0 Contents

EARTHING, SHIELDING AND SURGE PROTECTION OF ELECTRONIC EQUIPMENT FOR INSTRUMENTATION AND CONTROL

ACS Automated Control Systems - Training Division
140 Railway Parade, West Leederville, 6007, Western Australia

About this Book

This book aims to cover the current theory and practice of lightning protection, earthing and surge protection of electronic equipment used for industrial automation and control. It largely follows accepted International (IEC) practice and covers the mainstream of the current practice and future direction of the technology.

The objective is to provide engineers and technicians, working in the instrumentation and control environment, with a practical reference book for the correct earthing of electronic equipment used for industrial control. It will appeal to those who want to understand the mechanism of lightning and surges and who want to learn how to safely operate electronic instrumentation and control equipment under these adverse conditions. It aims to gather as much useful technical information about the subject of Earthing and to provide practical solutions to common earthing problems.

This book supports the one day technical training course with a record of all the material covered during the lectures. To gain a deeper understanding of the subject, additional reading is recommended. A list of useful references has been provided in the Bibliography.

Acknowledgments

We register our gratitude to those manufacturers and vendors who have made available additional material for this book. We are sure that this will benefit industry as a whole by providing a more informed and competent approach in applying the principles of earthing, shielding and surge protection of electronic equipment for control system applications.

Disclaimer

While all reasonable care has been taken to ensure that the descriptions, opinions, facts and figures expressed in this book are accurate at the time of printing, we do not accept any legal liability for any direct, indirect or consequential loss or damage suffered by any person or organisation, however caused, which may result from the use of this book or the associated lectures.

If there is any uncertainty about the material, we recommend that you contact ACS Automated Control Systems - Training Division for clarification or assistance.

Copyright

All rights to this publication are reserved. Except where allowed by the Copyright Act, no part of this book may be reproduced, stored in a retrieval system or transmitted in any form or by any means, either electronic or mechanical, without prior written permission from ACS Automated Control Systems - Training Division.

©1995 ACS Automated Control Systems Ver: Aus5.04

CONTENTS

CONTENTS

Chapter 1 : THE SOURCES OF ELECTRICAL INTERFERENCE

1.1 Introduction

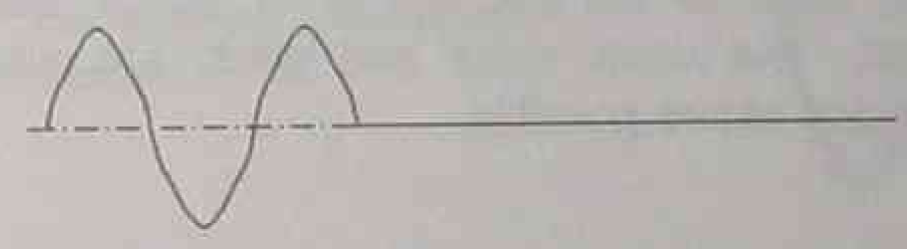
Electrical Interference refers to the presence of unwanted voltages or currents, in cables or electronic equipment, which can damage the equipment or degrade its performance.

Much of the uncertainty associated with electrical interference can be attributed to the lack of clear understanding of the meaning of the *terminology* used to describe various situations. Loose terminology such as *'Disturbance'*, *'Dips'*, *'Spike'*, *'Glitch'*, *'Surge'*, etc mean different things different people.

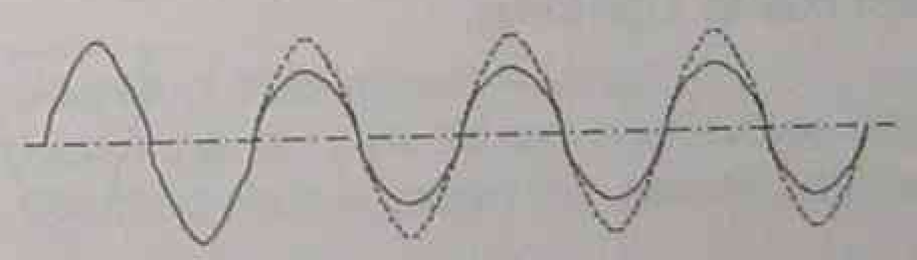
The commonly used terminology may be clarified as follows :

- A *Disturbance* is a general term describing a voltage or current signal which **deviates from what was expected**. Many disturbances are not necessarily damaging, although the performance of the electronic equipment may be impaired in some way. Some examples of disturbances on a 50Hz power supply are :

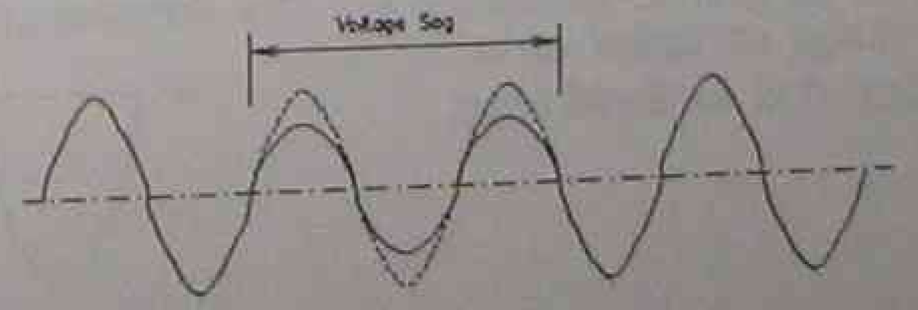
  - *Power Failure, Power Outage, Voltage Dip or Blackout,* which is total break in the supply voltage for a period from a few milliseconds to several hours.



  - *Under–voltage or Brownout,* which is a sustained reduction of supply voltage lasting for a period from a few seconds to a few hours.

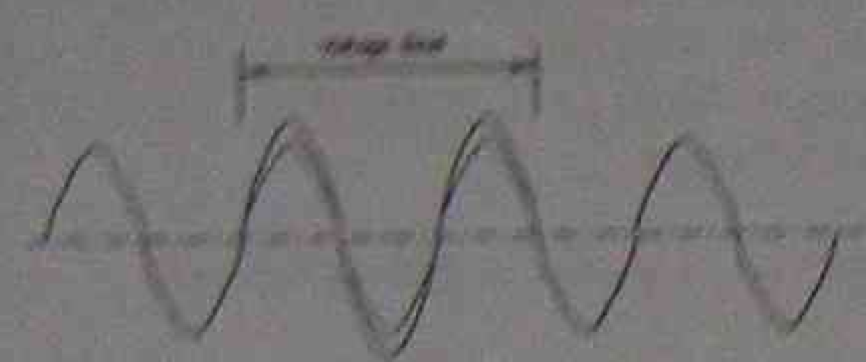


  - *Sag,* which is a temporary reduction of supply voltage lasting a period from a few cycles up to a few seconds.



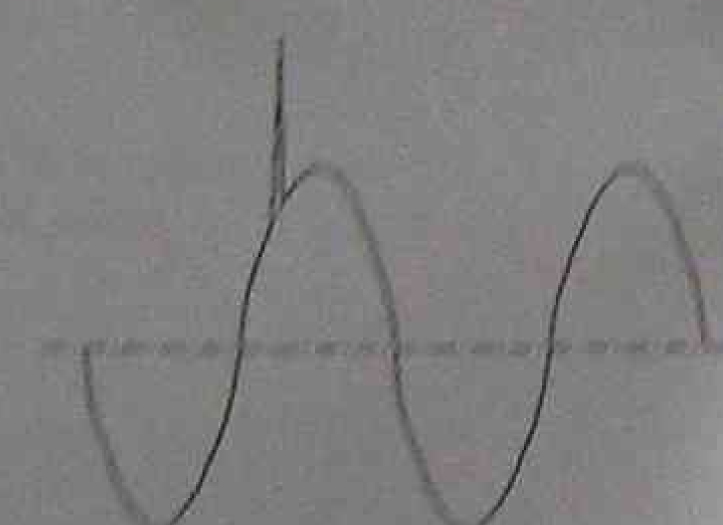
- *Over-voltage*, which is a sustained increase of supply voltage lasting for a period from a few seconds to a few hours.

- *Swell*, which is a temporary increase of supply voltage lasting for a period from a few cycles up to a few seconds. In some countries, such as UK, Swells are sometimes also called *Surges*.

