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Culham – Exxon Guide to protection of Process Plant Control Systems against Lightning

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Report

CULHAM - EXXON GUIDE TO PROTECTION OF PROCESS PLANT CONTROL SYSTEMS AGAINST LIGHTNING

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1. INTRODUCTION

The need for this guide has arisen from the increasing use of computers to control major process plants of considerable capital cost, size and complexity, and for which lightning outages are a very expensive and undesirable occurance. Protection against lightning is not normally standard practice, indeed, at present there are no national or international codes of practice dealing with this, although the IEC has tasked committee TC81 to draw up such a standard, but this is several years away from completion.

For the protection of the building structure itself, a UK code of practice is available (BS6651) which does not deal with electronic systems at all, only the building itself. However, recently the terms of reference of the B.S.I committee GEL 106, which wrote BS6651, have been altered to include protection of equipment. So a national code might also be available some time in the future unless overtaken by European Community codes of practice.

BS6651 is useful as a starting point for lightning phenomena and for the design of basic building protection but there is no guarantee that equipment inside a building protected by use of this standard will be satisfactory, particularly for equipment comprising interconnected units in several buildings as is common in process plant.

Low current, low energy control systems are more susceptible to lightning surges than previously used thermionic valve equipment. Moreover computers are being designed to give very comprehensive control of very complicated process plants in order to simplify the task for the human operators and to allow for automatic process optimisation. Computers also undertake safety functions; for example, the safety systems on nuclear reactors.

Lightning is a very high energy phenomenon. Cloud to ground strikes release many hundreds of mega-joules of energy, which may be contrasted with perhaps a few tens of milli-joules which could affect sensitive electronics. A rational engineering approach to protection is therefore required. This document attempts that approach and explains lightning strike phenomena to buildings, lightning current flow through them, the coupling mechanisms giving transients and the means of preventing these transients entering the electronics.

2. SUMMARY OF THE NEED FOR PROTECTION AGAINST LIGHTNING

Protection of systems fulfills several requirements:

1. The need to prevent electrocution hazards to plant operators.
2. The need to avoid serious loss of production through plant stoppages.
3. The need to avoid serious health and safety hazards resulting from plant instability after loss of control.
4. The need to avoid the adverse publicity arising from health hazards.
5. The need to prevent costly repair programmes to control and instrumentation systems and the plant.

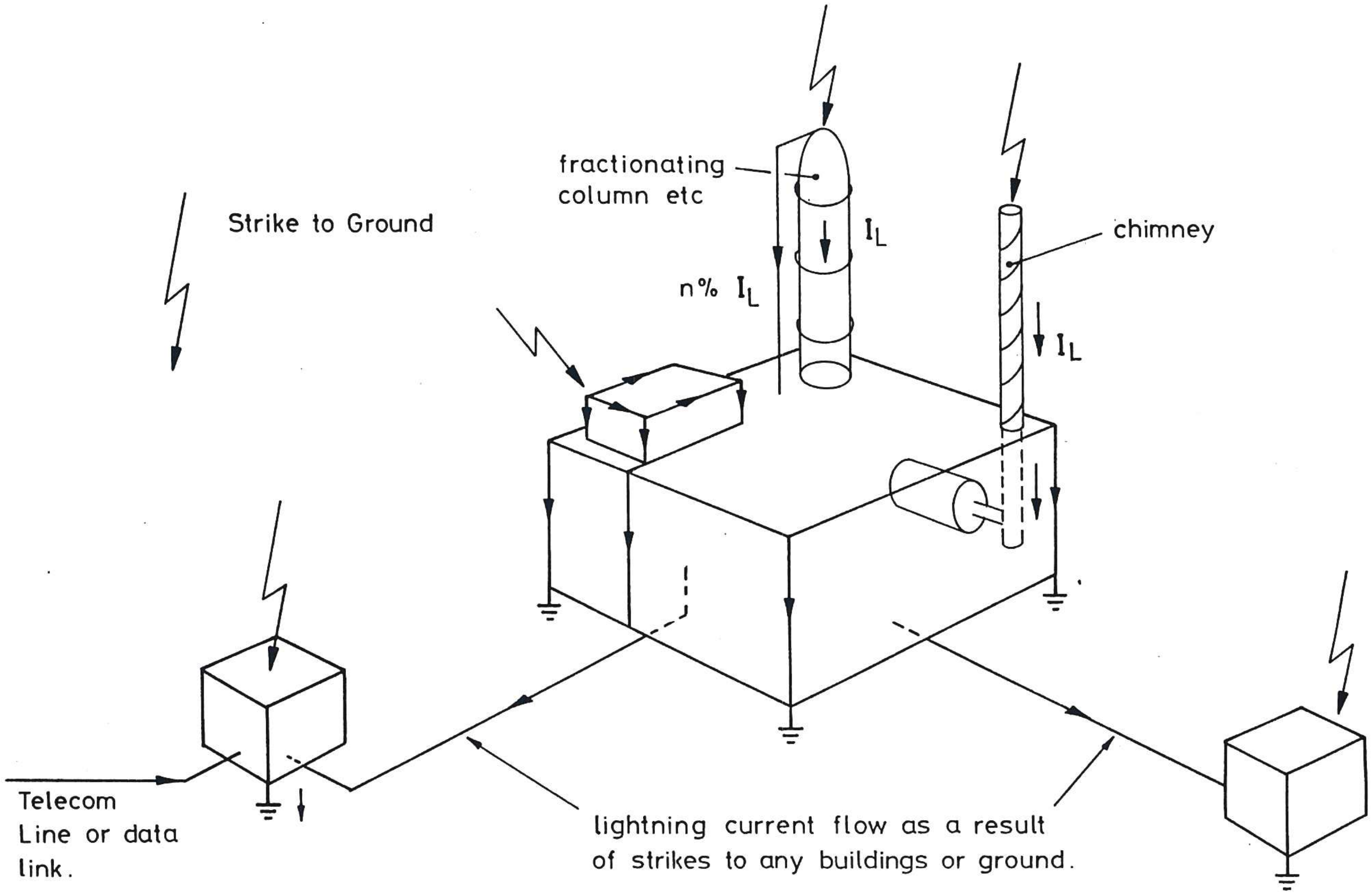


Fig. 2.1: Lightning Interaction with interconnected building complex.

Lightning protection should preferably be integrated with protection for other forms of electro-magnetic interference including switching surges, earth faults, high power radiation sources and other electro-magnetic sources. All of the techniques discussed in this guide are compatible with and assist protection against these other EMC problems.

Figure 2.1 illustrates how lightning currents can get into plant and control systems by strikes to the buildings, the plant, the control room or the ground around the plant.

3.0 LIGHTNING CHARACTERISTICS AND STRIKING POINT

3.1 Lightning Characteristics

The broad range of lightning current pulses in terms of amplitude, rise time, duration etc makes it necessary to refer to statistical values of these parameters which have been measured extensively in many parts of the world and which are commonly accepted to apply to Britain and indeed throughout Europe. These are summarized briefly in BS6651 (reference 1) and are as follows:

Amplitude exceeded by 1% of strokes, 200kA
Amplitude exceeded by 10% of strokes, 80kA
Amplitude exceeded by 50% of strokes, 28kA
Amplitude exceeded by 90% of strokes, 8000 A
Amplitude exceeded by 99% of strokes, 3000 A

Likewise the maximum rate of rise (di/dt) values have also been obtained as follows:

di/dt exceeded by 1% of strokes, 100kA/μs
di/dt exceeded by 50% of strokes, 30kA/μs
di/dt exceeded by 99% of strokes, 10kA/μs

Other parameters of the lightning pulse are important for other aspects of lightning damage, but peak current and peak di/dt are the principle ones for interference voltage considerations, and the duration of the pulse is significant for energy ratings of suppressors. The representation of a severe negative strike to ground is shown in figure 3.1.

3.2 Strike Rate to Ground

For analysing the likelihood of strikes to any particular buildings, the starting point is the average value of strikes per square kilometre per year for the particular location. Figure 3.2 from reference 1 shows these values for Great Britain and shows that in the Midlands, Central and Southern England rates of about 0.6 to 0.7 occur.

Thus, over say a process plant of 1 square kilometres, 12 to 14 strikes in 20 years might occur, and 3 to 4 might occur for a 0.5 x 0.5 sq. kilometre plant in the same period. On continental Europe the rates are mainly higher, especially south and east. Strikes can occur at almost any time of year, but in general there are more in the summer months than the winter months.

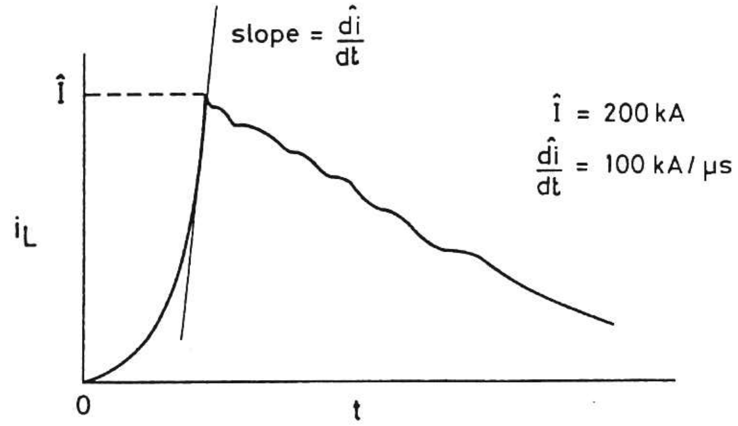


Fig. 3.1: Severe Negative Ground strike. This may be followed by several shorter duration lower amplitude pulses of current called 'subsequent strikes'.

3.3 Strike Points for Lightning

Although phrases such as 'lightning never strikes the same place twice', are often heard, this is not a fact of nature, and strike position depends on the topology of the terrain and the presence of buildings, especially tall ones, and other factors. To flat ground with normal size houses on it, the strike position would be in fact very random, though tall trees and tall houses might have a slightly higher risk of a strike than small trees and buildings. However strikes to flat ground amongst buildings is quite common when the buildings are separated by a distance of more than twice the height of the individual buildings.

As regards process plant installations, strike location will tend to favour the chimneys, taller fractionating or distillation columns etc, tall lamp posts etc, so minimizing strikes to parts of the plant close to these tall features, but again, parts of buildings which are outside the 45 degree cone of protection of the tall buildings are liable to be struck. (See figure 3.3).

As well as an increased risk of being struck, equipment on towers or tall individual buildings are especially at risk from lightning strikes owing to relatively high exposure of the sensors and their wiring, so such systems must be carefully protected. This will be considered in a later section. A generalized process plant in plan and elevation showing areas subject to being struck is shown in figure 3.3. For buildings up to 20m in height the '45°' cone of protection system is a good working tool for considering lightning protection. However for tall buildings, towers etc (over 20m tall), the rolling ball theory is better for considering the likely strike points and protection needs since it allows a proper assessment of the strike points on the side of buildings which are known to occur. A rolling ball radius of 20m is recommended.

As can be seen from figure 3.3, strikes to the control room A are possible as well as many parts of the plant B and also the ground around them both. Thus ground currents from nearby strikes to ground or other connected or unconnected buildings must be considered in a review of the lightning damage of control systems.

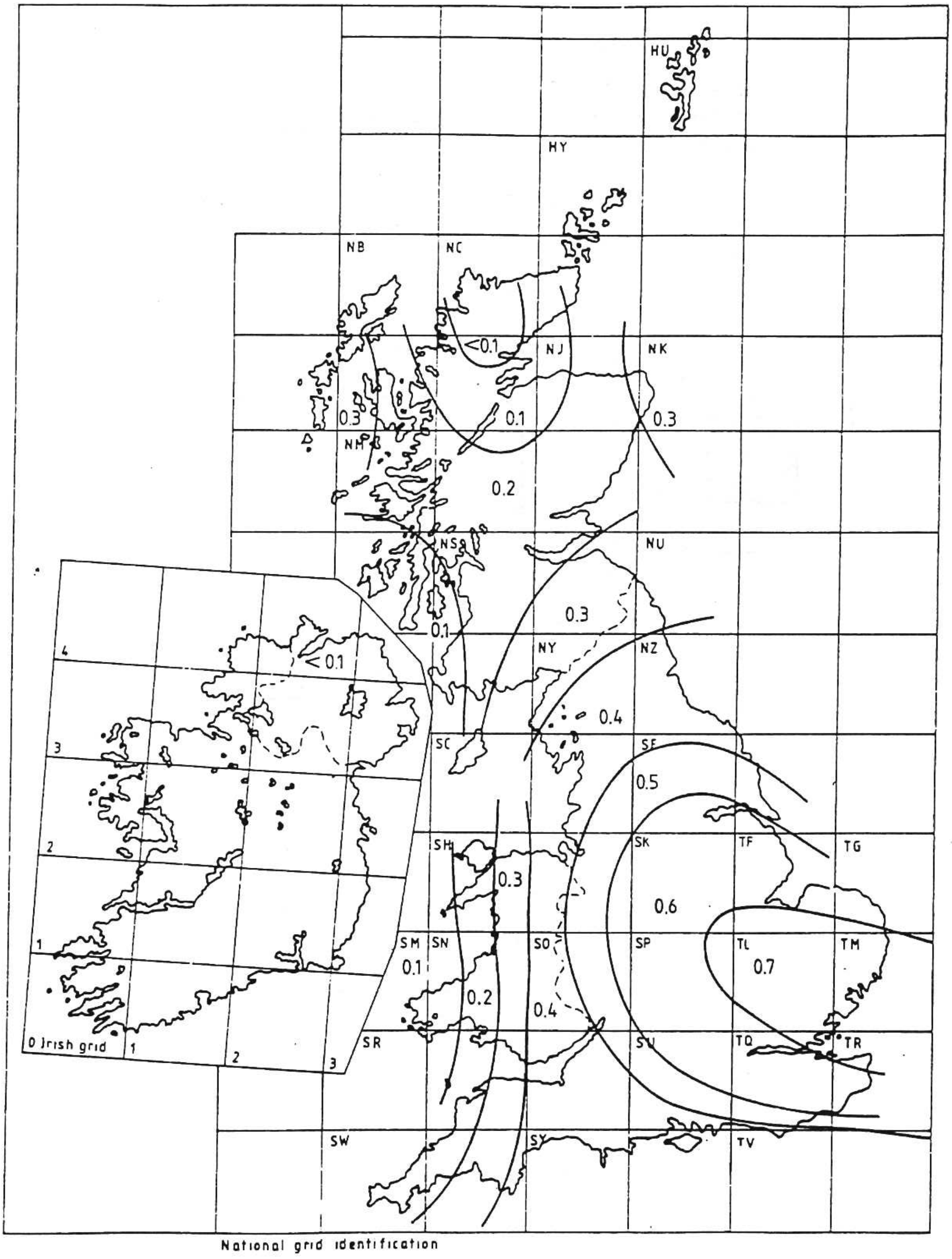
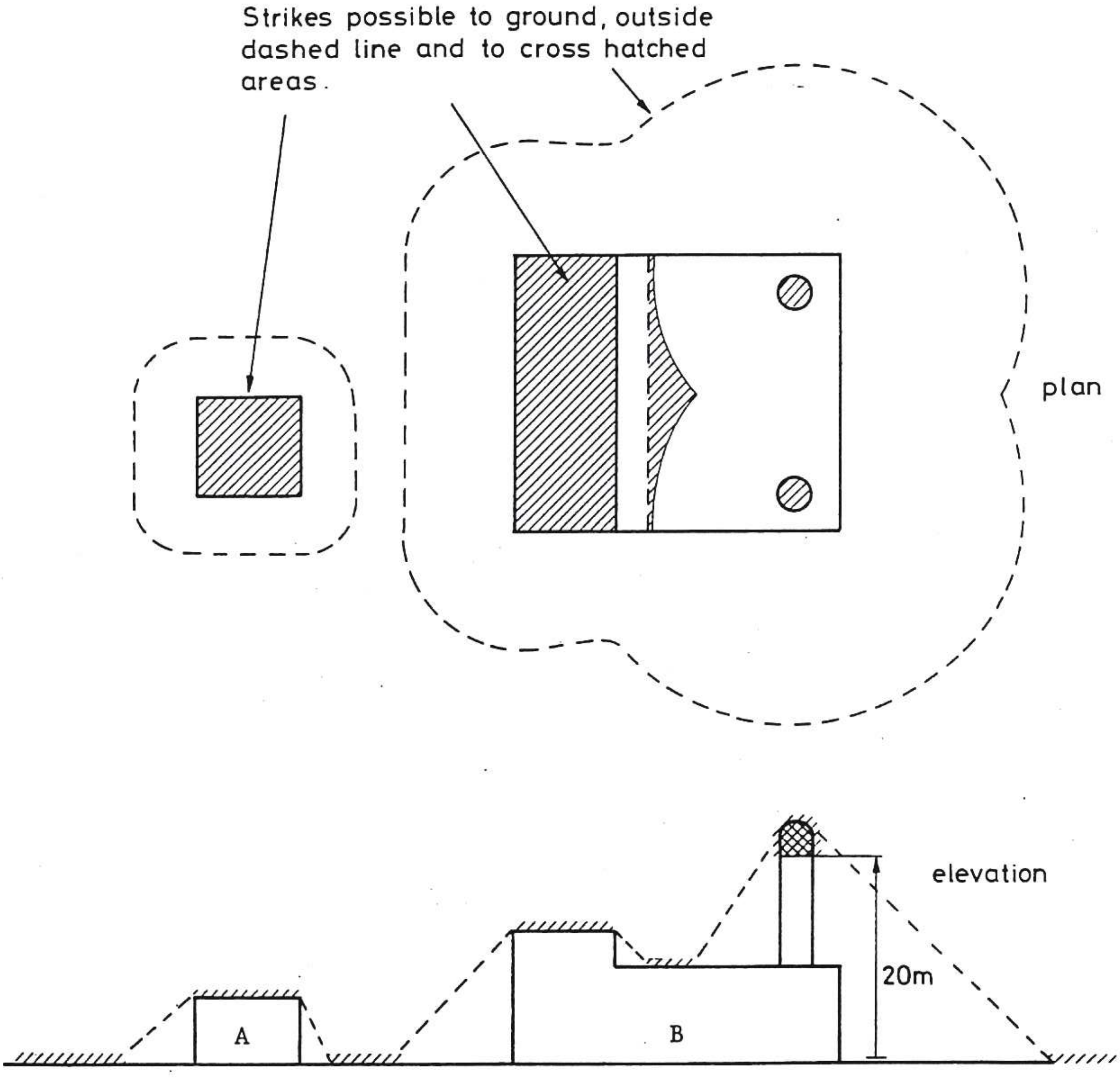


Fig 3-2 **Number of lightning flashes to the ground per km² per year for the UK**



Strikes possible to ground, outside dashed line and to cross hatched areas.

