the end of this Memorandum.

2. Lightning

During thunderstorms, electrical charge passes between cloud masses and the surface of the earth in the form of violent arc discharges which we recognize as lightning. Discharges also take place between clouds, but as they pose little threat to ground installations our main concern is with discharges to ground.

The incidence of lightning varies widely on both the large and small scale. Electrical storms are most frequent in wet equatorial areas and their incidence diminishes towards the poles; in a given area lightning will occur more frequently on hill tops than in nearby valleys. Objects that project upwards from the ground – like antenna structures – distort the local distribution of electric field between the charged clouds and ground, and cause local intensification of the average field strength. This results in an increased probability that a strike in the vicinity will pass to ground through the projecting object.

We may note that the area round the projection has a correspondingly reduced chance of receiving a direct strike – very low near the base of the obstacle, increasing to the local average at a distance equal to several times the height of the obstacle.

Lightning statistics are available from many meteorological administrations. These usually the form of maps with isoceraunic (also spelled isokeraunic) contours, which indicate the number of days during an average year on which thunderstorms will be observed at any location. They do not provide small-scale data, or indicate the likely severity of storms.

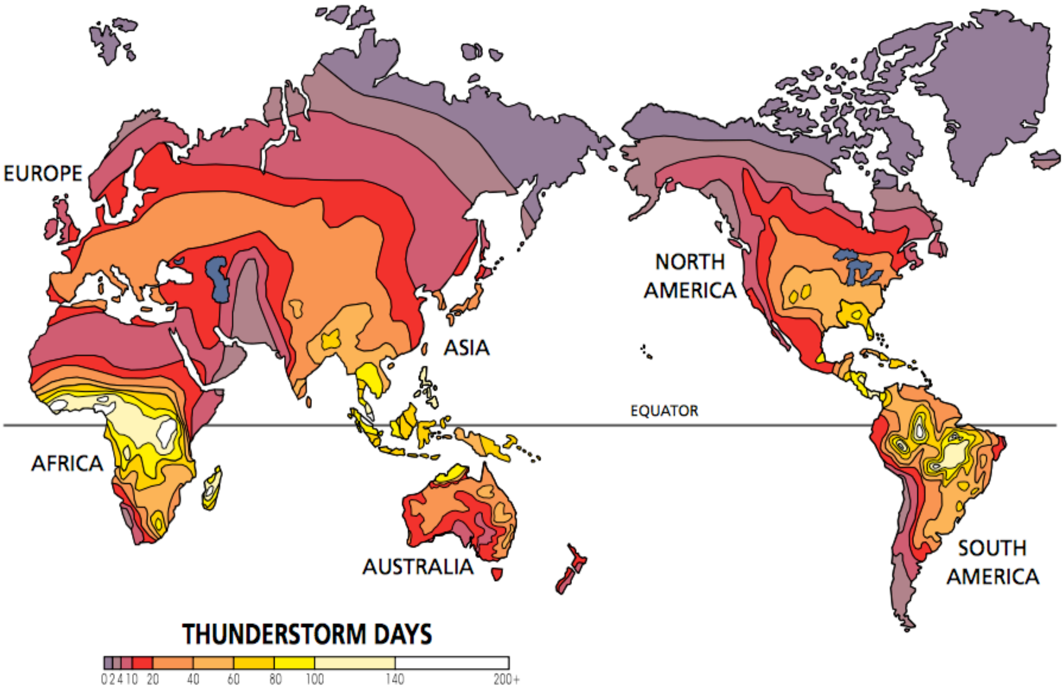

Figure 1: Lightning days worldwide. Maps at larger scale show significant local variations and should be consulted for system evaluation [1].

Photographs taken during thunderstorms, usually made by leaving the camera shutter open for a long time interval while many strokes occur, indicate the very random and unpredictable nature of lightning strokes. Some travel by fairly direct routes, others appear to travel large horizontal distances in their search for a path to ground.

2.1 The lightning stroke

The processes involved in the formation and discharge of a classical lightning stoke have been described many times and will not be repeated here. Those interested are referred to the references contained in the bibliography. The speed of events precludes the possibility of pre-empting the strike once the leader current has been initiated, but the precursors of the strike in the form of a severely increased local electric field strength could allow early preventive or protective steps to be taken; this increased field gives rise to reported audible crackling, visible discharges (St Elmo's Fire) and phenomena such as hair standing on end.

2.2 Some numerical information

A number of useful conclusions arise from a quantitative study of the nature of lightning.