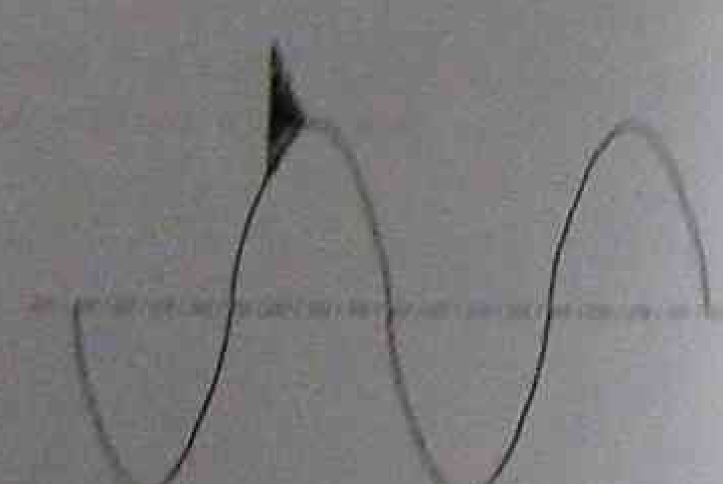


- A *Transient Over-voltage* is the descriptive term for a short duration over-voltage (no more than 1 millisecond), usually of high magnitude. These are usually caused by lightning strikes or switching events. The figures below illustrate this type of interference, which are also sometimes referred to as 'surges', 'spikes' or 'glitches'. In some countries, such as the UK, the word 'surge' can be confused with the definition of a Swell. The words 'spike' and 'glitch' are considered to be slang and should also be avoided where possible.

A transient overvoltage or 'spike' on a sinusoidal waveform due to ***Lightning***.



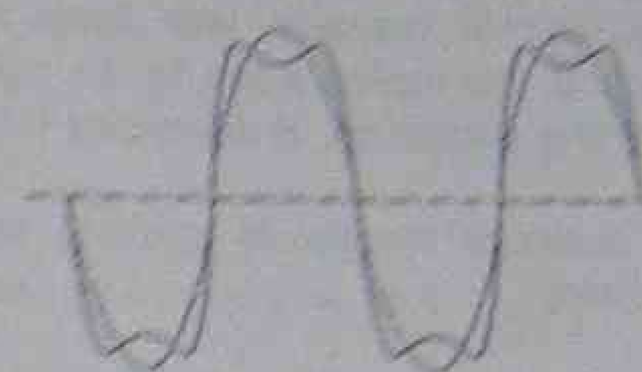
A transient overvoltage or 'spike' on a sinusoidal waveform due to ***Switching***.



Consequently, the term *transient over-voltage* is preferred because it clearly describes the nature of the interference.

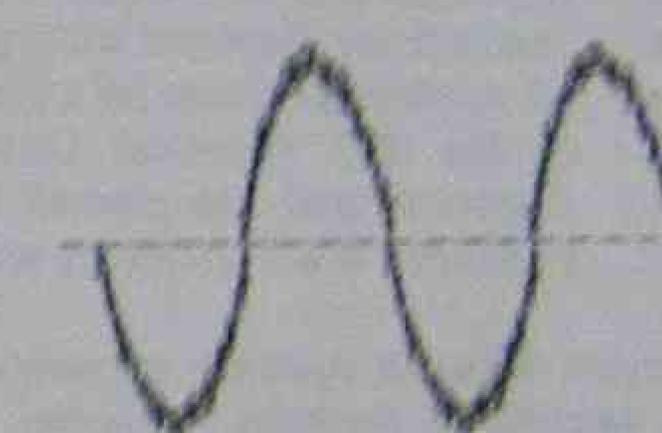
- *Harmonic Interference* is a continuous distortion (up to 3kHz) of the normal sinusoidal waveform. The distortion frequencies are multiples of the fundamental 50Hz frequency. Harmonics are a result of non-linear loads, such as rectifiers, which are connected to the power supply system.

Harmonic Interference comprising mainly low order odd harmonics



- *Radio Frequency Interference* is a continuous high frequency distortion (above about 5kHz) of the normal sinusoidal waveform. RFI is the old terminology for the more modern and more general term *EMI (Electromagnetic Interference)*. EMI covers interference due to electric and magnetic fields over a wide frequency spectrum, including frequencies in the radio spectrum.

Radio Frequency Interference superimposed on a sinusoidal waveform



A simple, but effective, way to understand interference problems is to remember that there are always three elements to every interference problem :

- There must be a *Source* of interference energy
- There must be a *Victim* that is upset by the interference energy
- There must be a *Coupling Path* between the *Source* and the *Victim*

The art of solving interference problems is to understand the mechanism of all three.

This chapter examines some of the most common *sources of electrical interference* and how the interference is transferred into the electronic control equipment.

1.2 Electrical Surges due to Lightning

The worst *transient over-voltages* in electrical power supply and control systems are usually associated with lightning. This chapter analyses the magnitude of the Voltage and Current surges due to lightning.

Lightning is an ionised channel that connects regions of opposite charge between a cloud and the ground and permits charge to be transferred along this conducting channel. These high electric currents, with steep rates of rise, also cause intense electric and magnetic fields in the region close to the point of lightning strike. The mechanism of lightning, and lightning protection, is described in considerable detail in Appendix A.

To evaluate danger of lightning to electronic equipment, it is necessary to analyse the following :

- the **probability** of a structure being struck by lightning
- the **electrical stresses** imposed by a direct or adjacent lightning strikes

Extensive research and investigation has been directed over many years into the causes, mechanism and effects of lightning. The collective knowledge is largely summarised in the following national and international standards. This manual is mainly based on the above Standards and Application Guide. A number of other relevant standards, such as those used in USA, are listed in the Bibliography at the end of this book.

- Australian and New Zealand Standard *AS/NZS 1768-1991 : Lightning Protection*
- International Standard *IEC 1024-1993 : Protection of Structures against Lightning*
- An *Application Guide for Lightning Protection Systems* is currently under preparation by the IEC Technical Committee TC-81. This guide follows the IEC 1024 Standards and has passed the final voting stage, with Australia as a consenting signatory. It will shortly be released for general circulation.

Different areas in Australia experience different degrees of lightning activity, ranging from the extreme in Northern Territories & Queensland to the minimal in Western and South Australia. An overview of the lightning activity in Australia is shown on the map in Appendix A, Figure A.12, which shows the *Average Annual Number of Thunderstorm Days.*

1.3 The Lightning Current Waveform

Once the conductive lightning channel has been established between the cloud charge region and an object on the ground, the charge flows along the channel to the ground. The associated current waveform has a very fast rise-time and lasts for a few microseconds.

Like many other natural phenomena, the characteristics of this current waveform varies widely from one lightning discharge to another. For calculation and testing purposes the wide variety of lightning current waveforms actually measured is **approximated** by a unipolar waveform known as the double exponential waveform as shown in the figure below. Since the current flows from the negatively charged cloud downward to positively charged ground, the polarity of the first current pulse is negative.