Fig. 3.3: Strike points on process plant.

4. LIGHTNING CURRENT PATHS THROUGH BUILDINGS FROM DIRECT AND ADJACENT STRIKES

Current paths through buildings from a strike to the building itself depend on two major factors:

1. Is the building an insulated structure with a Lightning Protection system (LPS).
2. Is the building a metallic construction (with or without an LPS)?

4.1 A building which is essentially of insulating construction, (stone, bricks, timber etc) with little or no metal reinforcement has in principle no safe lightning path through it. Such buildings need an LPS for structural integrity and safety of the building and its services, and given that one is installed, the current paths for lightning are then determined solely by the strike point and the way the various parts of the LPS are inter-connected and earthed.

In general, lightning current will share between all the available paths as a function of the inductive and resistive impedance, and is dependent on the shape of the current pulse, the earthing resistance and geometry. For a pulse as shown in fig 3.1, inductively controlled current sharing is likely to occur during the fast rising front of the waveform where the di/dt is very high (and thus when inductive voltages are very high because these equal L x di/dt). Late in the pulse when rates of change are slow, resistive sharing will normally take over depending on the ratio of resistance to inductance of the current paths (the resistance is determined by the earthing resistance, conductor resistances are usually negligible). Current paths for a strike to a simple insulating building with various LPS's installed are shown in fig 4.1. The essential feature of these illustrations is that the current shares between all the available paths and does not go ... 'straight down the nearest conductor' to ground, as is often believed. (Lightning current flow in conductors with inductance and resistance is determined by the usual laws of electricity as will apply to currents of 1 amp or even 1 milliamp. The main effect of the high current and high di/dt is that poor joints between conductors caused by corrosion affect the current flow very little since voltages are high enough to break down the high resistance of the insulation and allow current to flow). High currents can however cause large forces in adjacent conductors and in addition make conductors which are rather thin very hot.

4.2 Steel framed or reinforced concrete (RC) and other metallic structures with or without an LPS.

Steel framed or RC buildings, and those buildings with steel roof trusses, metal skin roofs (eg lead, copper or corrugated iron etc) and buildings with metal facades all have, in principle, a lightning protection system without the need for a complete conventional LPS, since the building structure provides many safe routes for lightning from the roof area to the ground. (Note where the roof is metal but the walls are all insulating, the metal roof, which acts as the air termination will need several down conductors to join it to earth, and some wholly or partly metal buildings may need conventional earth

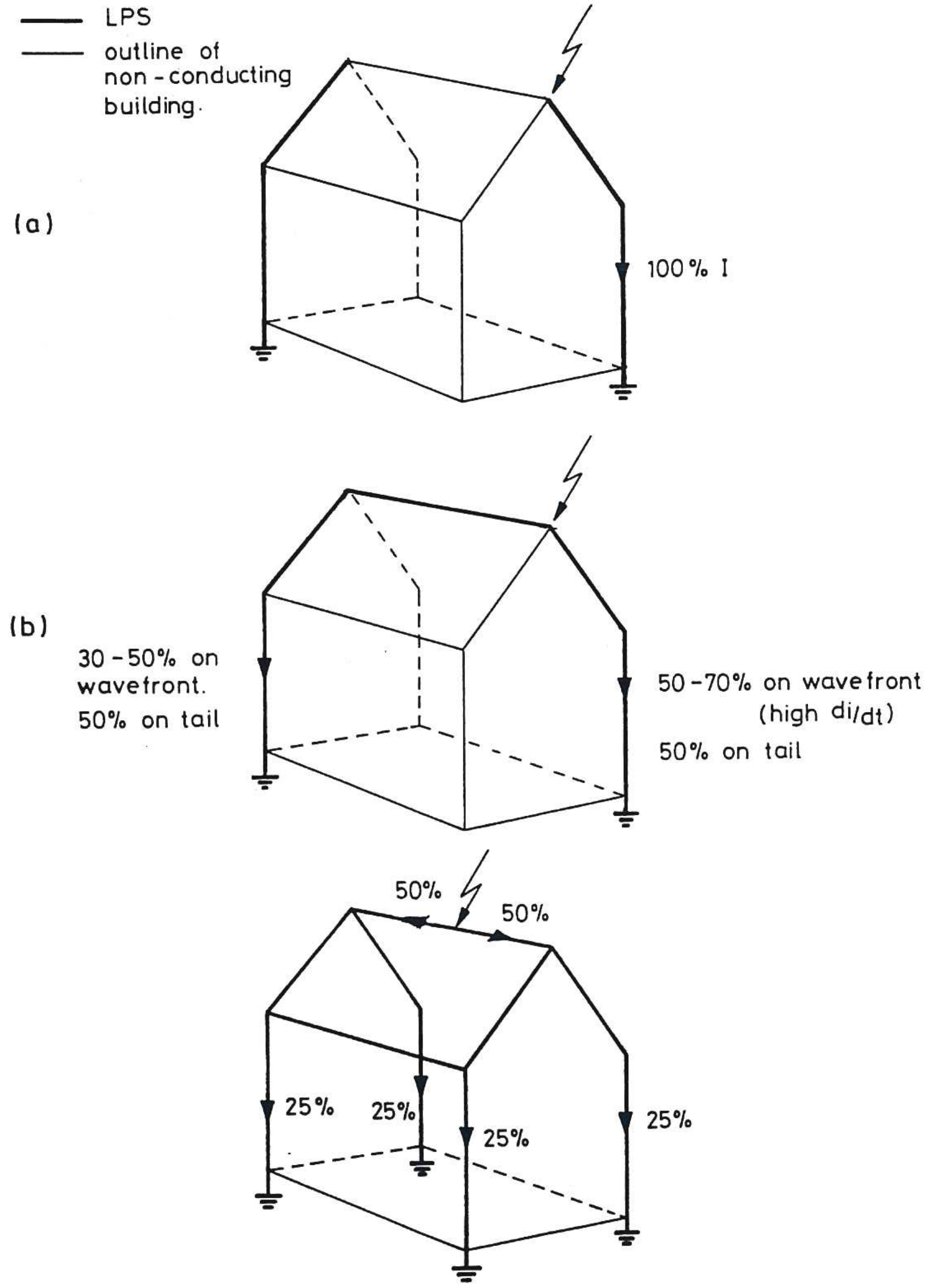


Fig. 4.1: Strikes to various LPS configurations.

terminations added to them). There is little point in adding air terminations to a metal roof, since the metal will provide sufficient attachment positions for lightning, and will be as likely to be struck as the 'official' air terminations.

Thus, the obvious merit of these structures containing metal is a multitude of paths to ground for lightning current, and in addition the low inductance provided by large conductors, eg the steel stanchions and the reinforcing bars of RC buildings form conductors whose effective actual size is much larger than the usual 20 mm by 2.5 mm down conductors of a simple LPS, and since inductance varies inversely as the logarithm of the cross section dimensions, the inductance of the large stanchions is appreciably lower.

Thus in a simple building of steel girders or RC, the current distribution would look like figure 4.2 for a strike to the top, reference 2. This scale model building has only 9 stanchions, note the final distribution of current at ground level is not uniform; the corner stanchions take more than a simple proportion (which would be 11% ie 100 over 9), whereas the internal one carries much less than 11%. If more realistic sized conductors are used instead of thin wires as in the Hadrian model, to represent real size conductors, the 12.5, 10.5 and 8.0 % figures become 13.6, 9.9 and 5.86% respectively so emphasizing still more the tendency for current to flow on the external conductors. Figure 4.3 shows a calculation for a 15 stanchion building, again with 2 sizes of conductors. In this case the internal stanchions show very small fractions of the current (3.6 and 2.8% with the smaller stanchions or 3.1 and 2.3% with the larger ones).

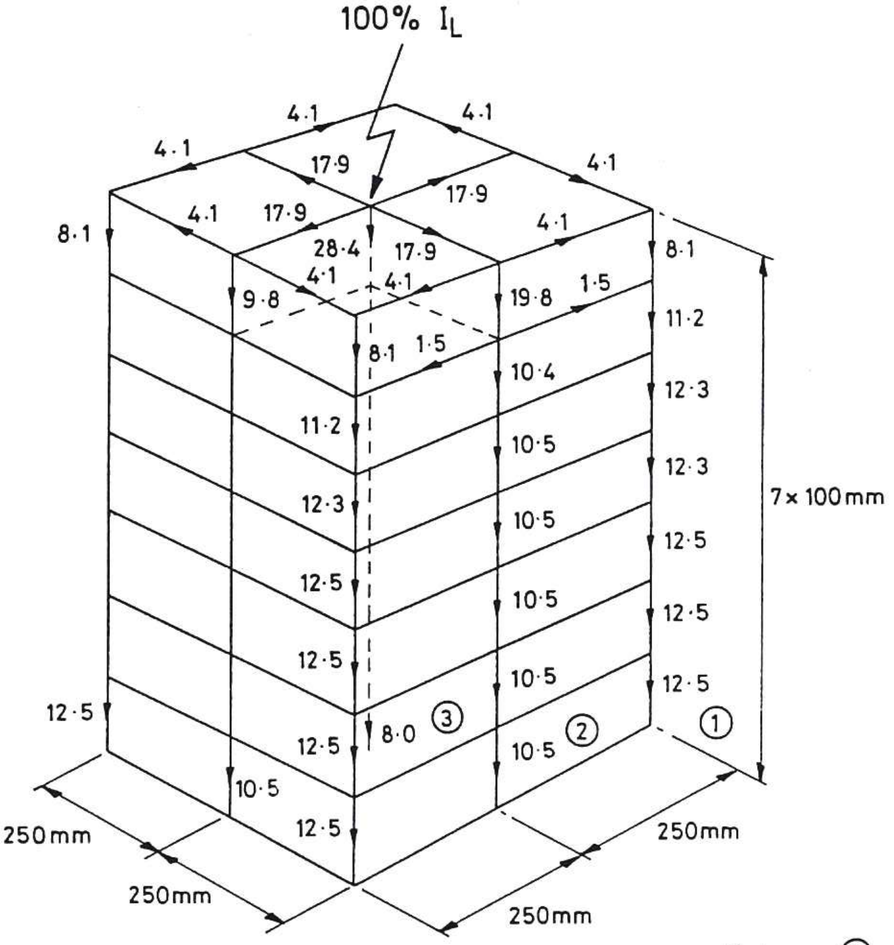
If the outer walls of the building comprise some form of continuous metal sheets, bonded top and bottom to the air terminations and the earth system, currents internal to the building would be negligible apart from near the roof, and if the roof itself comprised metal sheets, these would keep current out of the building even at the top.

The general rules are 1) The more the stanchions the more the parallel paths for current and the lower the current in each, especially the internal ones. 2) In addition to 1), when conductors form a more nearly continuous conducting skin around and over the building, internal currents become negligible, and in fact the building approaches a 'screened room'. For these general rules to apply in practice, it is necessary that any antivibration, expansion, sealing or other insulating joints or mounting points in the structure and on plant items are bypassed by bond straps.

Where an LPS system is added to a building incorporating much metal (or all metal) it is superfluous as a down conductor since in general there will be better current paths via the building metal work.

However, an LPS system fully bonded to the building steel work, if appropriately spaced on the building, between the building conductors, will provide even more useful conductors and increase the trend towards current on the outside only, so minimizing internal fields.

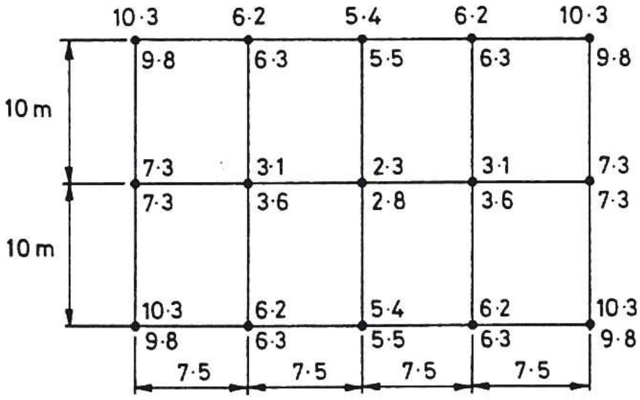
With respect to air terminations, many buildings comprising metal frames with concrete or masonry above the metal and insulating materials on the roof may require roof air termination networks to prevent puncture and the resulting damage to the roof.



Values	①	②	③
Model	12·5	10·5	8·0
INDCAL (same dimension)	12·7	10·35	7·7
INDCAL (thicker stanchions)	13·6	9·9	5·9

Current distribution in model building. Represents steel framed or R.C. structure.

Fig 4·2 Measured current distribution in small scale model of steel or reinforced concrete building determined by Hadrian (ref 2); & Culham calculation using INDCAL.



Values above each dot are 32cm dia stanchion.

Values below each dot are 16cm dia stanchion.

(Note small values on centre stanchions)

Fig. 4·3: Plan view of current distribution 15 stanchion building (INDCAL).

4.3 Special Case of Process Plant

Process plant, chemical complexes etc are nearly always built with a combination of different types of construction but essentially comprise 3 types, 1) exposed towers (distillation towers, fractionating columns, reaction vessels etc. 2) Plant with a structure like a steel frame building with no roof and no walls, with the majority of the smaller items of equipment within this framework. 3) Plant within a completely enclosing building, normally a structural steel building with metal roof trusses.

Cases 2 and 3 are similar to that described above in 4.2 but case 1 is an interesting and important case in its own right since it can give high current parameters and high current densities on the tower itself and around the sensors etc.

Referring to figure 4.4, current density on the surface is shown around:

a) a simple circular tower 2 metres diameter,
b) one with added pipes
c) tower, pipes, rung ladder and cable trays.

From these figures it can be seen that locating the cable trays between the rung ladder or pipes and the tower is a better place than exposed on the sides since the currents, and hence the fields, are much less. Better still cables should be run in tubes or metallically closed trays but the trays or tubes must be electrically conducting along their length and bonded to the tower top and bottom.