The damaging part of a lightning flash is the so-called '*return stroke*' in which charge is transported along an already-established ionised pathway between the cloud and ground. In most ground flashes the cloud is negatively charged with respect to ground, although occasional flashes occur from positive regions of a cloud.

In the time domain, the peak current in the return stroke is reached after a few microseconds and the current then falls to half its peak value in a further 50μs or so. Some flashes comprise two or more strokes whose individual characteristics correspond with those of single strokes, but which are separated by 50 to 100ms.

The range of peak currents found in lightning in the UK has a log-normal distribution, approximately as follows :

1% of strokes exceed 200kA
10% of strokes exceed 80kA
50% of strokes exceed 28kA
90% of strokes exceed 8kA
99% of strokes exceed 3kA

Reference [20] suggests that in the UK, lightning protection systems should be designed assuming a peak current of 200kA and maximum di/dt of 200kA/μs. Different criteria are will apply in other countries.

It often seems to be imagined that lightning conductors must be of very large cross-section in order to avoid being melted by passage of the very large lightning discharge current. Much more important considerations are the inductance of the wire and the ability of the conductor to withstand the large electro-mechanical forces caused by the passage of the lightning current. If we take the case of the 200kA stroke defined above, an inductance of only 1uH will cause a potential difference of 200kV. ($V = -L.di/dt$).

3 Lightning protection

The objective of conventional lightning protection systems is to minimize the damage to equipment and the danger to personnel that occurs when a lightning stroke passes to ground by a direct strike to part of the installation. When an antenna support structure, or the antennas mounted on it, is struck, a current of many kiloamps is suddenly injected into the system to which they are connected. Protective measures are essential to ensure that:

1. All the lightning current passes to ground without passing through sensitive components that are prone to failure;
2. The passage of the lightning current does not generate sufficient potential differences between various components of the system to give rise to flashover or hazard to personnel.

A number of less orthodox lightning protection systems are available whose objective is to divert or gradually discharge the lightning. Many vendors offer these – for example [15] – but most national standards rely on the use of more conventional methods.

The general principal by which all conventional protective systems operate is by acting as potential (or current) dividers. At each point where protection is applied, a low impedance path must be provided to ground and a higher impedance presented to currents flowing along the line of the radio signal. This principle will be repeatedly invoked. The standard definition of one volt is one joule/coulomb; remembering that a typical stroke allows a charge of perhaps 100 coulombs to fall through more than 100 megavolts, it is obvious that the available destructive energy is very large indeed (fortunately most of it will be dissipated along the whole length of the stoke). Typical failure energies of circuit elements fall many orders of magnitude below this:

A very large degree of isolation of the lightning current must be provided by the design of the communications system if trouble is to be avoided, or even reduced to manageable levels.

3.1 Structures

The antenna structure is the most commonly struck point in the equipment of a radio station. If the current can be diverted effectively to ground before it passes into the communications equipment, many of our problems will be reduced.

The base of every structure, whether a self-supporting tower, a radiating mast or a transmission line gantry, must be grounded to the mass of the earth by a connection which has as low an impedance as is practicable. In fertile lowland regions the achievement of a low impedance ground connection is simple, but in arid conditions, or areas of solid poorly-conducting rock it presents a severe challenge.

3.1.1 Standard grounding connections

The resistance-to-ground often recommended for a lightning protective ground system is 10 ohms, but lower values will generally reduce the incidence of side-flashing and damage to equipment.

The standard ground termination in most soil conditions takes the form of a number of long conducting spikes driven into the ground, and/or conducting plates buried in it. The critical features of the arrangement are the integrity of the contact between the ground conductors and the earth around them – drive spikes into undisturbed ground where possible. The inductance of the conductors by which they are bonded to the base of the structure must be kept as low as possible.

Where possible the ground conductors should extend below the water table, even in the driest part of the year. Spikes may be easier to drive more deeply, but in general the much larger surface area of buried plates makes them a better choice when conditions permit. The objective should be to get 4 square metres of ground contact surface close to the base of a tower or mast. Typically one plate 0.5 sq.m. in area (1 sq.m. allowing for contact with both sides) should be buried adjacent to each leg of a tower. The conductors that join the plates or spikes to the base of the structure should be wide, low inductance straps. Many ground systems built with driven rods have excessive inductance in the connecting straps (and in the rods themselves, if they penetrate a long way to the water table). When designing ground systems, remember that sharp-radius bends have a significant series inductance (and they are often encountered at the point of connection at the top of a ground spike).

Copper is traditionally used for ground conductors; the critical feature in selecting materials is not so much their low resistance, but their low rate of corrosion and long life when buried. The cost of a good ground connection may appear high, but it must be set against the lower costs of repair and outage time resulting from lightning-induced system failure.