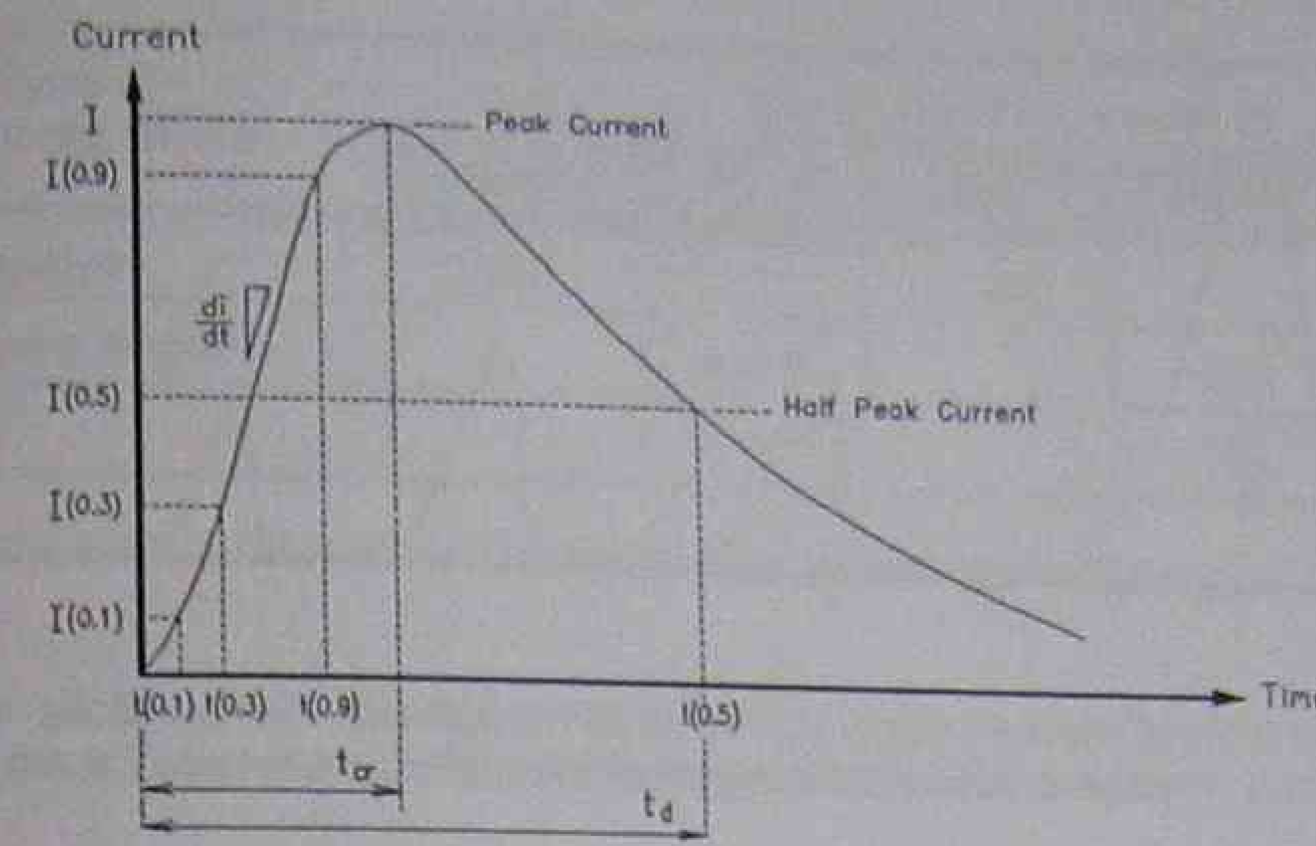


Figure 1.1 : The Lightning Current Waveform

These waveform definitions are from AS 1768-1991 and IEC 1024.1.1-1993

where :
- **I** is the *peak current* in kAmp
- **di/dt** is the *rate of rise of current* in kA/μs
- t_{cr} is the *time to crest* in μs
- t_d is the *time to half-value* in μs

Some of the most important values are :

- the peak current = I
- the maximum rate of rise = $\left[\frac{di}{dt}\right]_{max}$
- the average slope between the 10% and 90% points on the wavefront

$$\left[\frac{di}{dt}\right]_{10\%/90\%} = \frac{0.9I - 0.1I}{t(0.9) - t(0.1)}$$

- the average slope between the 30% and 90% points on the wavefront

$$\left[\frac{di}{dt}\right]_{30\%/90\%} = \frac{0.9I - 0.3I}{t(0.9) - t(0.3)}$$

Observers of lightning events (*lightning flash*) noticed quite early on that the strike appeared to "flicker". Scientific measurements have confirmed that lightning usually consists of a number of individual current surges (*strokes*), each of similar form to the current waveform above. There can be as many as 20 surges of current through the same ionised path. Usually, the first surge is the highest in magnitude.

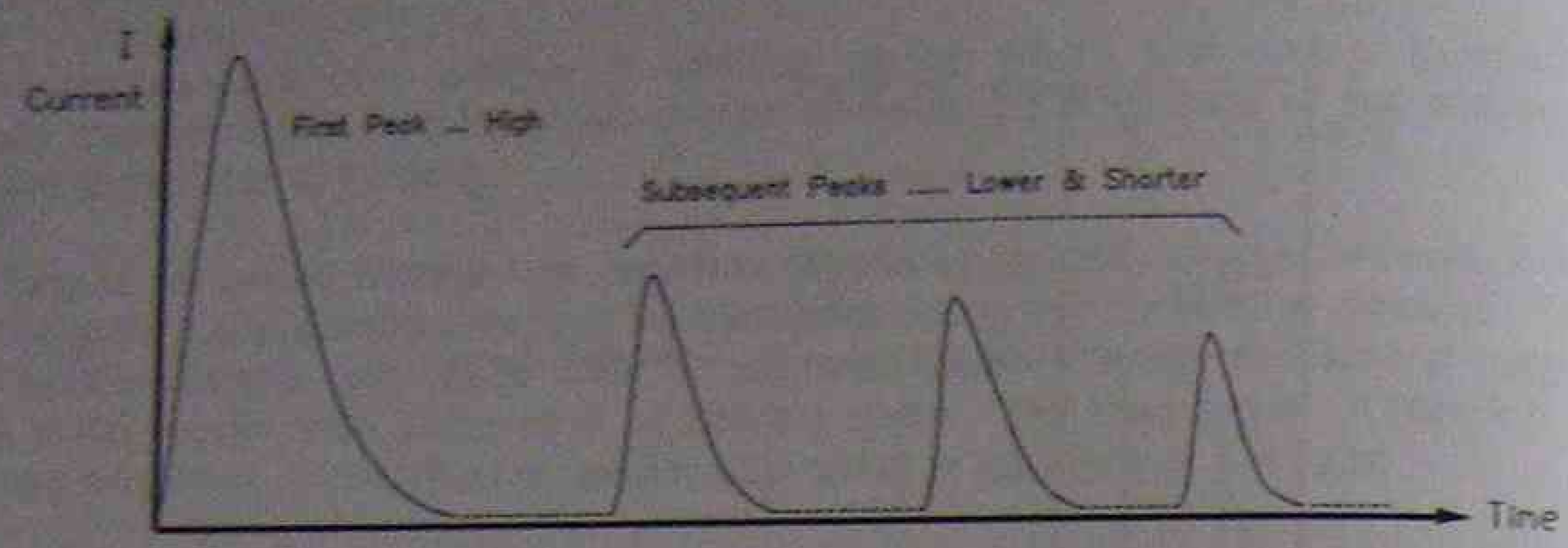


Figure 1.2 : *A typical Lightning Flash showing the first negative stroke and several subsequent negative strokes of smaller peak currents*

1.3.1 The Peak Lightning Current (I)

The first stroke within a lightning flash usually has the largest peak current, typically three times that of subsequent strokes. This implies that the peak current of a flash is usually that of the first stroke.

The new International Standard IEC 1024-1-1 (1993) lists a number of important values derived from measurements taken from extensive studies on lightning phenomena over several decades in many countries of the world, including Australia.

The measured values of the peak current are scattered over a wide range. Consequently, the peak currents are usually given in terms of a probability ..... the probability of the peak current (I) exceeding a particular value. For example, the graph and table below show that there is a 5% probability of the peak current (I) of a first negative stroke exceeding 90kA .... written as p(> 90kA).

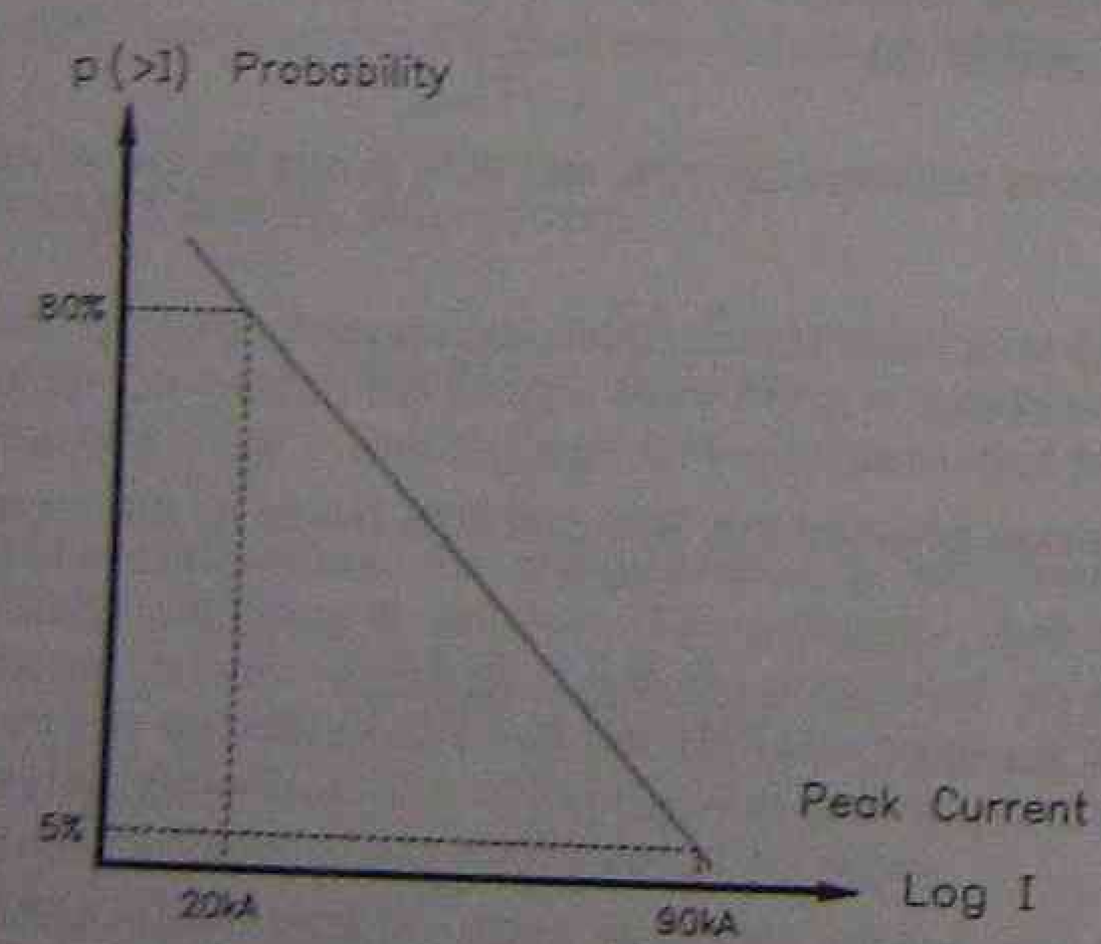


Figure 1.3 : *The Probable Peak Lightning Current for the First Negative Strike (lognormal distribution)*