The same inductive sharing rules apply for figure 4.4 as for figures 4.2 and 4.3 except that the geometry is so different. As a comparison the currents in a 1 cm diameter conductor placed in positions 1, 2, 3 and 4 for 200kA strike are as follows:

Table 4.1

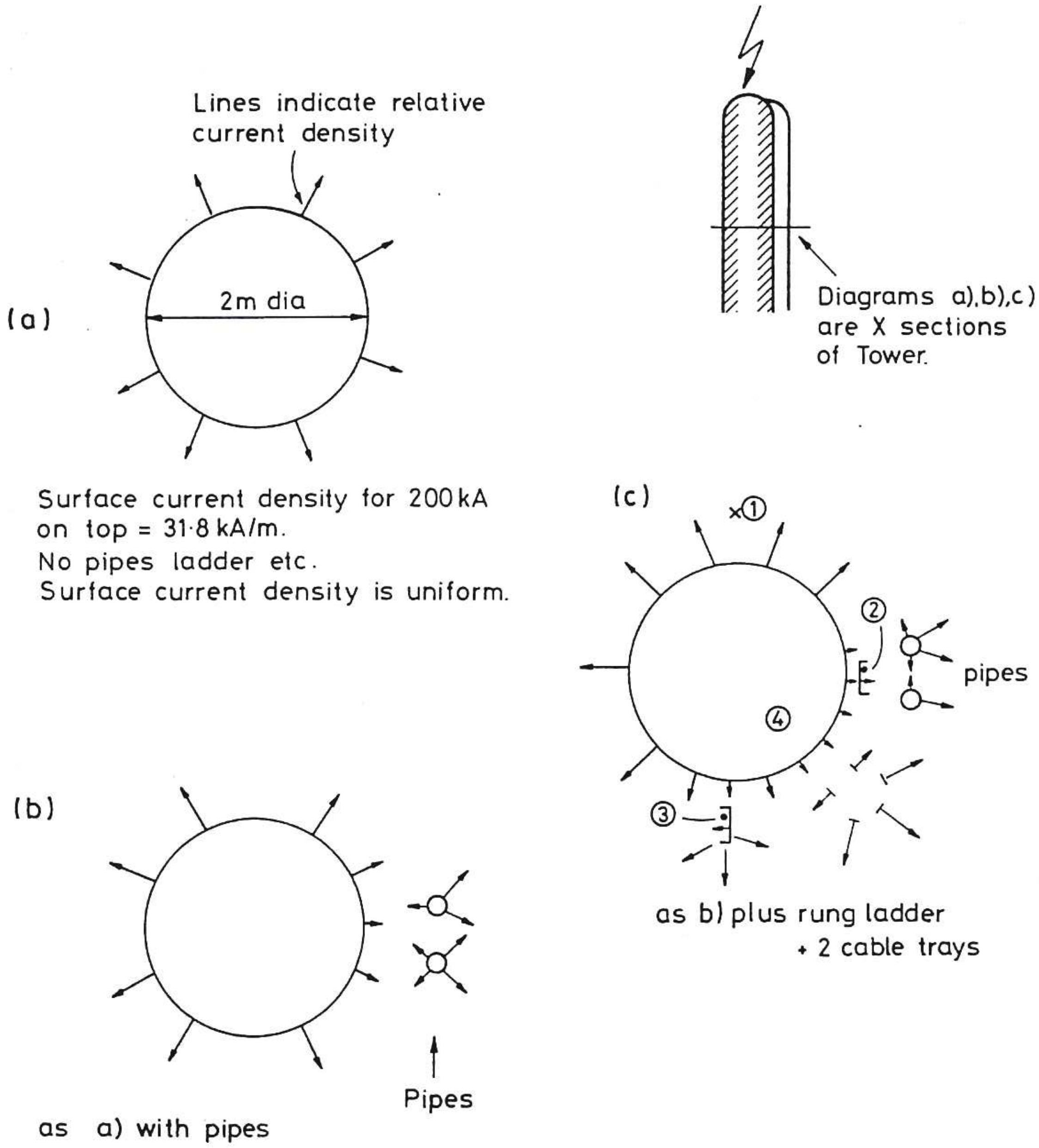
Position	Current
1	13.5kA
2	0.08kA
3	0.37kA
4	≈0

These calculations assume the 1cm diameter conductor is bonded at both ends. If it were an electrical cable bundle, whether current flows or not depends on the voltage produced (see section 6.2) but normally in case 1 and probably 3, enough voltage will occur to break down the insulation of sensors and the computer so allowing the current to flow.

In summary:- 1.A large current flows on the external surfaces of tall single vessels which are subject to direct attachments at the top.

2. Large currents will also flow in pipes and cables, but suitable locations and/or enclosing the cable in a tray or tube will effectively screen it.

3. To be effective any metal work which takes part in the current diversion or screening action <u>must</u> be effectively bonded top and bottom so that it can carry



Surface current density for 200kA on top = 31·8 kA/m.
No pipes ladder etc.
Surface current density is uniform.

as a) with pipes

as b) plus rung ladder
+ 2 cable trays

Fig. 4.4: Current distribution through a simple vertical metal tower or reaction vessel etc. with various extra metal parts & cable trays.

a part of the lightning current. An unbonded screen, tube, pipe etc is ineffective.

5.0 CURRENT FLOW BETWEEN BUILDINGS

Section 4 has described how current flows down and distributes around buildings with an LPS and/or metallic structures. This section deals with current flow between adjacent buildings which a) do not and b) do have metallic connections between them.

5.1 Buildings Without Metallic Connections Between Them

Where adjacent buildings have entirely separate earth systems as in figure 5.1a there is minimal interaction between them when one building is struck and the other is not. During the strike, building A might rise to many tens or hundreds of kV above the general potential of the ground remote from the strike say at point C owing to the earth resistance of building A. Most standards quote that the effective ground resistance for a single building should be 10 ohms or less, but 10 ohms is not low where 200kA is involved since V = I x R = 2MV. Since the lightning event can be considered as a constant current source, this process is not limited by even higher earth resistances.

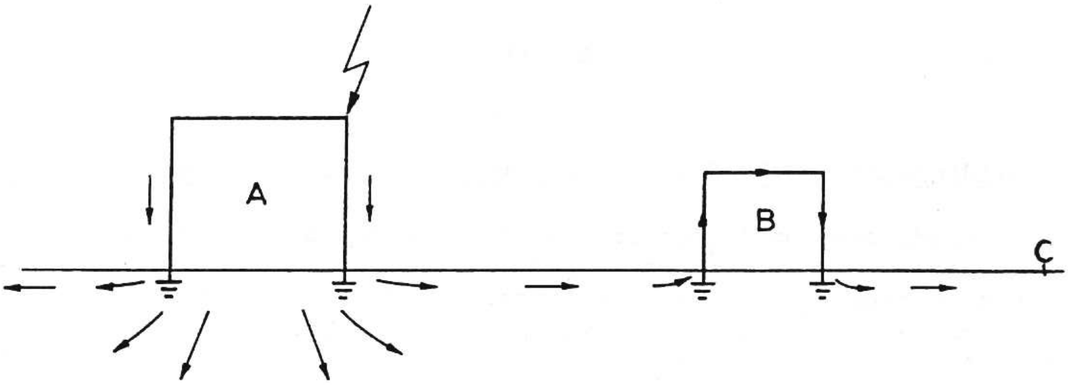


Fig. 5-1 (a): Current flow between two isolated buildings A & B
A is struck by lightning.

Clearly strikes to either building A or to any other point on the ground will cause at least some current to flow through the structure of B as shown by the arrows. However the current flowing through B is fairly low in this case, and self contained systems in B will be affected much less than in A, since building B currents will be of the order of a tenth or less than A, and if B were tall, very little current would flow in the upper storeys or upper levels.

In practice, buildings are not usually entirely separate, since they have common services which may join them up, eg electricity supplies, gas or water pipes, although with the trend to plastic, gas and water pipes are less important these days. The effect of having conducting services will tend to spread current between numerous adjacent buildings and so each one will tend to receive only a small part, and the contact between the armouring of cables and pipes to ground would improve the earth resistance for all of them.

One of the significant facts (reference figure 5.1a) is that for a strike to a building, as at A, a large fraction of the potential gradient on the ground occurs very close to A as in figure 5.1b so that even for very close buildings there might be very large potential difference between them. If so then a significant fraction of the lightning current will pass through any metallic connection to the other building.

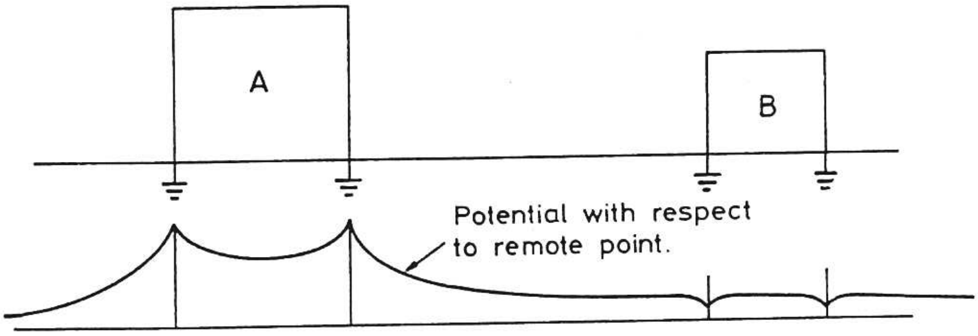


Fig. 5·1 (b)

5.2 Buildings Joined by Services or Otherwise Interconnected

Where adjacent buildings are directly joined by conducting links, whether mains cables, water, gas or other pipes, or electronic system data lines or instrument wiring, all of these services are likely to take lightning current as it finds the lowest impedance path to earth. The worst situation is where building A is otherwise isolated from B except for say a wired data link or instrument cable. In this case hundreds of kV will be available to flash over insulation at each end to provide a current path. Where inadvertent links exist between A and B at each end eg power cable armouring, the effects of the resistance and the inductance of these will still induce tens of kV or more, so breaking down insulation on the data lines as above. (See figure 5.2).

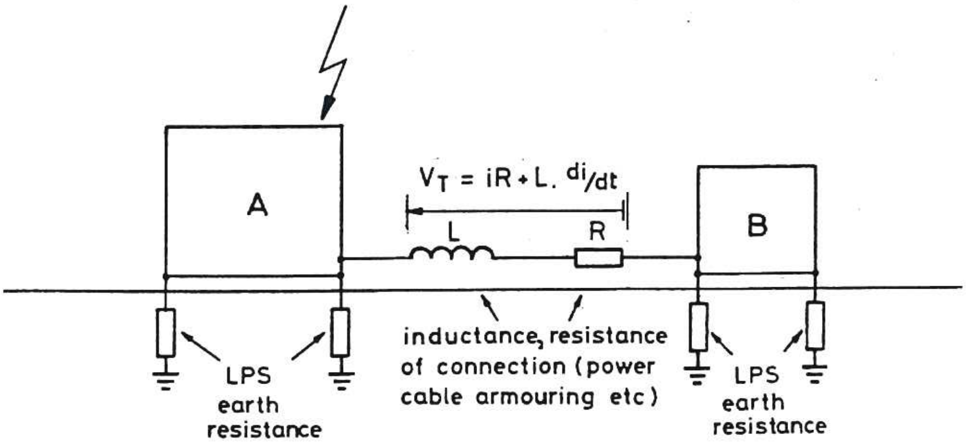


Fig. 5·2 : Connected building.

As an example of the order of magnitude of the voltage, for a severe strike, assume 20% of the current flows along the link shown. Let the buildings be 50 metres apart, and the cable and armouring has a resistance of 1mΩ/m and assume the cable is 30% longer than the building separation.

Current in cable = $0.2 \times 200\text{kA} = 40{,}000$ amps
Total resistance = $50 \times 1.3 \times 1 \times 10^{-3} = 0.065\Omega$
Therefore V_R = $i.R = 40{,}000 \times 0.065$
$= \underline{2{,}600\text{V}}$

di/dt of current in cable is 20% of 100kA/μs = 20kA/μs
inductance of cable is:

$$L = 0.2 \times 65 \times \left(\log_e \frac{2 \times 65}{.0165} - 1\right) \mu\text{H}$$

$$= 103\ \mu\text{H}$$

Therefore V_L $= di/dt \times L = 2 \times 10^4 \times 103$
$\approx 2\text{MV}$

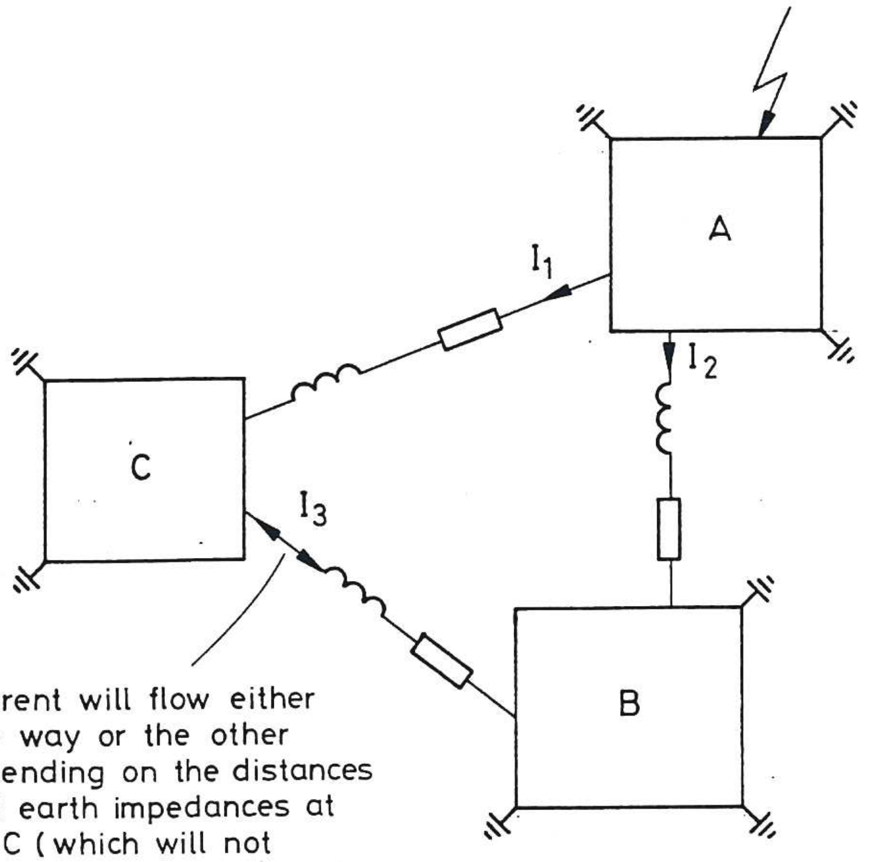
(This is based on a cable diameter of 33mm)

In practice such high voltages (ie the V_L = 2 MV) will not be reached because such a high value will affect current sharing between building A and the cable, so the relatively low inductance route into the ground at A would preferentially reduce the current below the 20% on the fast rising part of the waveform of the peak, but on the slow tail the 20% value will be realistic.

Thus to achieve safe operation of the systems between buildings, where fibre optic links can not be used, requires that data links between buildings are 100% shielded from the prospective inductive voltage of hundreds of kV. Fortunately this can be achieved very readily by the use of the instrument cable armouring itself or cable trays and screens. This topic will be discussed in the next section.

Where more than one building is involved the same principles still apply, namely, links between them will all carry lightning currents as it distributes between the various earthing points. See figure 5.3. For a strike to any of these the same basic effects occur as shown in this diagram.

Cables with an external insulating 'serving' over the armouring which are laid directly in the ground can suffer damage from puncture of the serving by the high voltages refered to above. For this reason, and others, cable trays are preferred.



Current will flow either one way or the other depending on the distances and earth impedances at B & C (which will not necessarily be the same)

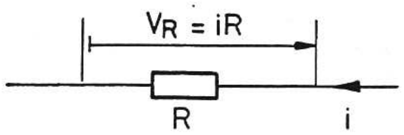
Fig. 5·3 : Current flow between 3 buildings when one is struck (plan view).

In figure 5.3 where one building say C is very poorly earthed, or not earthed at all, all three paths 1, 2, and 3 will take a substantial fraction of the lightning current thus giving similar problems as shown in figure 5.2 for two buildings, and similar calculations will yield high resistive and especially very high inductive voltages.