3.1.2 Grounding in difficult conditions

The precautions to be taken when local ground is of low conductivity depend on two factors:

1. whether the station has external electrical connections to other systems, in particular an external source of mains power and external telephone or other signal or control lines, and
2. whether local ground is soft and penetrable, (such as dry sand) or is hard and impenetrable (such as the top of a rocky mountain).

Where there are no external connections – for example microwave relay sites on remote rock outcrops with local diesel generators or solar power, and with no line connection to the station – the main concern is to ensure that all parts of the system are solidly bonded together. Lightning is particularly destructive when it strikes dry buildings, as it does not encounter a wide conductive sheet of water over the surface and often penetrates to internal metalwork or reinforcing bars. Low ground conductivity can give rise to large potentials between different pieces of equipment unless they are all bonded together, and can cause potential gradients in the ground that may cause injury.

> **Bond all structures, feeders, generator ground, and all equipment racks to a single ground system constructed from wide tape; include all architectural metal fittings, plumbing, LPG storage tanks (and pipe-work), and any other metal objects on the station in the bonding.**

Where the ground is soft, a system of ground conductors should be buried below the main mast or tower; this should comprise at least 10 sq.m of plate surface, buried below the lowest part of the foundations of the structure (to reduce the chance of lightning passing along the re-bars in the foundation). Where part of the site forms a natural sump for seasonal rainwater it may be sensible to position the antenna structure at or near that point.

Ground conductivity can be increased by adding conductive or moisture retentive minerals to the sub-soil around the ground system; carry any rainwater drainage to the area, and where a sceptic-tank is used for sanitation, use its outflow to increase ground conductivity. There are many other methods of ensuring that a ground system is kept irrigated; at one Middle-East radio station the author noticed a small vegetable garden strategically located at the bottom of the tower – the on-site security guard tended the garden and irrigated it daily, greatly benefitting the conductivity of the local ground system!

In hard rocky ground it is difficult to achieve adequate grounding. Where the site is at the top of a steep rocky hill, ground tapes, extended over the ground surface and attached by screws, will at least provide a path away from the station. Ring electrodes around the station will limit the surface potential gradient that can exist close to the station. An earth termination can also be made by rock drilling and back-filling the hole with a conducting moisture-retaining material such as Bentonite, or a conductive concrete or cement made with graded granular carbonaceous aggregate. Avoid the use of coke or fly-ash, which accelerate the corrosion of the ground conductors.

A more difficult situation arises where incoming power circuits are bonded to ground at a remote point where ground conductivity is high. Connection of station ground to the neutral conductor of a star-connected 3-phase mains supply clearly helps to pass on the lightning current to someone else, but many electricity authorities have specific regulations about this practice, and these must be consulted.

Grounding to telephone lines is never acceptable where there is no good local ground, and isolation is the only policy. The simplest method is now to use optical fibre in the signal path, avoiding the need for high-voltage transformers and other hardware whose performance in lightning-strike conditions is always difficult to guarantee.

Very few radio installations on flat arid plains are properly grounded. Even a ground radial wire system, such as is used at the base of a radiating mast, provides a very high resistance to ground. A matrix of deeply-buried spikes is probably the best that can be provided, in the hope that the lightning current is headed somewhere down below.

3.1.3 Testing

Provision must be made for the periodic testing of the integrity of ground systems; test joints should be provided at convenient points at convenient points when the installation is designed, to avoid the need to excavate parts of the system when testing is needed.. The results of tests should be recorded in a book kept at the station for this purpose. Suitable equipment and standard test methods are widely available.

3.2 VHF/UHF and Microwave Antenna Installations

A typical installation is shown in Figure 2. The equipment room contains transmitters and receivers connected to an AC power supply and to incoming and outgoing signal lines. Various antennas are mounted on a steel structure and connected to the radio equipment by coaxial cables or waveguides. A number of important features of the lightning protective system are now identified.

The outer conductors of all the coaxial cables (and flexible waveguides) that run from the structure to the equipment accommodation are bonded at three points:

i. At their upper ends;
ii. At the point of exit from the structure;
iii. At their point of entry into the equipment building.

Bonding at the upper end of each feeder and at the point of exit ensures that no potential difference will exist between the steelwork of the structure and the feeders at any point. If this bonding is not provided, side-flash may cause damage to the feeders. Long cables should be bonded to the structure at intermediate points – cable manufacturers usually recommend the maximum spacing between them.

Bonding at the base of the structure and at the point of entry to the building reduces the amount of energy that is allowed to enter the building.