Type of Lightning Stroke	Cumulative Frequency				
	98%	95%	80%	50%	5%
First Negative	4kA		20kA		90kA
Subsequent Negative		4.6kA		12kA	30kA
Positive		4.6kA		35kA	250kA

Figure 1.4 : *Table showing lightning peak current probabilities*

The values of the peak currents obtained from this table and graph are useful for calculating the volt drop through the resistive components of the lightning protection paths.

1.3.2 The Rate of Rise of the Lightning Current (di/dt)

As outlined above, the measured values of the rate of rise of the lightning current are scattered over a wide range, and are also described in terms of a probability .... the probability of the rate of rise of current (di/dt) exceeding a particular value.

For example, the graph and table below show that there is a 5% probability of the maximum rate of rise of current $(di/dt)_{max}$ of a first negative stroke exceeding 65kA/µs .... written as p(> 65kA/µs).

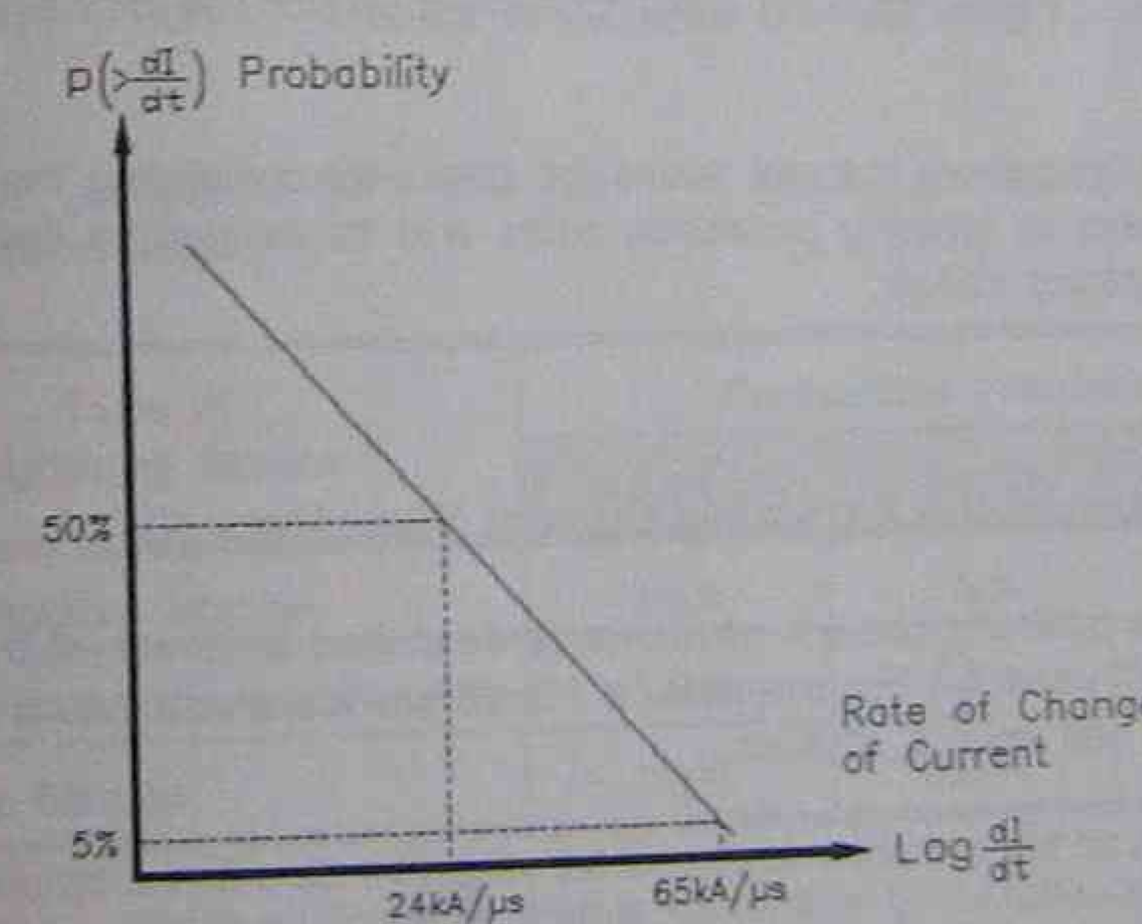


Figure 1.5 : *The Probable Rate of Rise of Lightning Current for the First Negative Strike (lognormal distribution)*

First Negative Stroke	Cumulative Frequency		
	95%	50%	5%
Maximum Rate of Rise	9.1kA/μs	24kA/μs	65kA/μs
Average Steepness between 30% and 90%	2.6kA/μs	7.2kA/μs	20kA/μs
between 10% and 90%	1.7kA/μs	5.0kA/μs	14kA/μs

Subsequent Negative Strokes	Cumulative Frequency		
	95%	50%	5%
Maximum Rate of Rise	10kA/μs	40kA/μs	162kA/μs
Average Steepness between 30% and 90%	4.1kA/μs	20kA/μs	99kA/μs
between 10% and 90%	3.3kA/μs	15kA/μs	72kA/μs

Positive Stroke	Cumulative Frequency		
	95%	50%	5%
Maximum Rate of Rise	0.2kA/μs	2.4kA/μs	32kA/μs

Figure 1.6 : Tables showing lightning current rate of rise probabilities

The rate of rise of the current in these tables are useful for calculating the volt drops across inductive components of lightning protection paths and for estimating the induced voltages due to adjacent lightning strikes.

1.3.3 The Duration of the Lightning Current Waveform (t)

The duration of the lightning current waveform is described in terms of the *time to crest* t_{cr} and the *time to half-value* t_d. For example, a 10μs/35μs waveform has a time to crest t_{cr} of 10μs and a time to half value t_d of 35μs.

The typical duration of the current waveforms for *negative downward strokes* are :

- First negative stroke 5.5μs/75μs
- Subsequent negative strokes 1.1μs/32μs

Typical values for t_{cr} obtained from IEC 1024-1-1 (1993) are shown in the tables below (lognormal distribution assumed).

First Negative Stroke	Cumulative Frequency		
	95%	50%	5%
Total Rise Time	1.8μs	5.5μs	18μs
Rise Time between 30% and 90%	1.5μs	3.8μs	10μs
between 10% and 90%	2.2μs	4.6μs	14μs

Subsequent Negative Strokes	Cumulative Frequency		
	95%	50%	5%
Total Rise Time	0.2μs	1.1μs	4.5μs
Rise Time between 30% and 90%	0.1μs	0.6μs	3.0μs
between 10% and 90%	0.2μs	0.8μs	3.5μs

Positive Stroke	Cumulative Frequency		
	95%	50%	5%
Total Rise Time	3.5μs	22μs	200μs

Figure 1.7 : Table of Probable time to crest t_{cr} of Lightning Current

Typical values for t_d obtained from IEC 1024-1-1 (1993) are shown in the table below (lognormal distribution assumed)

Type of Lightning Stroke	Cumulative Frequency		
	95%	50%	5%
First Negative Stroke	30μs	75μs	200μs
Subsequent Negative Stroke	6.5μs	32μs	140μs
Positive Stroke	25μs	200μs	2000μs

Figure 1.8 : Table of Probable time to half-value t_d of Lightning Current

It is interesting to compare the average values obtained from extensive field measurements, as listed in the tables above, with the waveforms traditionally specified for testing electrical equipment, such as transformers, motors, cables, etc :

- 1.2μs/50μs for voltage waveforms IEC 1024 and AS 1768-1991 Appendix D
- 8μs/20μs for current waveforms IEC 1024 and AS 1768-1991 Appendix D

The total energy contained in a lightning stroke, and the consequent damage, is a function of I^2t. Consequently, the length of the tail affects the amount of energy that must be dissipated. Extended lightning currents have been measured where the lightning current can have a tail that extends for hundreds of milliseconds. Fortunately, in these cases, the current is usually low (less than 1000A). This type of lightning is known as *hot lightning* and is often associated with the ignition of fires.