6.0 INDUCED/INJECTED VOLTAGES AND CURRENTS IN ELECTRICAL SYSTEMS

Control and data systems (or in fact any electrical system) are subject to the effects of induced voltages from lightning currents, and these arise from several mechanisms; this section deals with 2 of the principle methods, namely resistive and inductive voltage induction from current flowing in the system and earthing conductors. In practice it is difficult to distinguish between the 'injected' and 'induced' voltages and the term 'induced voltages' will be used to cover both except that a

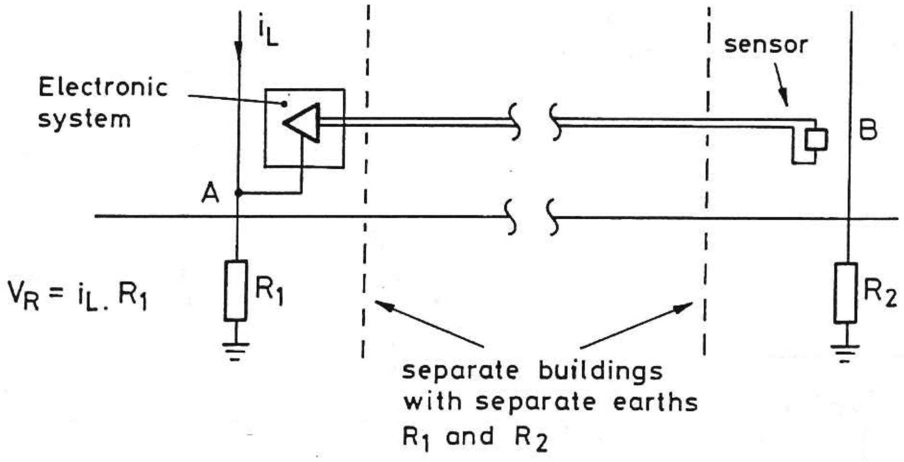
(a) Basic resistive voltage



i = time varying current

V_R = time varying resistive voltage produced by i across R.

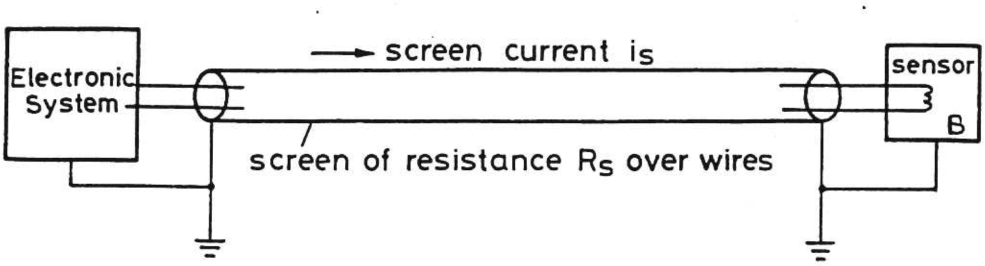
(b) Earth resistance voltage in data circuits, strike to building at left.



V_R (equal to $i_L \times R_1$) stresses insulation at sensor B (if isolated), or is injected directly into the sensor circuit if the sensor has an electrical connection at B. (If the strike were to the building on the right, a voltage $V_R = i_L \times R_2$ would be applied to the circuit)

If $i_L = 200$ kA and $R_1 = 10\Omega$, $V_R = 2$MV(!).

(c) Resistive voltages in screens or conduits



$V_S = R_S . i_S$. This is injected across insulation at sensor at B or into the circuit instead of V_R as in 6·1 (b)

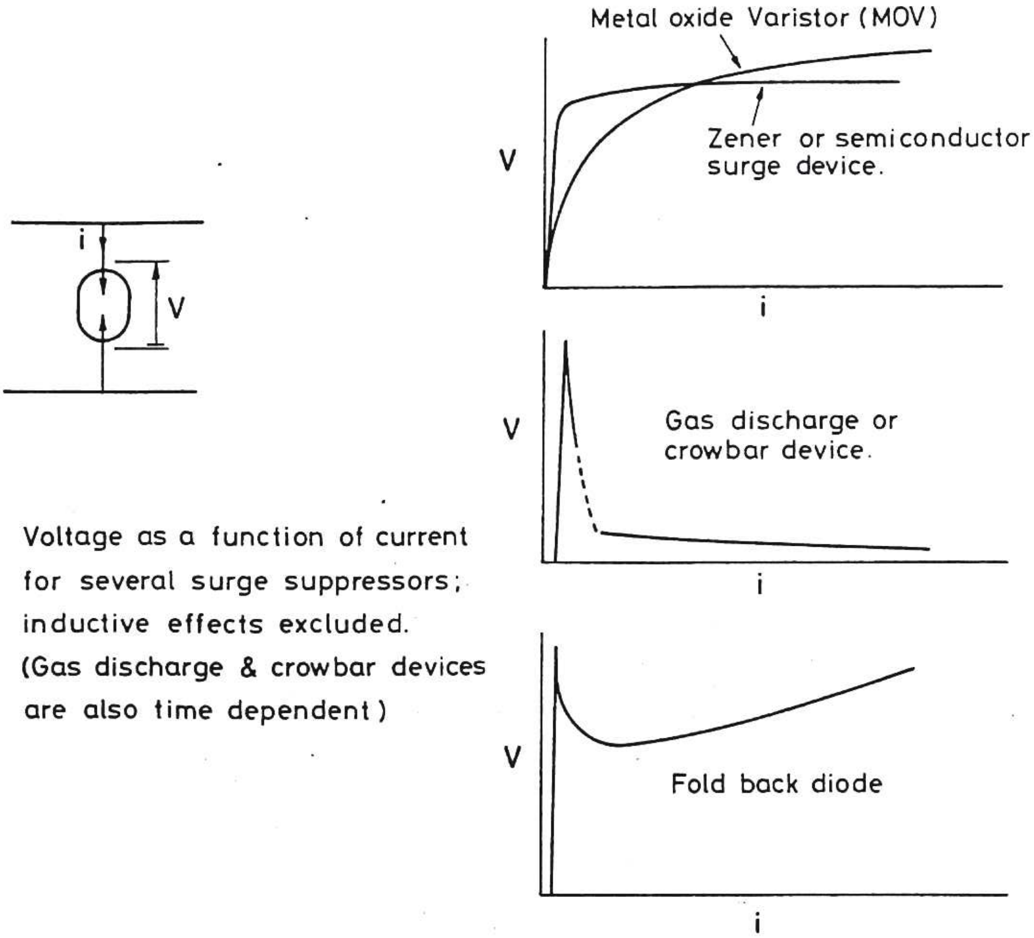
Fig. 6·1

mechanism called 'direct injection' caused by the lightning channel contacting the actual wiring itself is a sufficiently serious and distinct case to merit the separate title and consideration. (Owing to the severity of this mechanism the system should be designed and installed so that direct injection is not possible).

6.1 Resistive Induced Voltages

These arise as a result of current flow through conductors and/or into the ground resistance and depends very simply on ohms law (V = I.R). Typical instances of this are shown in figure 6.1, a), b) and c). Note that in general v_s will be orders of magnitude lower than V_R.

Additional resistive type voltages occur when surge arresters, limiters, clippers etc are used in circuits as surge protectors, and the voltage occurring depends on the current times the effective resistance of the device. All clippers and limiters have some type of non-linear resistance which is voltage or current dependent and so R is the effective resistance at a particular value of current. See figure 6.2.



Voltage as a function of current for several surge suppressors; inductive effects excluded. (Gas discharge & crowbar devices are also time dependent)

Fig. 6·2

All these voltages are resistive in nature; that is they depend on the current amplitude itself and not parameters such as di/dt. In practice however V will also depend on the di/dt of the current owing to the inductance of the leads of the device, and on the connections to the earth reference point. This is a serious limitation of the efficiency of a surge protector when used for fast transient currents (see section below).

6.2 Inductive Voltages

Inductance has an important role in electromagnetics and in lightning protection problems. On the one hand inductive reactance is an impedance which controls and limits current flow in conductors for alternating currents (ie currents for which di/dt is significant, which may be sinusoidal, or as normally encountered with lightning, pulse currents).

On the other hand, mutual or self inductances are a way by which large voltages might occur in circuits linked by the magnetic flux from currents flowing in conductors. Figure 6.3 illustrates the inductive voltage effect. In this figure the resistance of the wire is ignored.

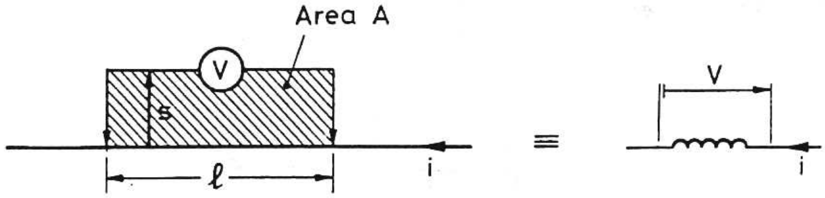


Fig. 6.3

Any wire, or conductor of any kind, whether straight, curved or coiled has the property of self inductance which produces a reactive impedance. So in lumped circuit terms the wire at left in figure 6.3 acts as inductance just as the circuit at right. However for calculations of transfer inductance and mutual inductance the natural wire geometry must be used as at left since it determins the geometry of the magnetic flux in the area A and therefore the $d\Phi/dt$ where Φ represents the magnetic flux.

The emf induced in the loop shown enclosing area A and connected to the voltage measuring device is a function of the distance s, the radius r of the current carrying conductor and the loop length. It is not simply dependant on area because the magnetic flux density is not uniform. It takes the form shown in figure 6.4.

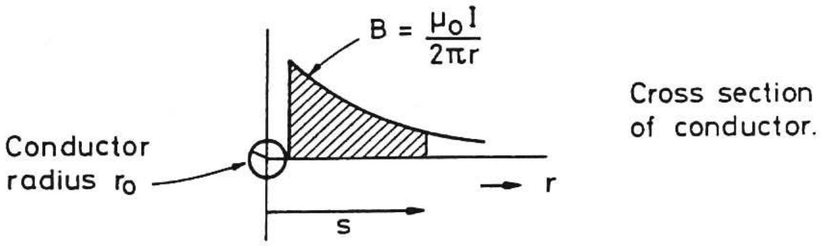


Fig. 6.4

Since $B = \frac{\mu_o I}{2\pi r}$
the total flux Φ per unit length out to position s is

$$\Phi = \int B dr = \frac{\mu_o I}{2\pi} \int \frac{1}{r} dr = I \frac{\mu_o}{2\pi} \log_e \frac{s}{r_o}$$

Therefore $L = \frac{\Phi}{I} = \frac{\mu_o}{2\pi} \log_e \frac{s}{r_o}$

$$= 0.2 \log_e \frac{s}{r_o} \ \mu\text{H/metre length of loop.} \tag{1}$$

This is termed the transfer inductance (M_T) of the loop shown. Any loop not involving the current conductor itself can be calculated in a generally similar way, eg a loop as in figure 6.5 separated from the conductor has a mutual inductance (M) of $0.2 \log_e \frac{r_2}{r_1}$ μH/metre. (2)

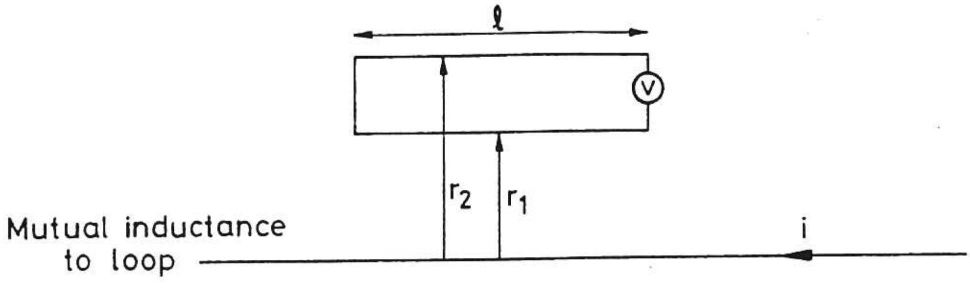


Fig. 6·5

Having obtained the transfer or mutual inductance as above, the maximum voltage produced from pulse currents with a peak di/dt of $\widehat{di/dt}$ A/μs is:

$$Vm = M_T \frac{\widehat{di}}{dt} \ell \ \text{volts}$$

where ℓ is length of the loop in metres, M_T in μH/m
and $\frac{\widehat{di}}{dt}$ in A/μs

For a sine wave of frequency f and peak current I_o, the peak voltage is

$$V_m = 2\pi f \ I_o \ . \ M_T \ . \ \ell$$

where M_T is in μH/m, I_o in kA, and f in kHz, ℓ in metres.

For a single conductor of radius r_o the self inductance is given by:

$$L = 0.2 \left(\log_e \frac{2\ell}{r_o} - 1\right) \mu\text{H/m.} \tag{3}$$

Whereas the self inductance L of a conductor is fixed by its dimensions, the transfer inductance to a loop as in equation (1) and the mutual inductance to a separate loop as in (2) can be readily altered and in fact minimized by the following procedures. For the transfer inductance, minimize s and ℓ and maximize r_0. For the mutual inductance, make $r_1 = r_2$ if possible and make both large and minimize ℓ.

The more surprising solution here is for the transfer inductance, (making s small) so that the loop under consideration is as close to the current carrying conductor as possible. It might, at first thought, seem reasonable to separate it from the main conductor, but obviously the larger s becomes the larger $\log \frac{s}{r_0}$ becomes, so making M_T larger. Ideally the log term should be made zero by locating the wires within the current carrying conductor, making the solution revert to figure 6.1 c) where only the conductor resistance causes voltages, inductive voltages are eliminated in principle. However the bonding links to the screen of figure 6.1c have inductance and this will couple an inductive voltage depending on its length and separation from the core conductors. See figure 6.6

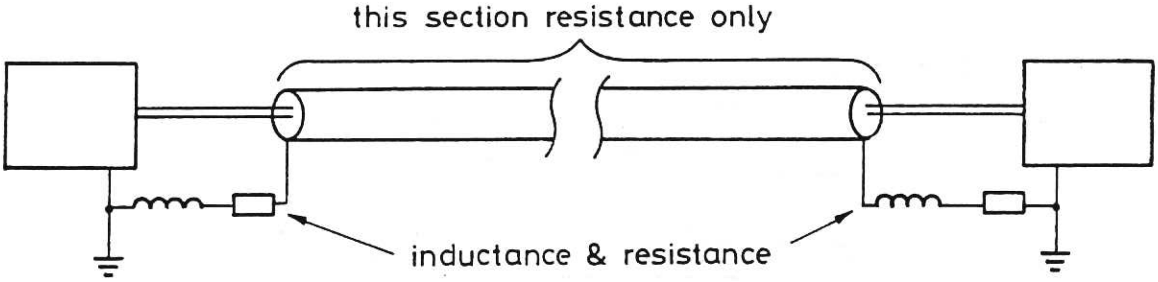


Fig. 6·6: Voltage depends on resistance & inductance of pigtails.

The method of bonding the screen is obviously vital in keeping the inductive voltages low. eg no long thin pigtails, preferably a broad but short connection directly to the local earth reference to the equipment is best as in figure 6.7.

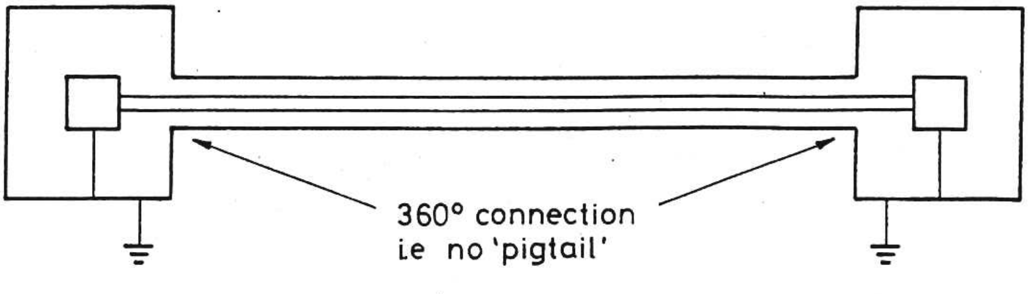
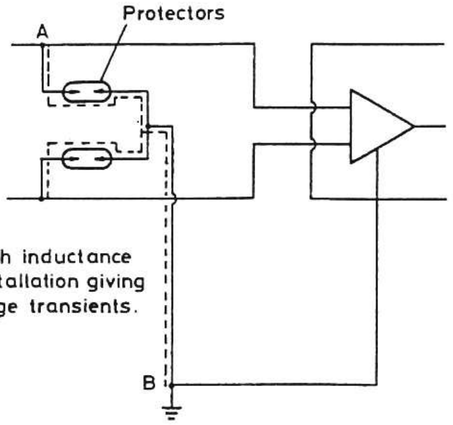


Fig. 6·7: Optimum cable screening, no pigtails.