Bonding is best carried out by fitting cable grounding kits, which are available from cable manufacturers. All bonds must be made with wide low-inductance straps, and kept as short and direct as possible.

The main station ground connection is described in Section 3 above.

External cables must be bonded to the station ground system at their point of entry, or isolated by suitable means. If they are left floating, dangerous voltages can exist between different items of equipment in lightning strike conditions.

Top-mounted antennas present a particular problem. A large majority of strikes will be to top mounted antennas (although not all will), so they must be designed and installed with the probability of strike in mind. When there is no top-mounted antenna, an air terminal (lightning finial) should be fitted to protect lighting fittings and antennas mounted near the top of the structure. The air terminal should be solidly bolted to the top of the structure; the practice of running a separate copper ground conductor all the way down the structure is unlikely to be effective, as the inductance of the tape is many times greater than that of the body of the structure, completely overwhelming any notionally lower resistance. Copper tapes also present a corrosion hazard to the rest of the structure due to the large corrosion potential between copper and zinc (or steel).

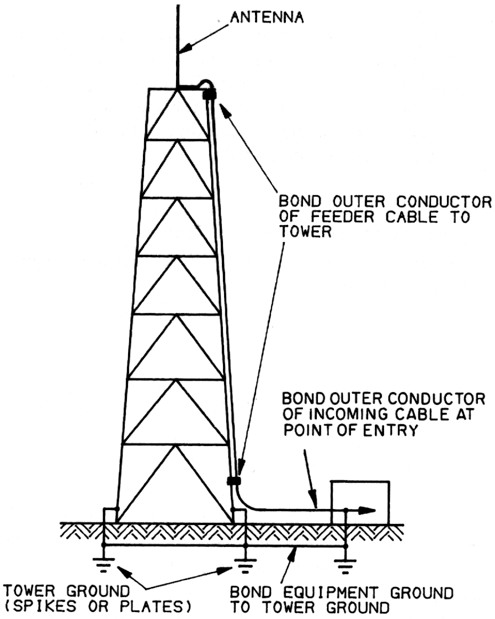

Figure 2: Typical grounding arrangement for a tower with VHF/UHF antennas

3.2.1 Antenna Design

Lightning damage to antennas takes many forms. These include:

1. Damage to antenna elements and distribution feeders. Feeder damage is usually internal - arcing across line spacers and connectors, but on some occasions, damage to the outer conductors of lines has been reported, usually caused by side flash between the cable and other components.

2. Puncturing of radomes, allowing subsequent water ingress or escape of system pressurization.

3. Damage to structural fibreglass cylinders supporting top-mounted antennas. This damage may be of sufficient severity to require the replacement of cylinders.

A well-designed installation will survive a large number of strikes, but it seems to be very difficult to guarantee indefinite survival. Once basic precautions have been taken, the most important design improvement is to provide redundancy in the system to make it more damage tolerant. VHF and UHF antennas are frequently designed in two identical halves, which in normal operation are both in service, fed from two separate main feeders. It is improbable that both halves of such an antenna will be disabled at the same time and service – with some reduction of erp – is maintained by the unaffected half. It is still noticeable that this practice is only used by radio and TV broadcasters, but the technique should be used by all services where reliability is critical.

The risk of equipment damage is usually limited by fitting gas discharge tubes, varistors or diode devices between the inner conductors of coaxial cables ad ground. Any multi-core cables passing out of the screened equipment accommodation, such as control or power supply cables, should be screened, and have protection fitted individually to each core.

3.3 HF and MF Antenna Installations

HF and MF antennas are bound to receive direct strikes from time to time. These will not just be to the supporting structures - which must themselves be protected in the manner already described – but will be directly to the antenna elements. Protection must take the form of additional current paths to ground, together with obstructions to the flow of lightning currents in the signal path. Where antenna tuning circuits and baluns are connected between the antenna and the feeder, the protection must be planned to safeguard these as well as to avoid damage to the transmitter or receiver connected to the remote end of the feeder.

The bottom end of mast stays must always be grounded using spikes or buried plates as described above. If grounding is inadequate, lightning currents passing through damp concrete can cause failure of the anchor block.

Standard stay (guy) insulators usually have provision for effective lightning discharge. High power MF and HF installations should be fitted with UV arc detectors that trip the transmitters off in the event of a lightning arc. This prevents an arc being sustained by the transmitters.

4 Conclusions

Lightning damage as well as danger to personnel is inevitable unless effective steps are taken to protect engineering installations. This document has indicated some of the most important points that need to be taken into account. The wide variety of material included in the bibliography provides detailed advice for designers.

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