1.4 Voltage and Current Surges due to Lightning

1.4.1 Surges due to Direct Lightning Strikes

Lightning behaves like a *current source.* Consequently, the voltage at the point of strike is equal to the product of the *lightning current I* and the *impedance Z* presented by the structure and the earthing system to the lightning current.

Simply, from Ohm's Law : **V = I x Z**

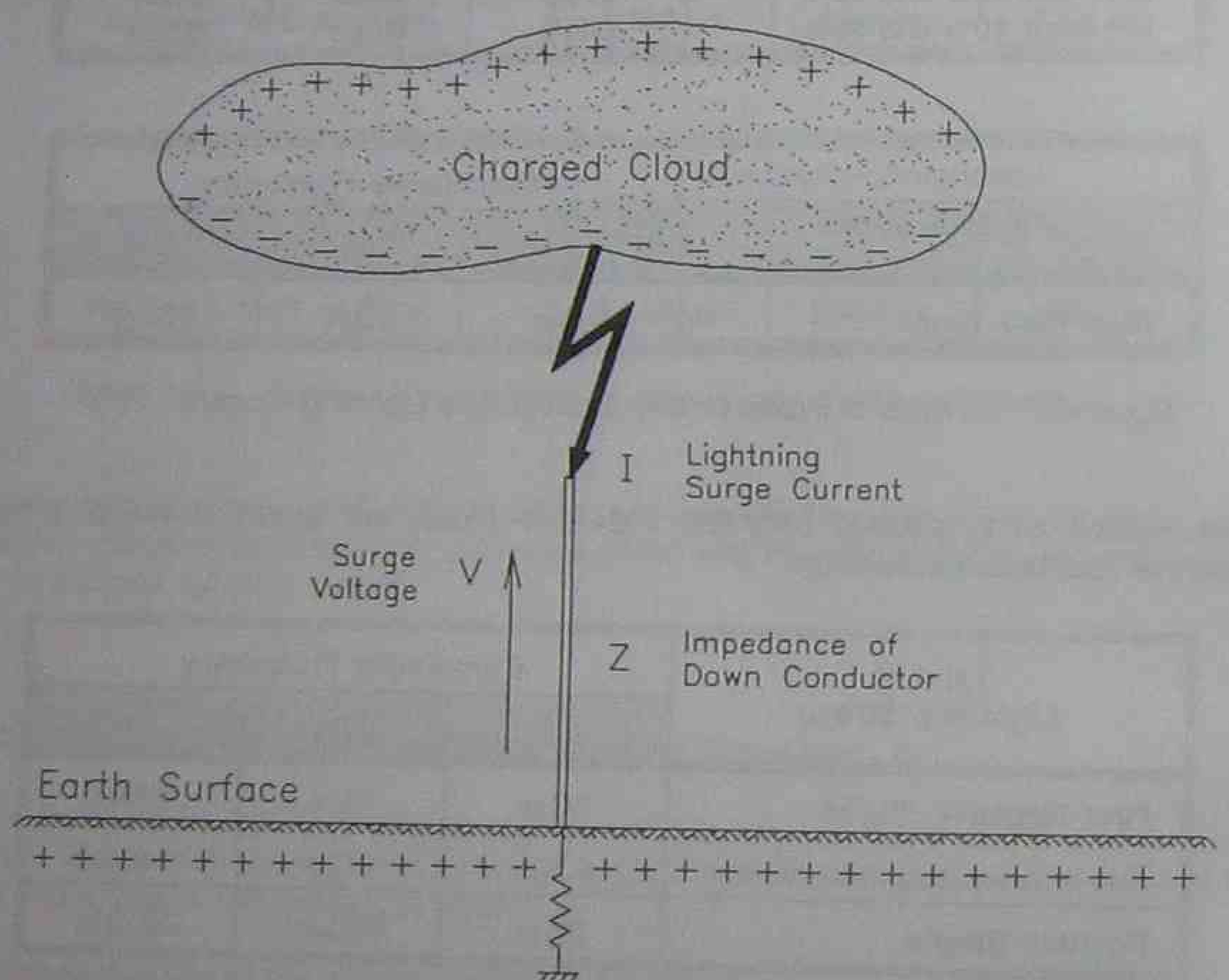


Figure 1.9 : The Impedance of the Earth Path

This value of the impedance Z is not the simple value measured at 50Hz. Since lightning current has a very sharp rise time, the *surge impedance* of the conductive path is the correct value to use.

For a vertical mast, the impedance Z is calculated from the resistance and inductance of the mast itself as well as footing resistance of the mast (the resistance presented by the earth electrode of the mast).

For a long horizontal conductor, such as a transmission line, the impedance Z is equal to the surge impedance of the conductor Z_o, if struck at one end, or $Z_o/2$ if struck at some intermediary point between the two ends.

For example, a horizontal transmission line conductor has a surge impedance of typically 300Ω. When struck by lightning with a peak current of 100kA the peak voltage to ground

$$V_{peak} = \frac{300\Omega}{2} \times 100kA$$

$$V_{peak} = 15{,}000kV$$

This would be sufficient for insulation breakdown and a phase-to-ground fault would occur on the transmission line.

Ideally, direct strikes to power lines and other facilities should be avoided, if possible. This can be achieved by :

- Shielding the overhead power cable using overhead earth wires
- Burying power transmission cables
- Shielding buildings using tall lightning masts

1.4.2 Induced Surges due to Adjacent Lightning Strikes

High voltages and faults on transmission lines and other structures are not only caused by direct lightning strikes. High voltages can also be caused by lightning strikes in the vicinity of these facilities .... called *adjacent lightning strikes.* These cause *induced voltages.*

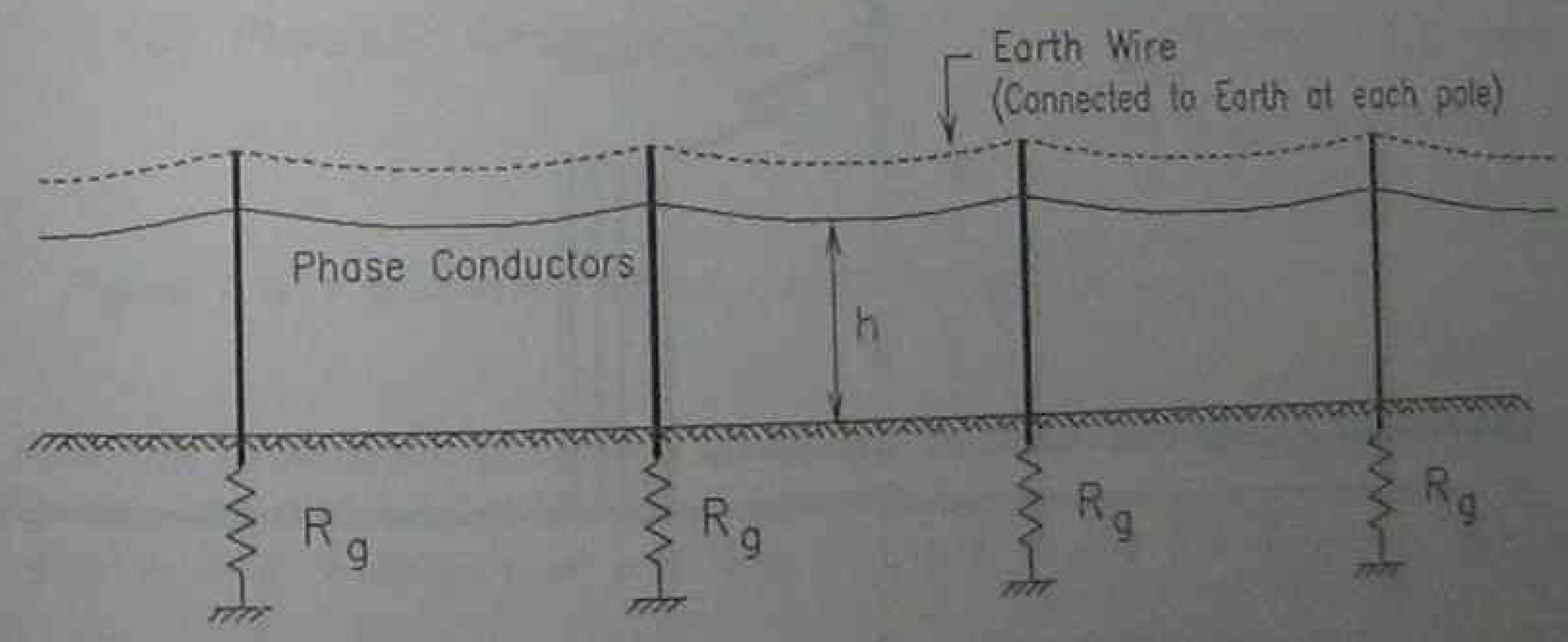


Figure 1.10 : Earthing of typical power transmission line

The transfer of electric charge during a lightning strike generates an intense electromagnetic wave which in turn induces voltages on adjacent conductors.