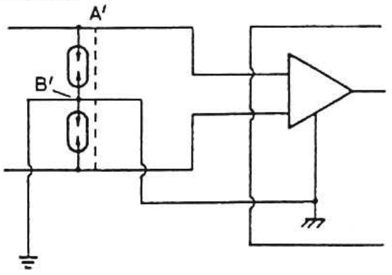
Figure 6.6, 6.7 showed two extremes, 6.7 is perfect but not often economically feasible, whereas 6.6 with long bonding leads is very undesirable because of the inductive effect. A compromise involves a careful installation which minimizes the length of the current carrying bonding conductor which provides the regions of inductive and resistive voltage shown in figure 6.6. Inductive effects are also important where limiters, clippers, surge suppressors etc are installed because of the inductance of the leads and the mounting system.



When protectors conduct, the voltage at the equipment input is the protector voltage plus the inductive and resistive voltage for the whole of route A to B.

(a) High inductance installation giving large transients.

(b) Good installation



Minimal extra voltages than the protector conduction voltage.

A′ - B′ is the total route for current to the earth reference.

Fig. 6·8

Figure 6.8a is a bad high inductance scheme, whereas b) is a good low inductance method, the equipment reference 0 volt level must not be joined remotely from the surge suppressor earthing point. In a) both the inductive and resistive voltages of the whole of the route A to B is applied to the input of the equipment at right. However in b) the current route involving common impedances which injects voltages into the equipment is very short, comprising only the length of the surge suppressors leads and this involves a very short inductance route to equipment ground, A′ to B′.

6.3 Summary of Resistive and Inductive Voltage Effects

Resistive voltages arise from the earthing and conductor resistances and are injected into circuits depending on the connection method and circuit flow paths. Where cables run within an over braid or other screening shield, a loop voltage is injected into those cables depending on the braid or sheath resistance and the current in that braid. Voltages are proportional to the current amplitude. Surge suppressors also have current dependent voltages.

Inductive effects arise from changing currents in conductors and produce voltages in loops incorporating the current carrying conductors

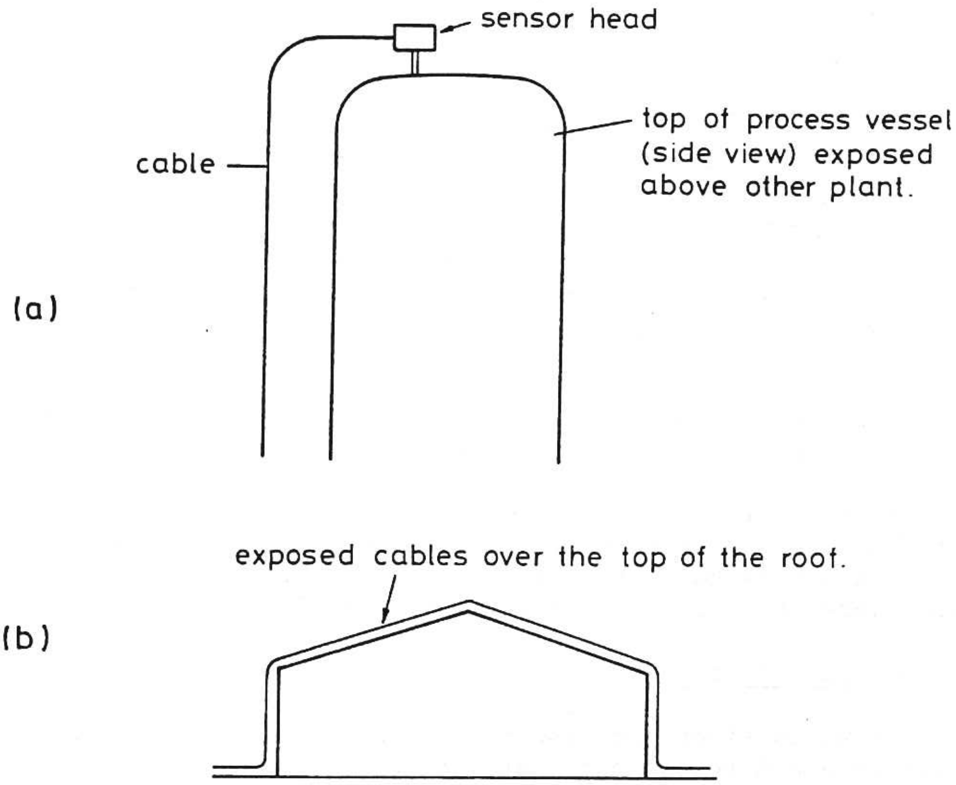


Fig. 6·9

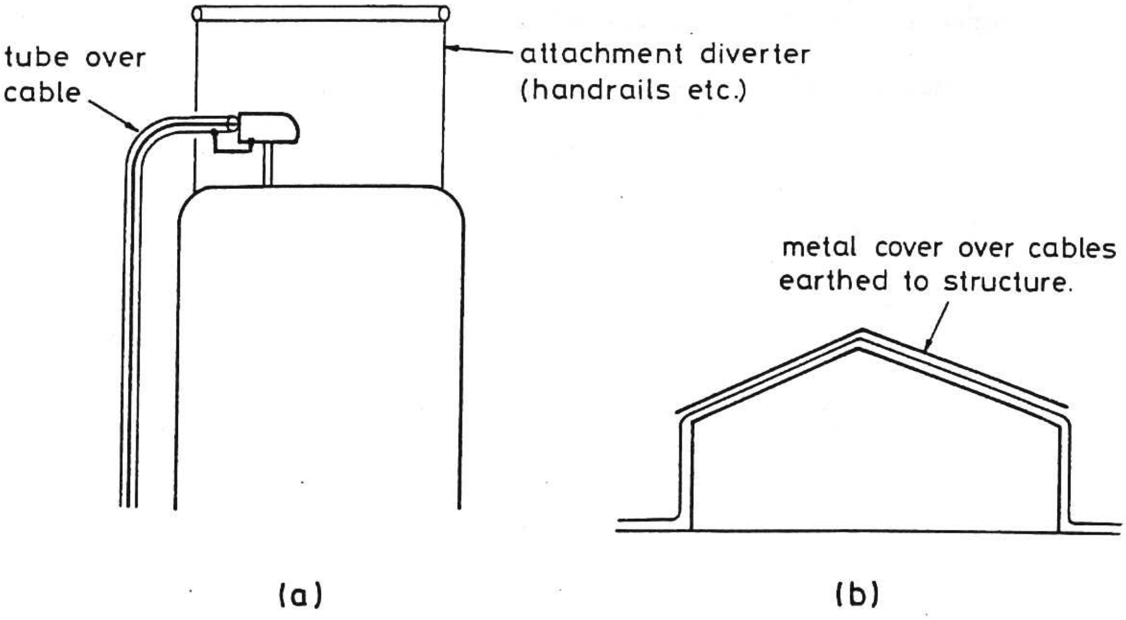


Fig. 6·10

and in separated loops, both by magnetic induction. Placing wires within hollow conductors shields out the inductive voltage, and minimizing loop areas always assists this too. (See figure 6.2). Shields do not work for this purpose if only bonded at one end.

6.4 Direct Injection

This occurs when lightning attaches directly to the wiring on exposed sensor heads and so drives currents directly into the system wiring. This might occur at some sensor with its wiring exposed at the top of a plant, or to an exposed cable route over the top of a building etc, or to whip antennas or similar. Such attachments are very destructive and may even be dangerous if they cause sparking in explosive atmospheres. (See figure 6.9).

Vaporization of the cable wires may well occur and extremely large currents and voltages will be injected into the systems, sufficiently large to flash over to other circuits and cause multiple failures.

By suitable relocation of wiring and/or the fitting of lightning attachment diverter rods such direct contact can and must be prevented. Eg in case 6.9a the wiring can be run closer to the tower, and earthed metal work installed on a higher level as in figure 6.10.

6.5 Example on section 6.0

If we consider the case quoted in section 5.2 and the calculation of inductance and resistance, data or instrument cables located within the armoured cable are shielded nearly 100% from the inductive voltages as explained above, although not from the resistive voltage quoted. However in practice usually many cables in parallel will be used and perhaps other bonding or earthing cables as well so reducing the current in each to a low value. So if there are say 10 cables and conductors, equally sharing the current, resistive voltage will be reduced to 2,600 ÷ 10 = 260 volts.

Inductive voltages will arise from the bonding arrangements on the cable armouring and these may vary widely depending on the installation. However a sample calculation will indicate the likely level. For 10 cables carrying a total of 20% of the lightning current, each with a bonding strip 0.5m long carrying the current of the cable, the di/dt in each link is $\frac{10^{11}}{10 \times 5} = 2$ kA/µs.

For the geometry below:

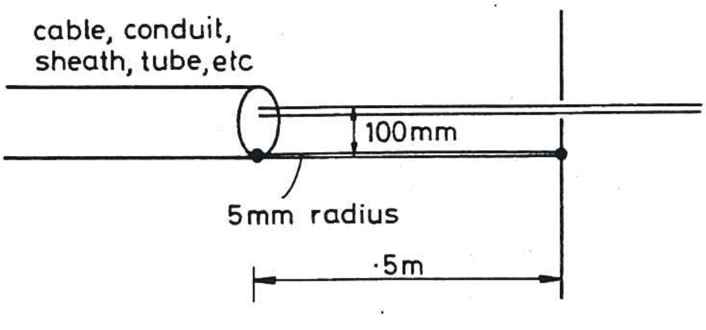


Fig. 6·11: Calculation of inductive voltage in bond lead to cable.

$$M_T = .5 \times .2 \times \log_e \frac{100}{5}$$

$$V = 2 \times 10^3 \times .5 \times .2 \times \log_e 20 = 600V$$

This is a relatively easy voltage to cope with by input circuits of equipments even in some cases without special surge suppressors.

The main implications of the inductive coupling processes described in section 6.2 are that a) within the plant instrument cabling should be close to bonded raceways, stanchions, towers etc in order to keep the transfer inductance low, since the loops in question here are the plant carrying the lightning current and the instrument wiring.

b) within the computer building the mutual inductance from the structure to all of the cables in the computer, instrumentation and display equipment is relevant, and here loops should be minimized by using a star point distribution system much like Appendix 4 drawing A, and generally keeping interconnection wiring away from the outer walls and from possible lightning current paths within the building.

7.0 LIGHTNING ELECTRO MAGNETIC PULSE AND ITS EFFECT ON EQUIPMENT AND SYSTEMS

The term LEMP is used to refer to the electric and magnetic fields radiated from either lightning ground flashes or cloud-to-cloud flashes and was coined in this form to correspond with another electro magnetic phenomenon, namely nuclear electro magnetic pulse (NEMP). There are important differences in the spectrum and magnitude of the two effects since NEMP produces much faster rising pulses (10×10^{-9} seconds) with very severe amplitude, and the NEMP only interacts with systems as a radiated pulse. By comparison the radiated pulse from lightning is quite small. (Sufficient to cause loud clicks on medium wave and long wave radio). Strikes either to the building of interest or to the ground nearby do not produce true LEMP but principally a near field magnetic coupling which induces voltages as in figure 6.5.

Electric field pulses within buildings and plant arising from lightning would usually be negligible although in one or two exceptional cases external wiring might be at risk as in figure 6.9a unless it was screened or enclosed (which is necessary for protection against injected currents and induced voltages anyway).

In general the effects of LEMP are protected against by adopting precautions necessary for protecting against direct lightning strikes. Direct strikes in any case produce much more severe transients than LEMP and direct strike protection is the primary requirement; the protection against LEMP being a worthwhile advantage and so ensuring that LEMP effects are very small.

8. INSTRUMENT EARTHING AND SAFETY/LIGHTNING EARTHING

The method of earthing, interconnection of building power/lightning/safety earths, and the instrument/computer system earthing policy advocated in this guide is best illustrated with diagrams indicating the preferred and the non-preferred methods.

The older system is shown in figure 8.1 where the control room/instrument earth is single point joined to the safety earth in the building and thereafter the instrumentation has to "fend for itself" when connected out to plant equipment/sensors.

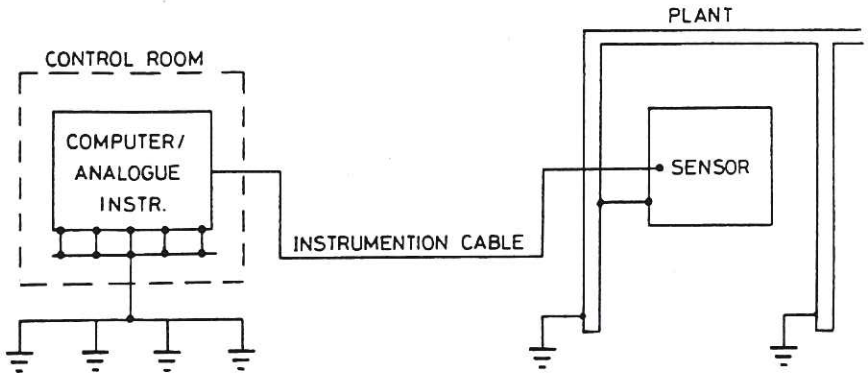


Fig 8·1 Non-interconnected earths

However by interconnecting the earths of the control room and plant and enclosing the instrument cables in bonded trunking and/or by bonding the cable armouring, in effect the safety earth is extended right under and alongside the instrumentation cables so diverting the lightning and other fault currents from the instrument cables and so virtually eliminating transient interference. Figure 8.2 illustrates this scheme.

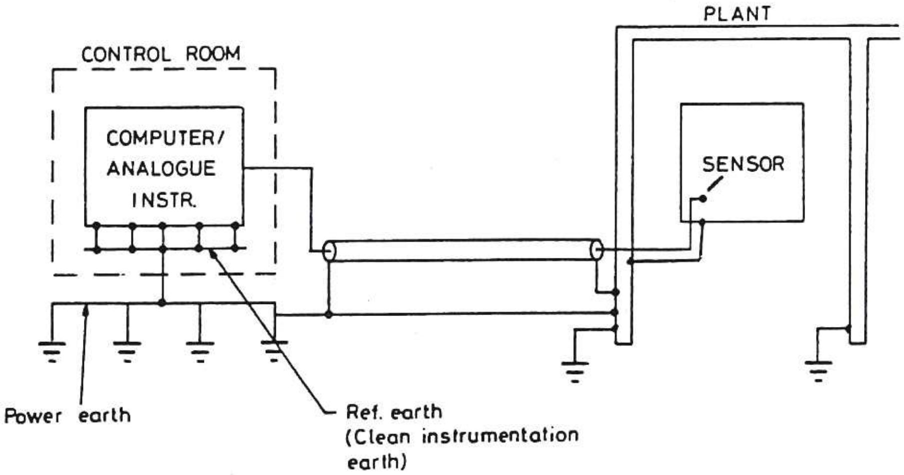


Fig 8.2 Interconnected earths & screened instrument cables (preferred).

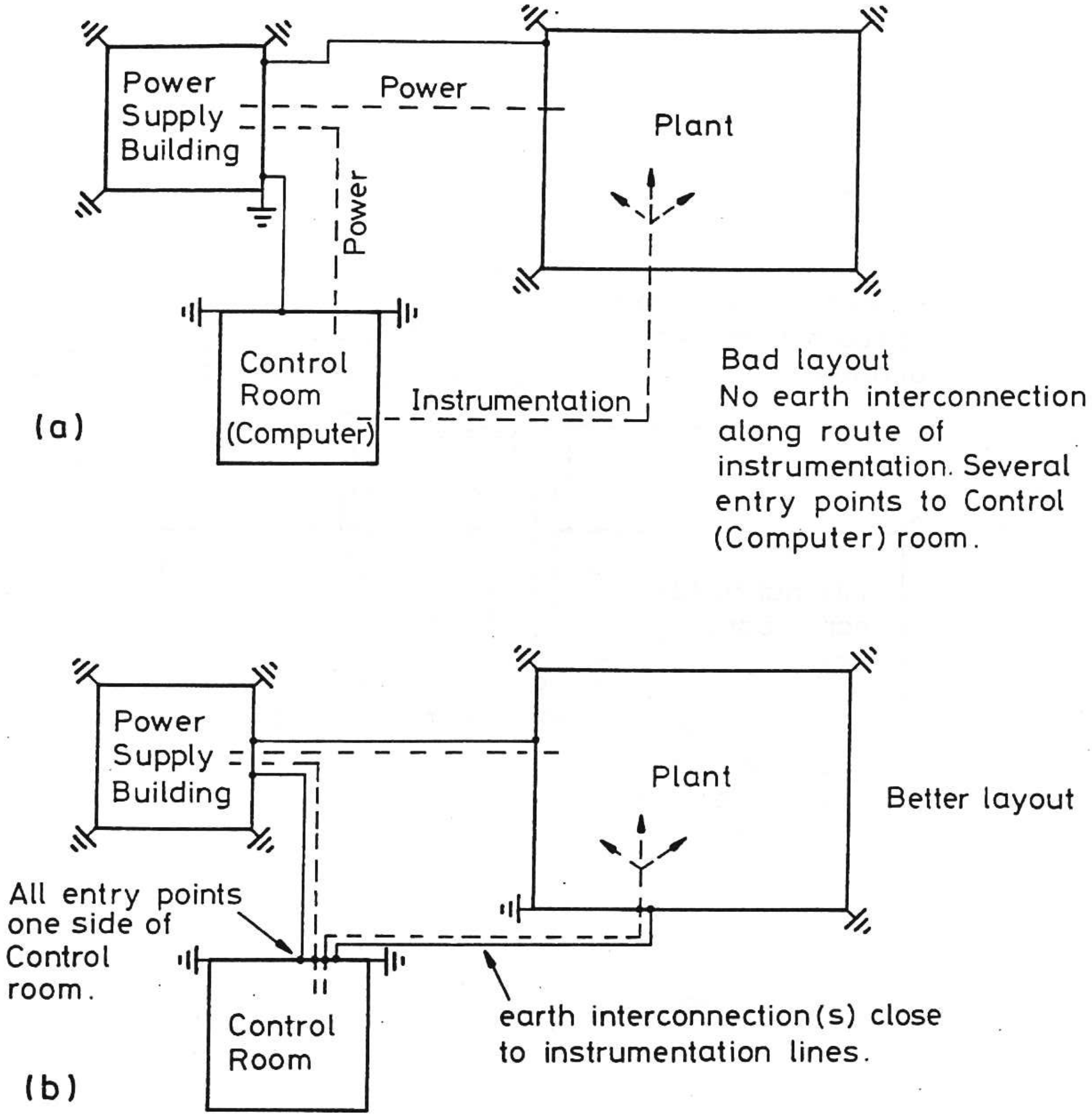
9.0 PROTECTION METHODS FOR TYPICAL INSTALLATIONS OF COMPUTERS AND CONTROL SYSTEMS

The foregoing sections have described the source and likely amplitudes of lightning currents and voltages which might occur in unprotected or protected systems. This section describes basic methods of incorporating lightning protection methods into control systems.

9.1 General

The first requirement is that all the buildings should incorporate standard lightning protection systems. In most cases, where the plant complex is of all metal construction nothing more than effective earthing to carry currents to ground and adequate bonding of the metal parts will be required. (The need for air terminations will be discussed below).

Normally the power supply enclosure or building will have its own very effective earthing system for fault current protection purposes,



Bad layout
No earth interconnection along route of instrumentation. Several entry points to Control (Computer) room.

Better layout

All entry points one side of Control room.

earth interconnection(s) close to instrumentation lines.

Fig. 9·1

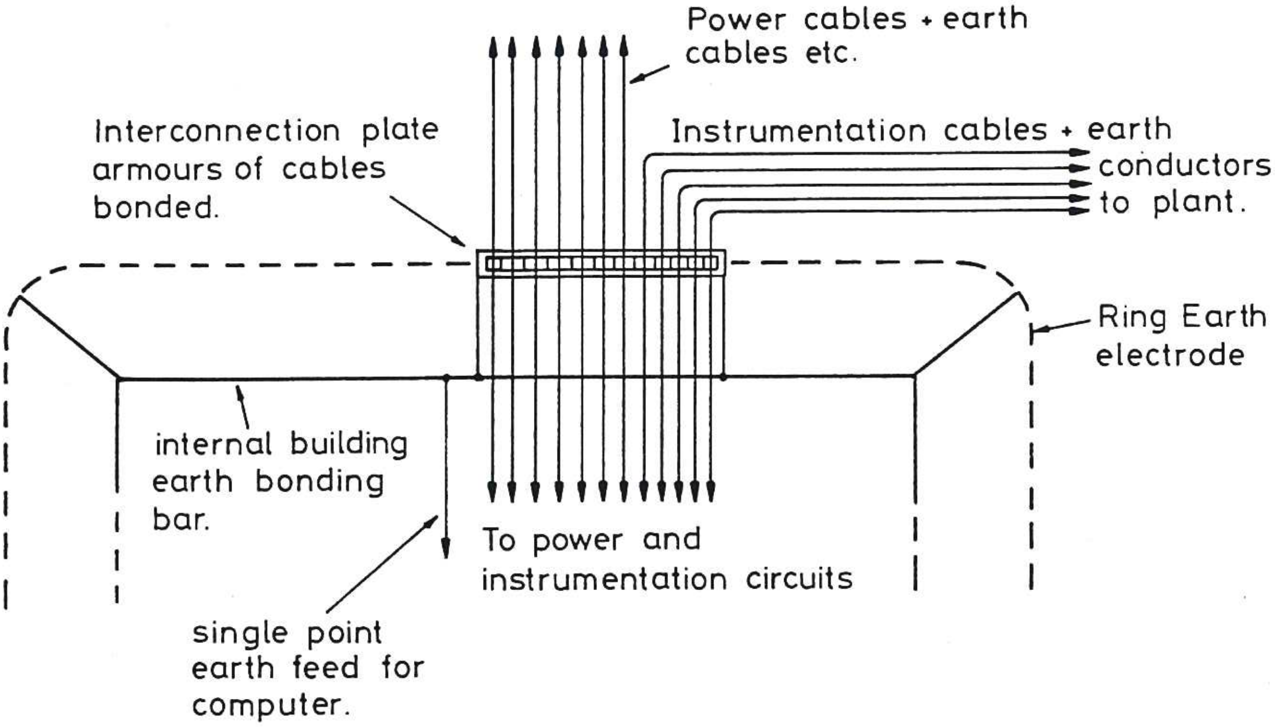


Fig. 9·2 : Control room entry & exit.

which, via connections from the buildings steel work will serve as the lightning earth as well. Additional buildings such as computer rooms, where separate from the plant and power supply building, would normally be earthed too; that is, structural steel work or the beams of reinforced concrete construction should be earthed preferably to a ring earth electrode.

Where plant comprises metal structures, metal pipes and metal vessels, in general there is no need for a lighting air termination as such since the metal components acts as their own lightning protection system including the function of air terminations.

There are individual cases where it is beneficial to prevent strike attachment to particular items of plant, notably sensor heads and wiring, and even exposed thin wall tubing, where lightning attachment divertion is an important requirement for safety and is described in section 9.3.

9.2 Interconnection of the Earthing Systems and Instrument Cable Bonding

Any two buildings which have control, instrumentation or data lines which comprise metallic conductors going between them need to have their lightning protection systems interconnected, preferably by more than one conductor.

The interconnection can comprise separate earthing conductors between the buildings plus the cable trays, cable armourings and metal sheathing etc which should be continuously conducting end to end and bonded to the earth systems at each end. At least some of the earthing conductors should run parallel, and close to the control wiring to minimize inductive loops especially when non conducting cable trays or ducts are used. (See figures 9.1 a and b). Although in a) the earthing system of the plant and control room are interconnected (via the power supply buildings) a direct interconnection is required parallel to the instrument cable route to by-pass lightning current which would otherwise flow in the instrumentation cables with serious consequences. Further notes on cable trays and current flow in multiple cable bundles is given in Appendix 1.

All cables and earths should come into the control room at the same side of the building so that all the earth conductors, cable trays and cable armouring and shields as appropriate can be joined together at the entry point of the building so as to minimize lightning currents flowing through the control room from one side to another. This is shown better in figure 9.2 where an enlarged view of the entry point is shown. This common earthing point should be as close to the entry point as possible but not necessarily outside the building. It could be just inside but in any case should be connected directly to the building earthing system. The most important consideration for data cables is that they must not become the only metallic link between buildings ie they must not be the weak link.

Effective parallel paths, for example armouring sheathing, cable trays, earth conductors etc must enclose and protect the wiring by carrying any lightning current from one building to the other without it flowing in the instrumentation systems. To do this the parallel paths have to be continuously conducting from end to end and effectively bonded to the earth systems at both ends. See also Appendix 3. The recommended method of sensor connections from the JB's in the plant is discussed in Appendix 4.

9.3 Protection of Exposed Sensors and Cables

As shown in figures 6.9 and 6.10 it is vital that earthed metal objects (hand rails, pipes, covers or (specially installed diverters) are available to prevent direct lightning attachment to sensor heads, cable interconnection boxes or cables themselves. Severe damage, both locally and even remotely will be caused by direct attachment. However, as illustrated in figure 6.10 protection is readily provided by ensuring that the metallic objects suggested earlier are higher than the sensor heads themselves. The earthing of these metallic objects does not have to be via a special tape to earth, but only implies connections to the local plant metal work, which is indirectly earthed via the plant itself or the supporting structure. Eg in figure 6.10 the hand rails of the walkway at the top of the column can serve as a lightning attachment diverter as long as it is metal and fixed to the plant solidly, and higher than the sensor. In the case of sensors exposed on the sides of high towers (higher than 20 metres above ground) it is a good idea to install lightning attachment diverters to the sides of the building jutting out further sideways than the sensor head to prevent lightning strike contact. The rolling ball theory, referred to in section 3.3 is a good method of determining where such lightning attachment divertors might be needed.

Protection against attachment is the first requirement for safety of exposed circuits.

9.4 Shielding of Cable Routes off Exposed Locations and From Tall or Isolated Towers

Having ensured that direct attachment of lightning as in para 9.3 can not occur, consideration should be given to routing and shielding of the sensor conductors. Figure 4.3 demonstrated the basic problem, which is that current tends to be driven down the various routes to ground depending on the inductive current sharing between the routes. Insulation on the instrumentation cables will almost certainly flash over by the very high initial inductive voltage, then giving inductive current distribution in the structure and cables (as in figure 4.3). Table 4.1 in section 4.3 illustrates the problem where for an exposed route current may be as high as 13kA, proceeded by a voltage of perhaps 40kV which would ensure that the inductive path is set up despite any typical insulation levels at the sensors or the cable junction boxes. For the better protected routes where the table shows much less currents, only a smaller voltage will be available to cause a flash over problem so that any of the better routes in table 4.1 is better in both respects.

In order to achieve multiple protection from both strike attachment and induced voltages, the ideal technique is to enclose the wiring completely in a closed conducting raceway or run the cables in a metallic tube which must of course be effectively bonded to structure top and bottom and at normal building roof height as in figure 9.3. When this is done the resulting induced voltages in the cables arise only from the IR drop in the tube or the raceway as explained in the section 6.1. This will reduce voltages and currents in the cables from tens of kVs and kAs to a few volts and virtually no current at all, since the sensor and connection box insulation levels will not be exceeded.

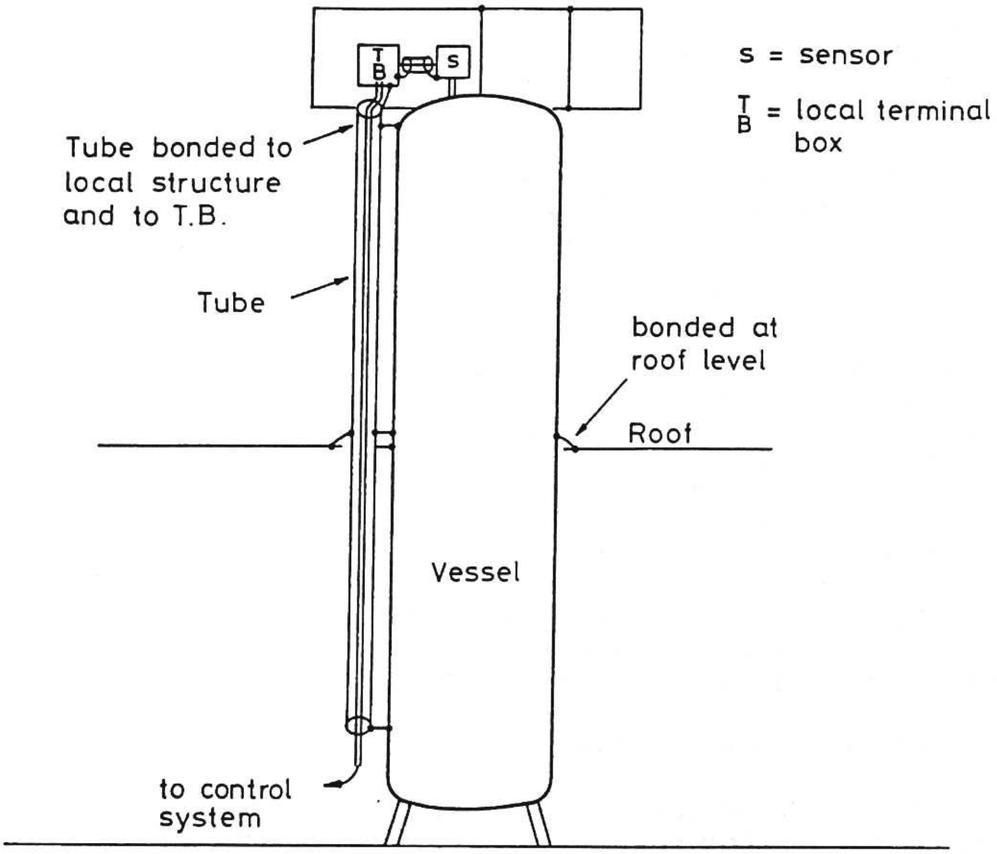


Fig. 9·3: Protecting cables off tall vessels and roof bonding.

The typical slotted raceways are not as good as a continuous tube, and if used they should be positioned as in figure 4.4c , position 2, between the tower and pipes or between the tower and the rung ladder. (It is assumed that position 4 within the tower is not available as a location for cables because otherwise it would be the best location). Figure 9.3 refers to bonding of the tube where it enters the general roof line. This is to disperse current over the whole of the building rather than it continuing right down to ground and causing relatively large fields which can interfere with equipment at ground level.

An important general principle here is that all tall objects, chimneys, columns, vessels etc which protrude above the general building roof line should be bonded to it at the roof level, so as to disperse the current into the building generally and so avoid the large current and field concentrations within the building lower down. Despite the size of a large process vessel, where the vessel is bonded to the building at roof level the current will nonetheless disperse over the building in the way described for inductive sharing in an earlier section.

9.5 Some Do's and Don'ts

1 Use of fibre optic data transmission lines. Where it is inconvenient or too expensive to interconnect the earth systems of two buildings between which data is transmitted, and only a few data lines are involved, fibre optic systems have many advantages for lightning, and for EMC reasons in general. In principle a fibre optic system allows two buildings to be completely electrically isolated from one another and thus quite independent, as long as the fibre optic link is fully insulating.

Some fibres have metal armouring for physical protection, and it is important that this armouring is bonded to the LPS as shown in figure 9.2, at the entry point to the building. If not bonded here, the armour could carry lightning current straight to the computer. Alternatively, to prevent current flow in the armour, it should be stripped back, but this would mean stripping back several metres to prevent flashover. Plastic armoured cable is to be preferred.

2 Protruding Conducting Parts.

Pipes, chimneys etc which might be struck and which come into the plant should be bonded to the structure at roof level so that lightning current is dispersed over the building.

3 Intrinsically Safe Circuits.

So called intrinsically safe circuits may not be safe for lightning purposes since they could have large voltages or currents induced in them. They need protection like any other low current circuits to ensure that large currents or voltages cannot occur which are big enough to cause sparks in explosive atmospheres.

4. Application of Surge Suppressors.

These are considered in section 10 but an important "don't" is that they should not be used at sensors without careful consideration of their function. Where sensors are isolated electrically from the local plant, with an insulation voltage of say 1000V, it is a mistake to put a low voltage device between the wires and ground locally because it will conduct frequently on earth fault currents and other minor transients, so carrying more interference onto the instrumentation circuit. However, such insulated sensors should be protected in certain locations by surge suppressors which conduct at about 20% below the insulation voltage of the sensor.

10 PHILOSOPHY OF EQUIPMENT HARDENING AND PROTECTION DEVICE INSTALLATION. LOCATION, RATING OF SURGE SUPPRESSORS, INTRINSICALLY SAFE CIRCUITS, TRANSIENT CONTROL LEVELS.

10.1 Ideally, the system and equipment should be hardened by its very design, ie. equipment should be designed so that either the interface circuitry is not vulnerable to moderate transients or that the system design prevents common mode transients from being effective in the circuit. This may be achieved in a wide variety of ways depending on the equipment type and the environment in which it functions. However bearing in mind that the most severe lightning transients will appear as common mode ie. lines to earth, some of the ways in which hardening is inherent in the design are:-

1. No direct connection of external lines to sensitive components (eg. external connections should not go directly to FET's, IC's etc).