The electric field generated by a lightning strike is the result of :

- The charge in the cloud
- The charge induced in the ground
- The charge distributed along the lightning channel

The magnetic field generated by a lightning strike is the result of :

- The rate of change of current flow through the lightning channel

The peak of the induced voltage can be fairly high. The experience of power system engineers in Australia has shown that the insulation levels of 95kV appear to be adequate for most 11kV/22kV lines.

1.4.3 Avoiding Side Flashes

When the lightning current flows to ground through the lightning down conductor, it produces high volt drops due to high series impedances (mainly inductance). High volt drops along the down conductor increase the probability of side flashes to adjacent objects. The non-uniform field breakdown voltage for air is about 500kV/m, so adjacent structures should be greater than 2m (at least) from the down conductor.

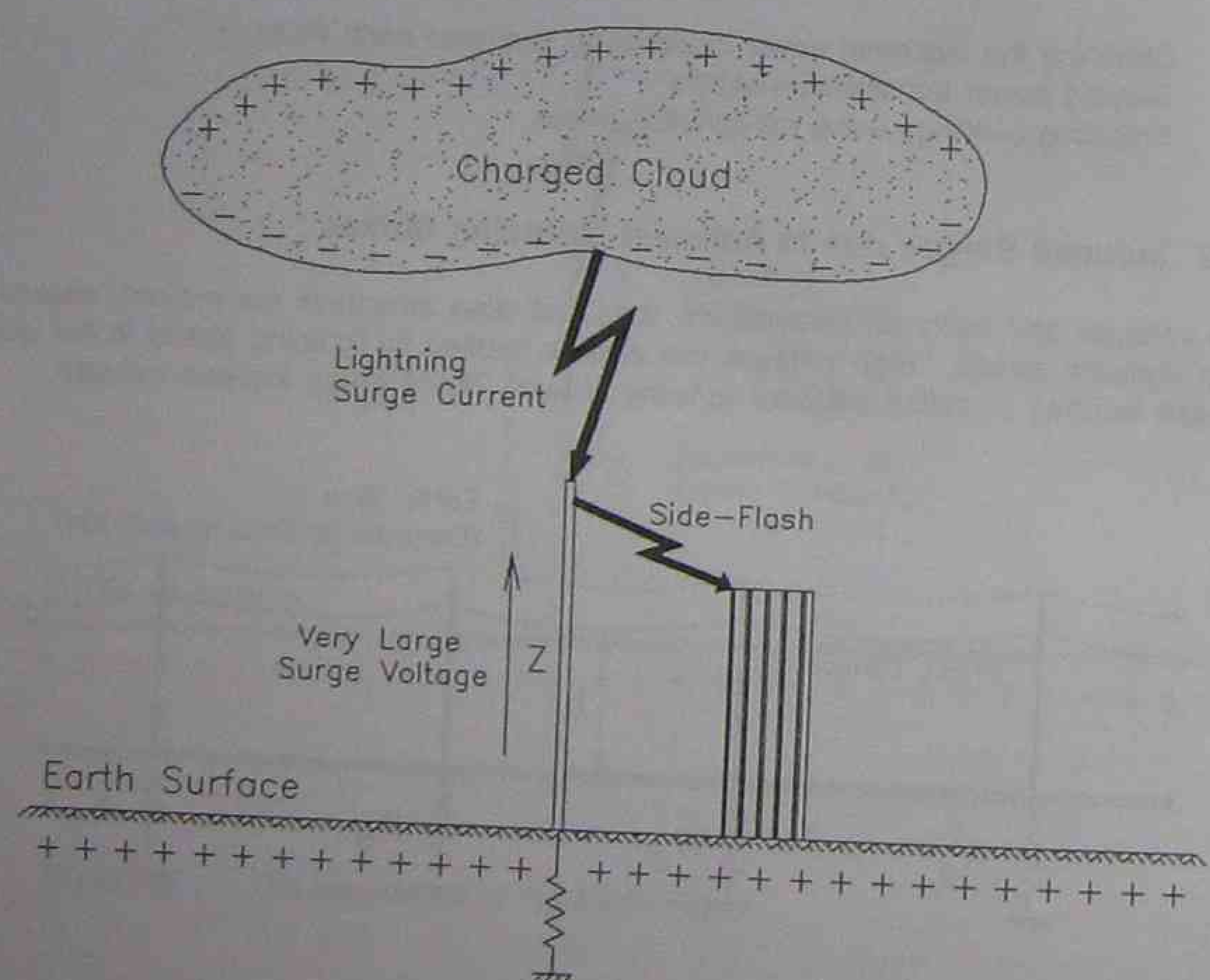


Figure 1.11 : Avoiding Side-Flashes

Even if a side-flash does not occur, dangerous voltages can be induced in adjacent earthed metallic objects due to capacitive coupling. Consequently, adjacent metallic objects should also be earthed.

1.5 The Impedance of the Earth Connection

During a lightning strike, the air terminal (on top of the structure), the down conductor (down the side of the structure) and earth electrode all contribute to the total impedance of the earth connection as shown in the figure below :

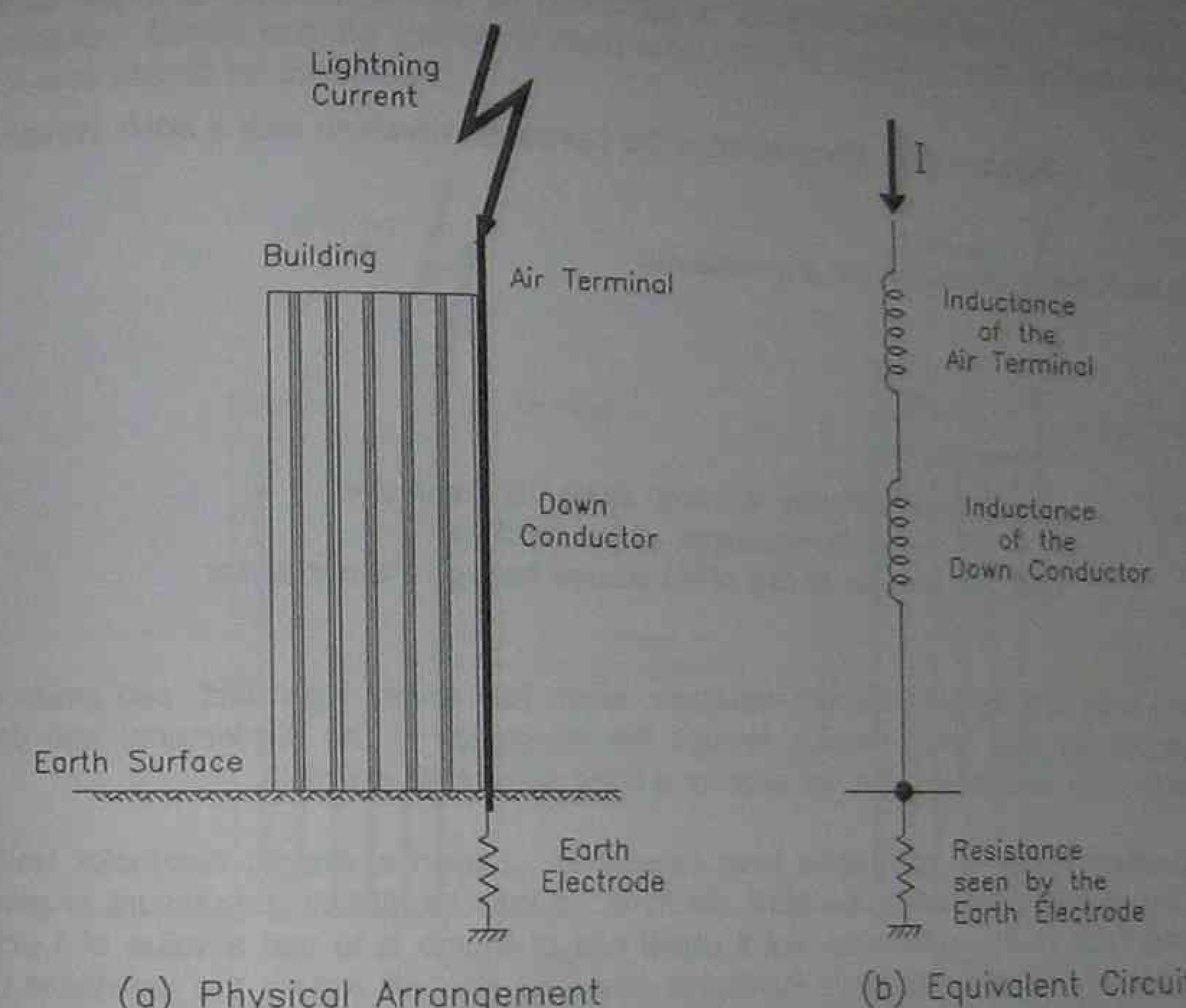


Figure 1.12 : Equivalent Circuit of Lightning Path

The minimum dimensions of bonding conductors, recommended by IEC 1024, are given in the Figures A.11 and A.12 at the end of Appendix A.