2 All inputs/outputs where possible should have resistors in series with them to limit transient currents.

3 The bandwidth of inputs should be limited to the essential minimum for the task eg. thermocouples do not need 10MHz bandwidth, the input should limit the input frequencies to lower than say 1Hz. A simple passive resistor capacitor low pass filter will achieve this.

4 Where feasible eg. on data lines, opto isolators should be incorporated into the input circuits to isolate electrically the incoming data lines. However in a poor installation these will not have a high enough flashover voltage to give protection.

System design to reduce transients can be as follows:-

5 Isolating transformers on digital data lines.

6 Sensors electrically floating, connected by a 2 wire system from the instrumentation equipment interface (ie. no electrical connection at the plant).

7 All wires associated with one circuit eg. as in 6 should be run as twisted pairs or triples etc within one instrument cable bundle. This minimizes differential mode transients.

8 Cable bundles have overall screens using the armouring etc which is bonded to the earth systems at both ends by short low inductance bonding strips.

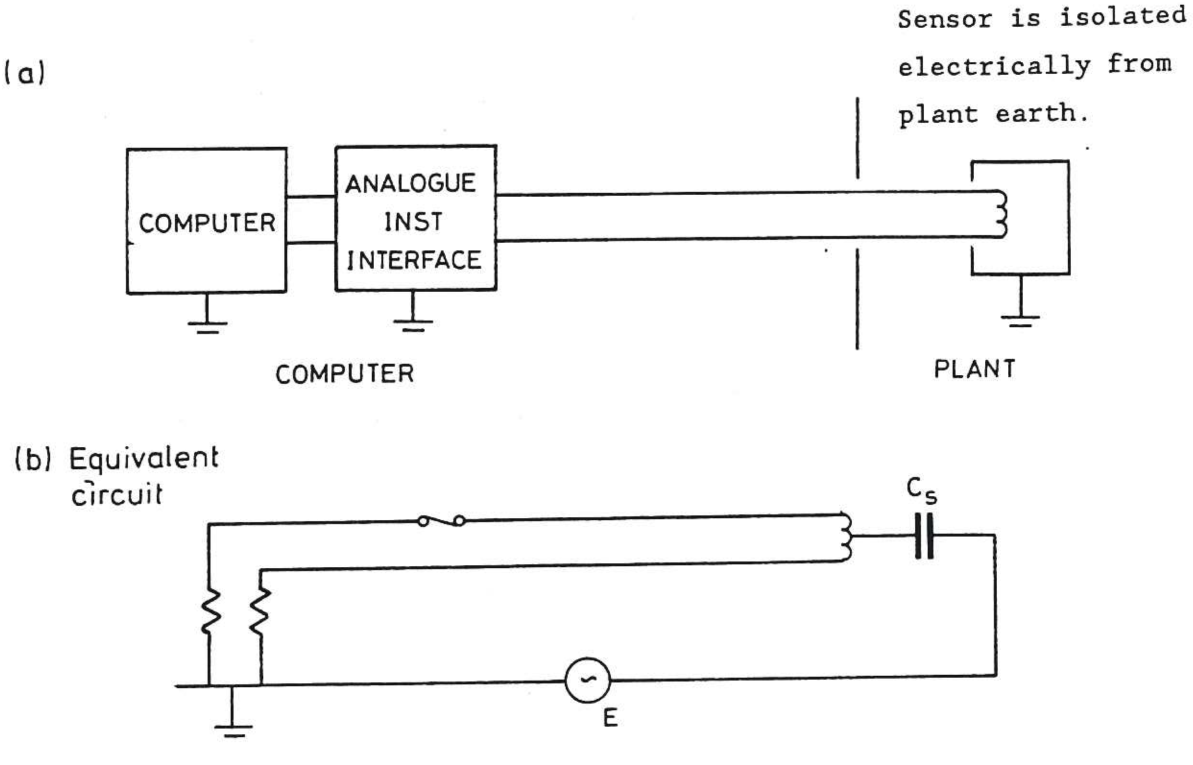
9 Electrical and signal cables are best not located on or in the surface of external walls.

10 Instrumentation cables likely to have severe transients on them should not be mixed in with other sensitive circuits in long cable bundles to the computer. Large transients should preferably be removed at or near the transient source and only clean, quiet circuits combined in one cable route.

10.2 Spectrum of Transients

The spectrum of the transients which are injected into the control system interface at the computer room depends on the coupling method, ie. whether resistive, inductive, capacitive or a combination, and on the circuit type including whether floating or ground reference circuits, and whether screened or filtered etc. In general the worst case will occur when the coupling mechanism is that a high voltage is developed first, causing insulation to break down then driving a current similar to the lightning current waveform into the circuit. In this situation the transients have the complete high, middle and low frequency spectrum of the current pulse, and will probably be very energetic, since the voltage was high enough initially to cause a break down. This situation has to be avoided by the design of the installation.

If we take a system like fig 10.1a where an isolated sensor is used, assuming that a transient voltage is prevented from exceeding the insulation breakdown level at the sensor, no current can flow along the lines at DC, or at low frequencies. Only high frequency currents which can pass the capacitive reactance of the sensor coil to case can appear as a common mode current in this system (see fig 10.1b where C_s is the stray capacitance to earth of the sensor circuit, an E is the lightning surge voltage) the effect of this is a 'high pass' filter, so excluding very effectively the low frequency part of the lightning transient spectrum and so minimizing energy into the circuit. If not otherwise protected small rated or simple filter capacitors would be effective in preventing the residual low energy h.f transients resulting from a lightning strike. (These transients will probably comprise short bursts of decaying oscillations, stimulated by the strike, whose frequency depends on the cable lengths etc).



Sensor is isolated electrically from plant earth.

Fig 10·1(a) & (b) Isolated sensor example

If the circuit shown is properly screened by bonded armouring or other screens which are joined to earth at both ends, the spectrum of the voltage applied at E is deficient in h.f and generally of a low amplitude. Since as described above the floating sensor only allows a little of the already depleted h.f spectrum into the circuit at left, protection is very good. (Note the h.f spectrum on wires within a cable is reduced at h.f owing to 'skin effect' in the screen or armour. The thicker and more conductive the armour is, the less the h.f. As a guide, the skin effect causes a cut off frequency, ie. the -3db frequency of $\frac{1.2\rho}{h^2}$ MHz where h is the metal armour or shield thickness in metres, and ρ is its resistivity in Ωm. Eg. 1mm (.001m) of aluminium of $\rho = 2.8 \times 10^{-8}$Ωm gives $f_c = 0.034$ MHz, ie 34 kHz, thus strongly attenuating frequencies above this.

Thus the combination of a screened system with floating sensors is very good as long as the sensor insulation is not broken down.

It is instructive now to look at the effect of adding surge divertors to such a circuit. It can be seen by inspection from the equivalent circuit in fig 10.2 that suppressors or clippers installed at A cannot reduce the voltage at B between line and local earth. Likewise suppressors installed at B do not reduce transients into the equipment at A, on the contrary, when the suppressors conduct they close the loop and so inject l.f currents into A, and the lower the voltage rating of the divertors at B and/or the lower their 'on' resistance, the more current is going to flow into A. Thus any suppressors installed at B should be rated as high a voltage as possible but no higher than the insulation flash test voltage for the 'sensor to case'. The divertors should not be gas discharge or crowbar types as they will tend to drive an even higher current into the equipment and the suppressors at A. MOV's or large semi conductor suppressors eg. 'zeners' are required for this duty.

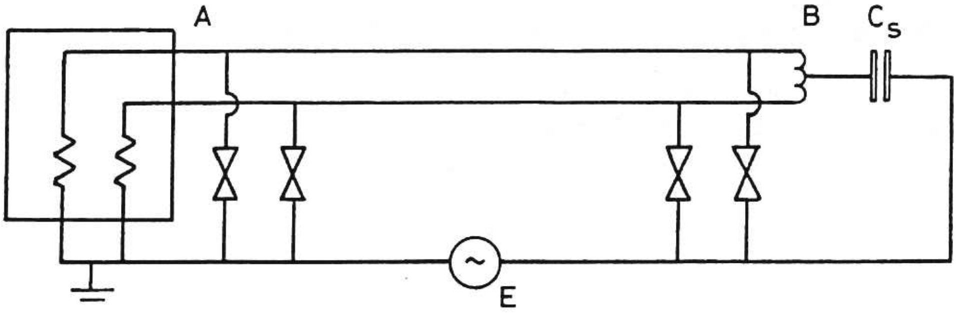


Fig 10·2 Surge diverters on fig 10·1 circuit

The 'turn on' voltage for the suppressors at A must be below the damage threshold for that equipment, bearing in mind not only the voltage amplitude but the duration as well.

10.3 Intrinsically Safe Circuits

Intrinsically safe circuits for monitoring and other operations in hazardous areas are not necessarily intrinsically safe regarding lightning transients and other severe EM environments.

Although they may be safe as far as the circuit energy source is concerned for normal operation, the circuit configuration may well be prone to coupling from lightning currents and RF sources. Some circuits need special attention to ensure that spark threshold voltages are not exceeded in the instrumentation circuit where it enters the flammable gas/air volume. Barrier zener diodes etc will often suffice to clamp voltages to low levels, as long as the circuits are only minimally exposed so that the lightning transients are not so severe as to overwhelm the diodes and damage them, so giving sparking. Thus exposed routes of intrinsically safe circuits should be well screened and protected as described in previous sections to minimize the energy to be absorbed by the zeners.

10.4 Transient Control Levels (TCL) and Equipment Transient Design Levels (ETDL).

These are concepts which can be borrowed from the aircraft industry with considerable advantage, and refer to the process of ensuring the electronic systems are protected.

The ETDL refers to the level of transients, either common mode or differential mode which a particular type of equipment or circuit can withstand safely, as demonstrated by test with idealised test waveforms, eg. 1.2/50μs pulse.

Therefore if this equipment or circuit is installed in the system so that the transients arrising from lightning are less than the ETDL the equipment will be safe. To be sure of safety, a T.C.L can be nominated which is the design value which transients will not exceed, to be achieved by appropriate installation or screening of the wiring. The difference between these levels is called the safety margin, or more simply the 'margin', see fig 10.3.

Application of this principle will show very easily those circuits which need special protection through exposure, lack of screening etc.

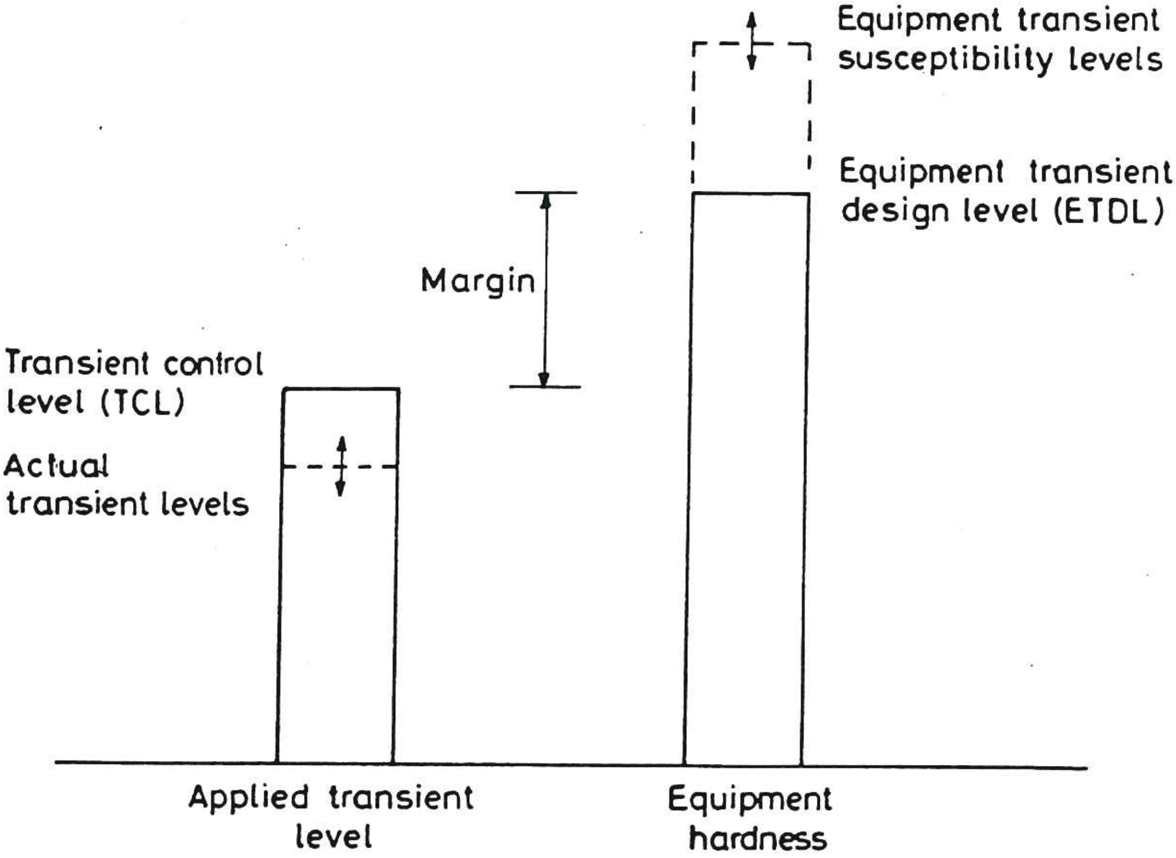


Fig 10.3 TCL and ETDL and 'margin'.

References

1 British Standards Institution, British standard code of practice for protection of structures against lightning. BS 6651:1985.

2 Hadrian W. Determining the current distribution in the protection system of geometrically simple buildings. International conference on lightning protection Szeged (Hungary) 1981.

Acknowledgements

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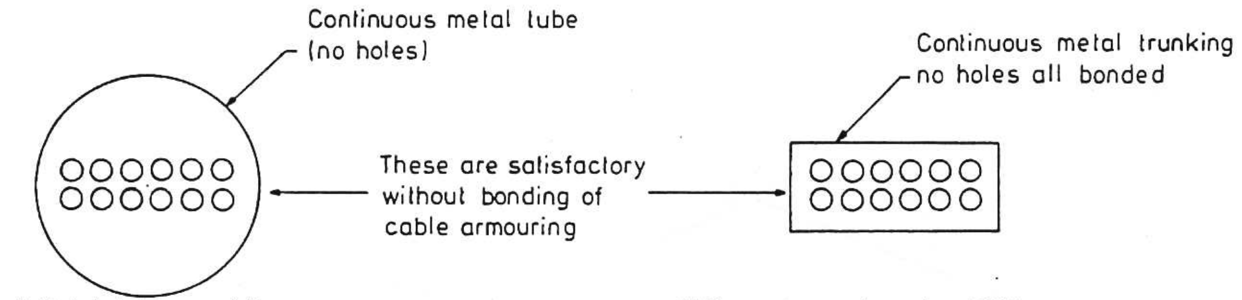
The author would also like to acknowledge the use of fig 3.2 provided by the Electricity Council Research Establishment Capenhurst for BS 6651: 1985.

Appendix 1

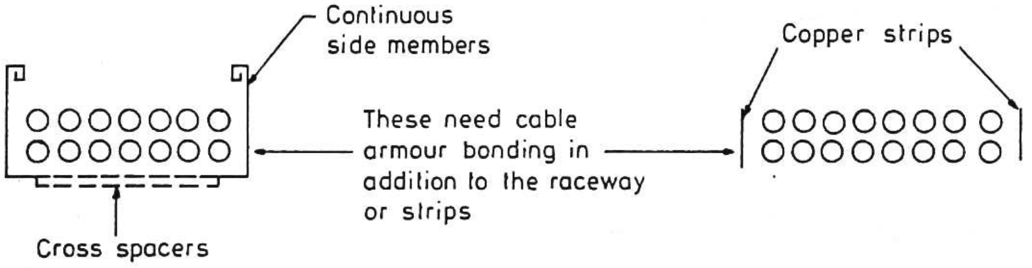
Further Notes on Cable Current Sharing, Use of Cable Trays Trunking Conduits etc.

Where instrument cables run between buildings, it is preferable to adopt a consistent installation and screening policy. It has been suggested that the metallic cable armouring should be used for assisting in the screening of the instrument cables by bonding it both ends. This can equally apply to aluminium armoured or lead sheath armoured cable. The figure below suggests some equivalent ways this could be achieved and notes some problems. Only if the instrument cables are fully enclosed in a continuously conducting tube, channel or raceway providing very close to 100% area coverage of the cables can the bonding requirement of the armouring be relaxed. Otherwise the armouring will need to be bonded or some other method used for protection. The figure below illustrates several different cases where a) and b) are satisfactory with cables unbonded (although of course improved if they are), whereas c) and d) must have the cable armouring bonded at each end.



a) Metal tube providing bonding & screening

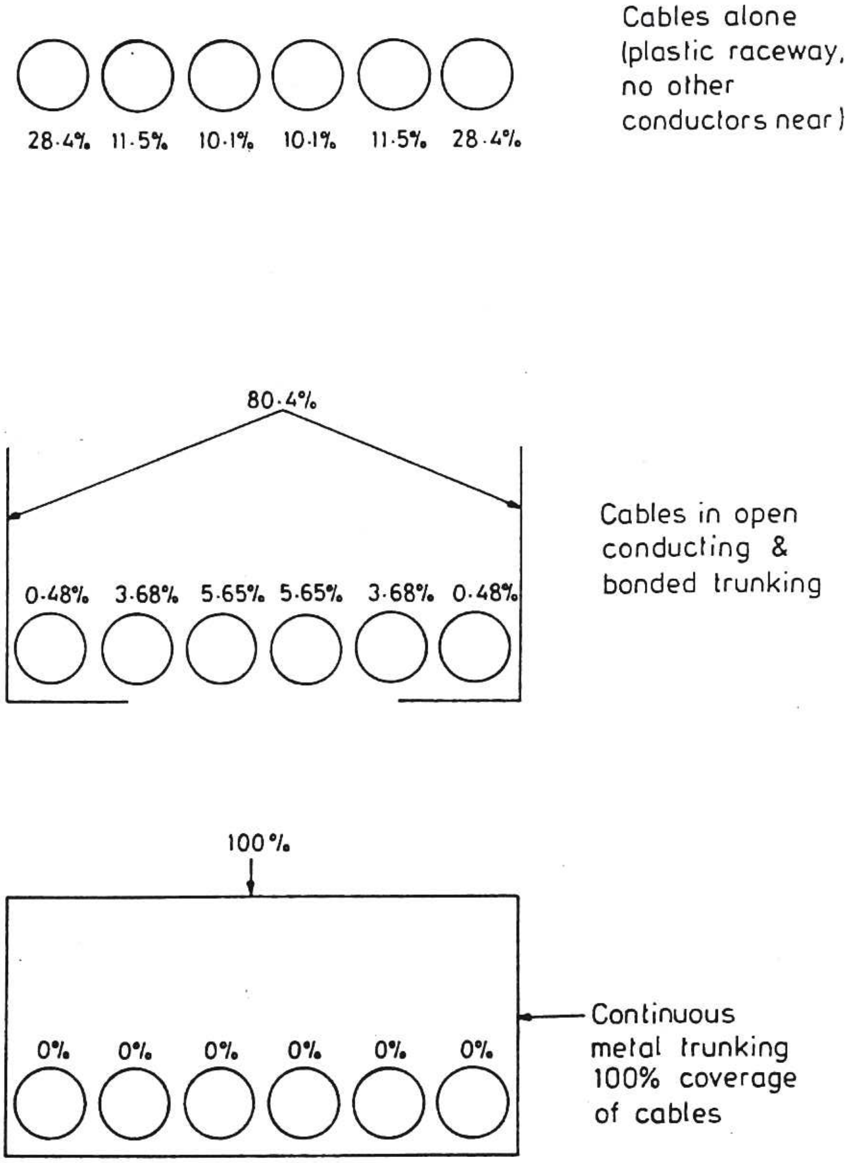
b) Raceway, rectangular 100% area coverage, as good as a)



c) Cable armours need bonding in addition to the protection provided by the metal side members

d) No tray or raceway, or plastic one. All cable armours must be bonded & extra copper strips are recommended.

In figures c) and d) inductive current sharing between the metallic raceways, the Copper conductors and the cable armours will occur, and the simple statement in section 6.5 that we assume the same current in each is not valid. Currents tend to peak in the outermost conductors with the minimum in the middle, but this is affected strongly by the presence of raceways as the following calculation demonstrates. The outermost conductors (the raceway side members) owing to their size take a large percentage of the total current, and in doing so shield the cables, especially the outer ones, so reversing the normal current distribution across the cables. The raceway does reduce the current in all cables, especially the outer ones, but even the inner ones the reduction is useful. Thus trunking supplements very well the effectiveness of bonded armouring where 'open' trays are used, but of course as shown overleaf an enclosed trunking is even better providing excellent shielding where 100% area coverage of the cables is achieved.

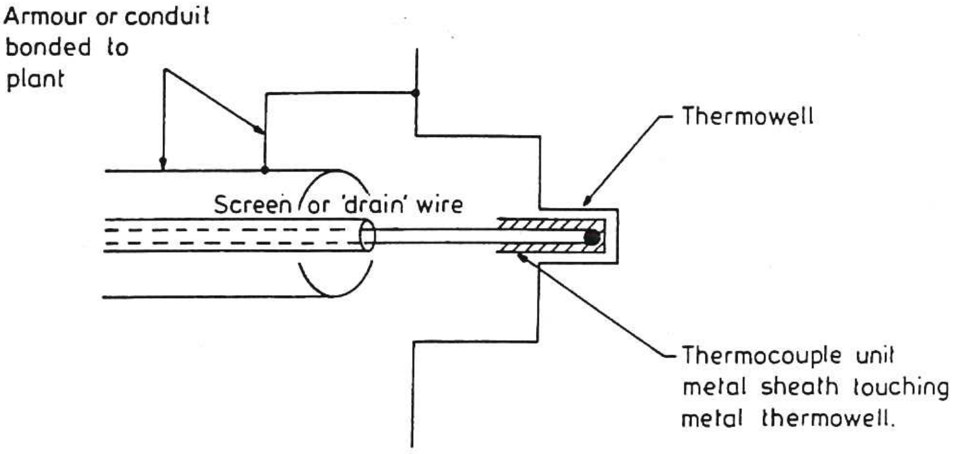


Inductive current distribution in cables, in open raceways, & in closed trunking.

Appendix 2

Notes on Instrument Screening and Insulation at Sensors.

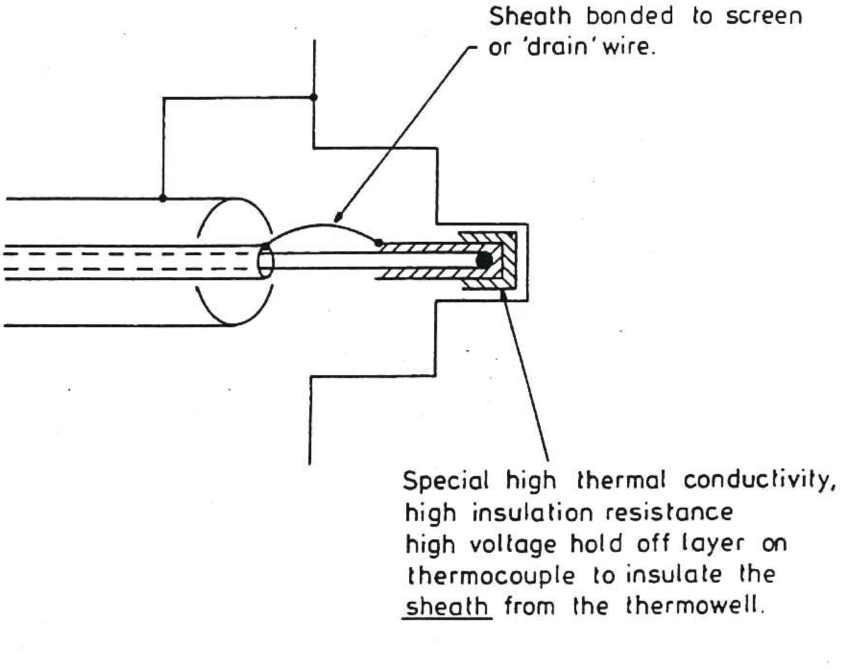
Typical installation practice is shown in the figure below.



A Standard method

This method of installation relies on the thermocouple insulation to prevent plant switching transients, earth full currents, lightning transients etc from being injected into the instrumentation system. Unless the insulation level in the thermocouple is very good ie. it has a very high voltage hold-off, say 5kV or more, and low capacitance, this is not an ideal scheme.

A more 'EMC' (Electro Magnetic Compatibility) sound design is as follows:



B Preferred method

In figure B, the transient voltages stress the outer insulation (which should be incorporated as an integral part of the thermocouple) to the thermocouple sheath. The sheath should be connected to the earth drain wire (or electrostatic shield) so that if a very high voltage transient were to occur resulting in breakdown, it would give breakdown only to the sheath and not to the thermocouple itself. This design, incorporating an insulator over the metal sheath, will give an altogether more EMC satisfactory design improving the vulnerability to all kinds of radiated interference from high frequency sources as well as lightning and switching transients.

Appendix 3

Notes on instrument wiring electrostatic screens, 'drain wires', bonding and mains supply derived circulating currents.

Where wiring, eg thermocouple wires, are provided with close electrostatic screens (drain wires) it is preferable to leave them unconnected at their sensor end as is present practice and not use them for lightning protection earthing. (Note: if the modified form of thermocouple is used as suggested in Appendix 2 the screen can be joined to the inner thermocouple sheath). This provides the usual low frequency electrostatic screening of the wiring as is normally recommended.

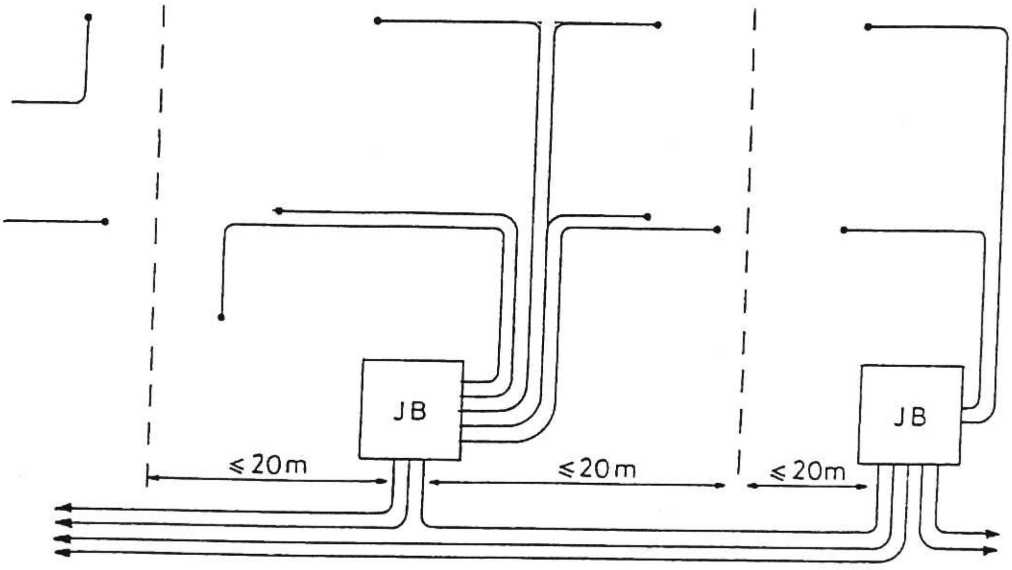
However, the outer armouring and/or the cable tray or trunking will normally be used for the lightning screens as suggested earlier. To minimize circulating currents at 50Hz and to provide mutual screening, the power and instrument circuits should be in their individual raceways, but the raceways positioned close as implied in figure 9.1b.

Note. Where 3 phase power circuits use separate armoured conductors for each phase, (ie does not use a 3 or 4 wire cable with just one overall armouring) it is not possible to bond the armouring at both ends; one end only is allowable owing to the current induced in the armour and the consequent reduction in the thermal rating of the cable. For such cables, a separate earth cable must be provided, and the phase conductor armours are bonded at one end only. This prevent excessive circulating currents in the armours. This problem does not occur if cables have all phases within one overall armour and the armour can be safely bonded at both ends.

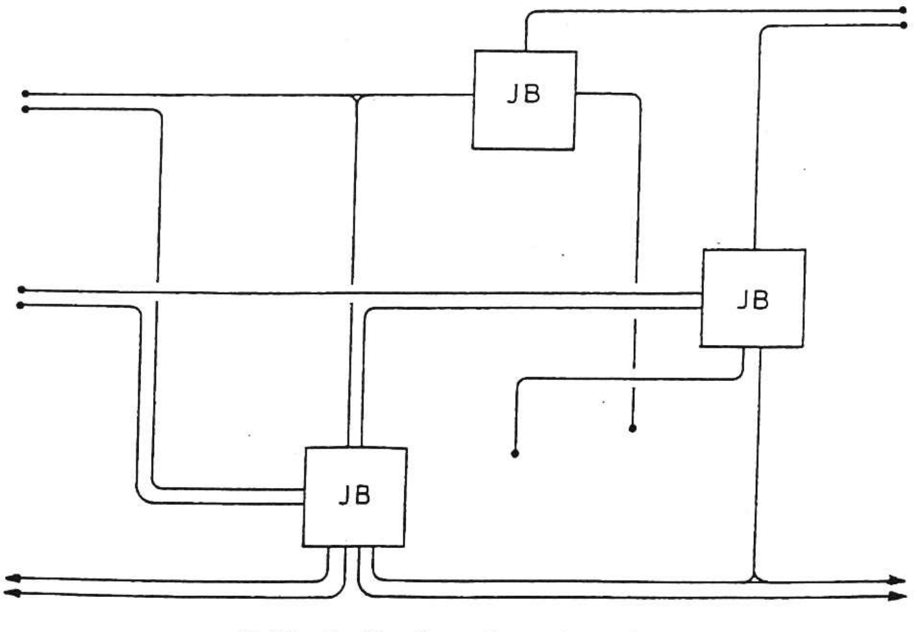
Appendix 4

Preferred Cable Layout to Prevent Circulating Currents.

Where the wires emerge from the junction boxes within the plant, metallic raceways are recommended bonded along their length and to structure. Preferably a multilayer star network should be used as in A below and not a criss crossed 'birds nest' as in B. The B layout is more susceptible to mains circulating currents since so many loops are formed between the separate instrumentation connections. Also the wiring routes from each junction box are on average longer, which is a disadvantage.



A Preferred



B 'Bird's Nest' - not preferred

Cable layouts in plant

Appendix 5

Test Methods for establishing ETDL's for equipment and TCL's for the system installation.

There are well established test techniques for determining equipment transient design levels which are already used by the aircraft industry, nuclear power industry, telephone companies and others. These comprise tests with certain waveforms and standardized voltage or current levels in which transients are injected into the equipment, usually line to ground, and also line to line where appropriate, to determine either the failure level, or to demonstrate that a particular piece of equipment, (or an interface circuit) is protected up to a certain level of transient without failure. This is often referred to as demonstrating the hardness of the equipment. Typically such testing requires transient pulses of between 100 and 1500 volts.

Thus interface circuits for analogue or digital instrumentation can be tested and the ETDL established as a basis for setting of the TCL's. Where tests show that an interface has a low ETDL, so requiring a low TCL, a decision can then be made to harden the equipment/interface circuit and retest or to impose a strict TCL on the system installers. In aircraft and other industry practice ETDL's of between 600 volts and 1500 volts are often used and represent a useful compromise between the equipment protection cost and installation shielding costs. Standard tests are specified in IEEE 472-1974, BS 3G100 and (for aircraft) DO160C/ED14C chapter 22. However test methods may need to be revised to suit the environment and circuit types used in the process control industry. The Lightning Test & Technology group at Culham Laboratory, which has been performing aircraft equipment tests for several years, is able to provide specialist advice on such test methods and can also provide an equipment/interface test service.

Having determined the ETDL's, the next step is to determine a suitable TCL. Therefore the likely level, waveform and energies of transients into the equipment needs to be assessed for comparing with the ETDL's, and this can be done by analysis of one or more cable routes, or by test. Testing involves using a pulse injection device at the plant (say during a shut down), to drive a current pulse from the plant to the control room of an amplitude and waveform similar to lightning (or a scaled down version of it, say 5-10kA) and measuring the voltage produced in the circuits. (The circuits would normally be disconnected from the computer and the sensors during the tests). The voltages so measured may need extrapolating in amplitude depending on the scaling of the test pulse, and then used to compare with the sensor insulation levels as described in 10.2 and the ETDL's established for the equipment interfaces.

High current injection tests for on site measurements have been performed by Culham Laboratory in conjunction with the Post Office for determining lightning induced transients in underground cables, the technique has been employed at a nuclear power station site in Germany, and is equally applicable to process intallations. Lightning Test & Technology of Culham are able to advise on the use of such techniques, design a test and provide and operate the capacitor bank current injection unit. Appropriate voltage diagnostics on the cables can also be provided and operated. Such a test could be performed on site anywhere in Europe.