1.5.1 The Inductance of the Air Terminal and Down Conductor

To understand the significance of the inductance of the air terminal and down conductor, the period of the lightning current waveform should be compared with that of the power system 50Hz waveform. The rate of rise of the lightning current waveform is considerably faster than the 50Hz waveform.

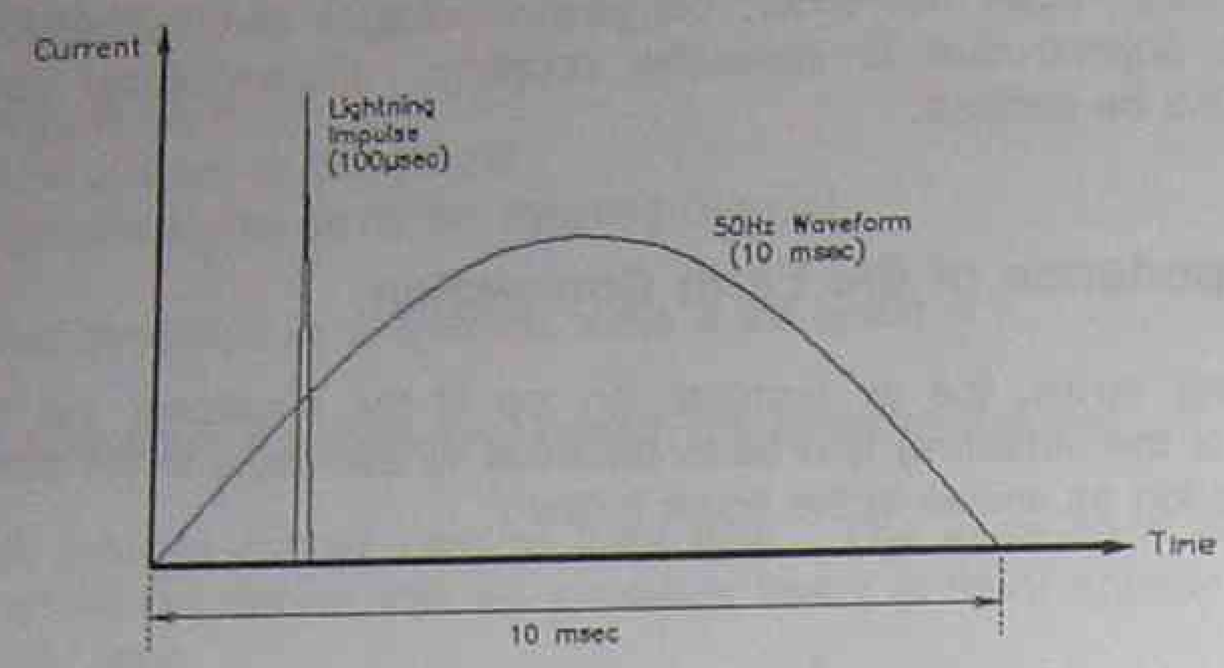


Figure 1.13 : Comparison of the Lightning Waveform with a 50Hz Waveform

Going back to first principles, for any conductor

$$V_L = L\frac{di}{dt}$$

where : V_L is the inductive volt drop along the conductor
L is the (self) inductance of the conductor
di/dt is the rate of rise of the current through the conductor

Consequently, the lightning current waveform, which has a very high di/dt, can produce a substantial volt drop when passing through the inductance of the air terminal and down conductor. By comparison, the volt drop for a 50Hz current is negligible.

The problem is that all conductors have inductance .... even a straight conductor leading from the air terminal down to the earth electrode. It may be difficult to measure or predict the magnitude of this inductance, but a useful rule-of-thumb is to use a value of 1 µH/m. It is interesting to note that, while increasing conductor size will reduce the resistance of a conductor, the inductance is not greatly affected by its cross-sectional area. The table below shows the calculated values of inductance for a range of conductor sizes.

Conductor Size mm^2	Inductance µH
1	1.2
2.5	1.1
4	1.1
6	1.0
10	1.0
100	0.7

Figure 1.14 : Inductance of Conductors of various cross-sectional area (Calculation is based on an 8/20µs waveform assuming a straight rising edge) Compliments of W J Furse & Co Ltd : Reference 3.25

Thus for 10m of down conductor, the total inductance would be ±10µH. If the rate of rise of current di/dt is 50kA/µs, then the total inductive volt drop would be :

$$V_L = L\frac{di}{dt} = [10 \times 10^{-6}] \times \frac{[50 \times 10^{3}]}{10^{-6}} = 500kV \;\; !!$$

This emphasises the importance of keeping the down conductor as short as possible and, by implication, as straight and vertical as possible. It also highlights the possibility of side flashes due to the high voltage at the tip of the air terminal.

Ideally each air terminal should be connected to an earth electrode by a vertical down conductor. Bends and the sharing of down conductors by lightning rods scattered over the roof area should be minimised.

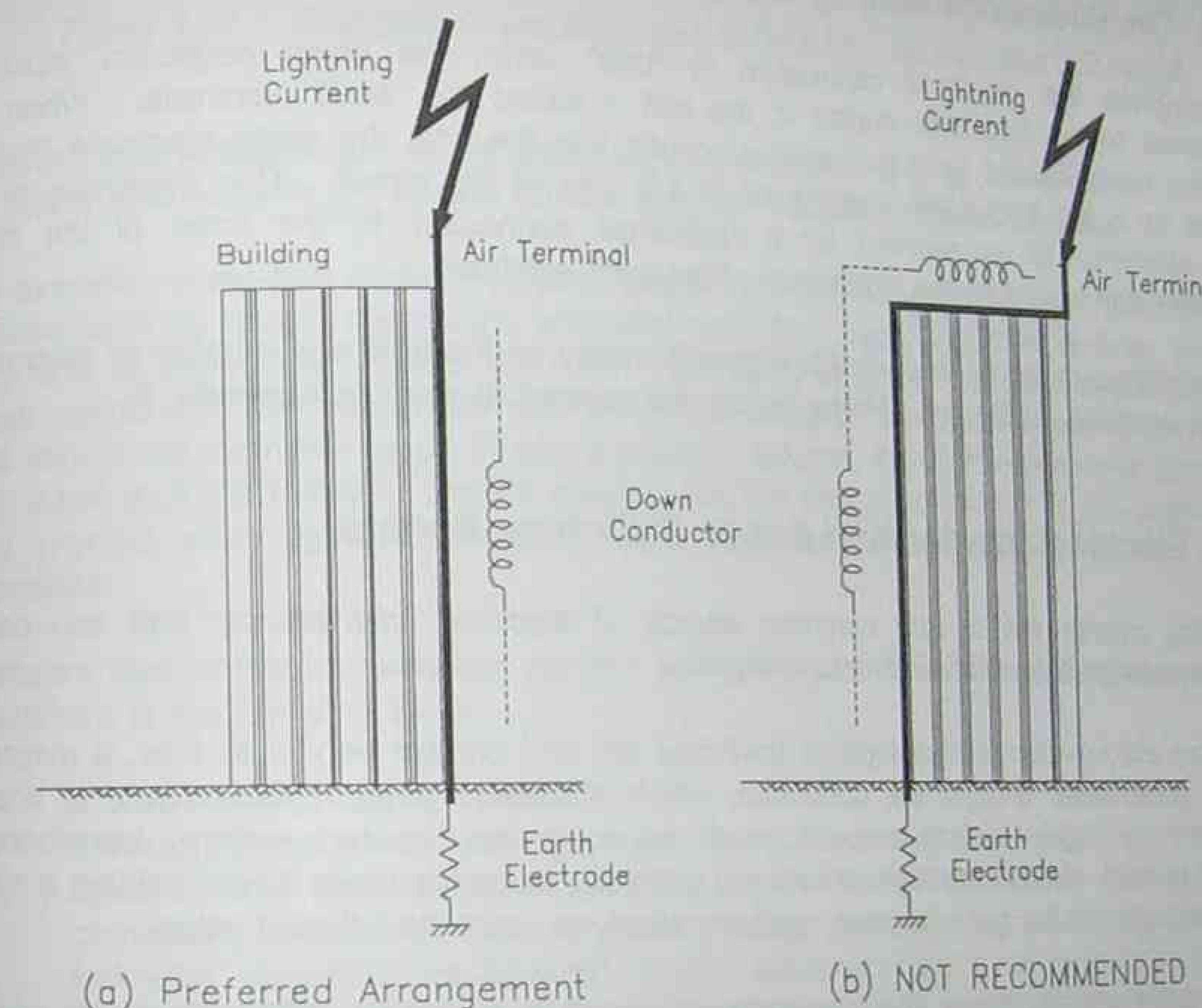


Figure 1.15 : Recommended down connection techniques

Another important rule is that inductance is lower for down conductors connected in parallel. Two down conductors separated by a few metres are better than one. The recommended minimum separation distances between down conductors are given in the table below.

Protection Level	Average Distance
I	10m
II	15m
III	20m
IV	25m

Figure 1.16 : Recommended Maximum Distances between Down Conductors from IEC 1024-1 1990

1.5.2 The Resistance seen by the Earth Electrode

To complete the electrical connection to "true" earth, the down conductor must be connected to an electrode buried in the soil - called the *earth electrode.* When the lightning current flows from the earth electrode into the soil, the earth electrode rises in voltage as a result of some impedance in this part of the circuit. This behaviour at the earth electrode is represented by a *resistance* connected to the base of the down conductor and known as the *resistance of the earth electrode.*

The resistance of the earth electrode depends mainly on the type and number of electrodes and the resistivity of the soil. These factors are covered in detail in Appendix B.

1.6 Electrical Interference due to Switching Events

Switching events are a very common source of electrical interference and can cause considerable problems for electronic equipment.

When an electric circuit is *energised (switched on)* and current begins to flow, a magnetic field is established around the conductor, which absorbs energy. The amount of energy absorbed by highly inductive loads, such as solenoids, electric motors, transformers, electric brakes, etc, is very high. However, switching inductive loads ON is seldom a major problem because the current grows relatively slowly to reach its full load value.

The problem usually arises when an inductive circuit is ***switched OFF***. When the current is interrupted, the magnetic field collapses. The energy, which is stored in the magnetic field, is then suddenly released. The energy is recovered in the form of current, which attempts to continue flowing in the circuit through the open contacts of the switch. The multiple restrikes which then occur across the opening contacts of the switch generate a sequence of voltage transients or 'spikes', which are conducted along the cables to other connected equipment. The higher the stored energy, the larger the resultant *transient over-voltage.*

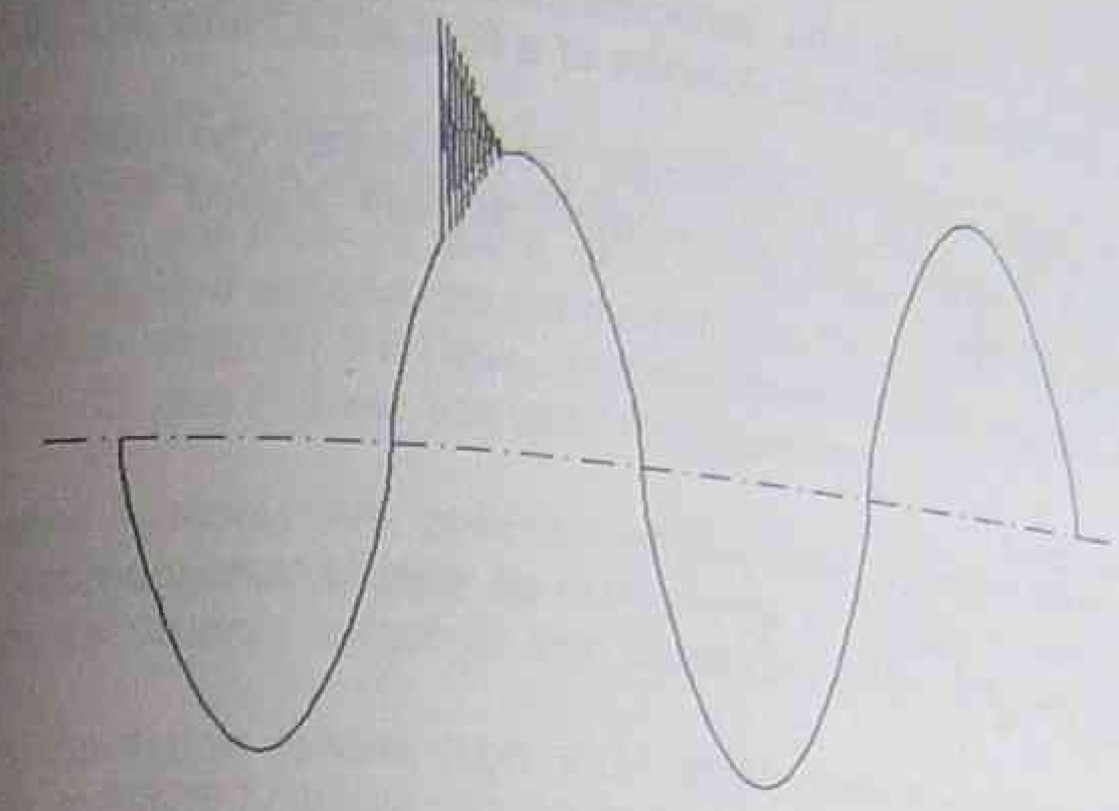


Figure 1.17 : Transient Overvoltage due to Switching an Inductive AC circuit

Transient overvoltages due to switching are not restricted only to AC circuits. Switching transients also occur in DC control circuits, even at voltages as low as 24 Volts.

For example, in modern control systems, where PLC outputs are often used to control field devices such as relays, contactors, solenoids and other highly inductive devices, switching transients of substantial voltage (200-300 Volts peak-to peak) are quite common. While these magnitudes of voltage are well within the designed insulation levels of the outputs and should not normally result in any equipment failures, the high frequencies associated with these multiple restrikes can be coupled into the electronic circuits of the output cards and interfere with digital communications, microprocessor sequences and data storage memories.

Transient over-voltages, whether caused by lightning or switching, can affect electronic equipment in the following ways :

- **Disruption of Normal Operation**
  Although no physical damage may appear to occur, the logic levels in digital systems and communications circuits can be disrupted, causing data loss, data corruption, unexplained communications 'hang-ups' (requiring re-setting), processor lock-ups (requiring 're-booting') and/or spurious tripping of protection devices. These problems all result in frustrating *downtime* and a lack of confidence in the integrity of the control system.
- **Degradation of Components**
  This problem is more serious because long term exposure to voltage and current stresses will degrade the electronic components, reduce their useful lifetime and eventually will result in equipment failure ..... more *downtime!!!*
- **Damage to Equipment**
  Severe transient over-voltages can sometimes result in immediate damage to the power supplies or I/O cards of the electronic equipment of the control system ..... more *downtime!!!*

Consequently, some form of suppression is highly recommended on control circuits which switch inductive loads, even small control relays. Switching inductive loads can significantly reduce the lifetime of the switching relay contacts.

Protection Level	Average Distance
I	10m
II	15m
III	20m
IV	25m

Figure 1.16 : Recommended Maximum Distances between Down Conductors from IEC 1024-1 1990

1.5.2 The Resistance seen by the Earth Electrode

To complete the electrical connection to "true" earth, the down conductor must be connected to an electrode buried in the soil - called the *earth electrode*. When the lightning current flows from the earth electrode into the soil, the earth electrode rises in voltage as a result of some impedance in this part of the circuit. This behaviour at the earth electrode is represented by a *resistance* connected to the base of the down conductor and known as the *resistance of the earth electrode.*

The resistance of the earth electrode depends mainly on the type and number of electrodes and the resistivity of the soil. These factors are covered in detail in Appendix B.

1.6 Electrical Interference due to Switching Events

Switching events are a very common source of electrical interference and can cause considerable problems for electronic equipment.

When an electric circuit is *energised (switched on)* and current begins to flow, a magnetic field is established around the conductor, which absorbs energy. The amount of energy absorbed by highly inductive loads, such as solenoids, electric motors, transformers, electric brakes, etc, is very high. However, switching inductive loads ON is seldom a major problem because the current grows relatively slowly to reach its full load value.

The problem usually arises when an inductive circuit is ***switched OFF***. When the current is interrupted, the magnetic field collapses. The energy, which is stored in the magnetic field, is then suddenly released. The energy is recovered in the form of current, which attempts to continue flowing in the circuit through the open contacts of the switch. The multiple restrikes which then occur across the opening contacts of the switch generate a sequence of voltage transients or 'spikes', which are conducted along the cables to other connected equipment. The higher the stored energy, the larger the resultant *transient over-voltage.*

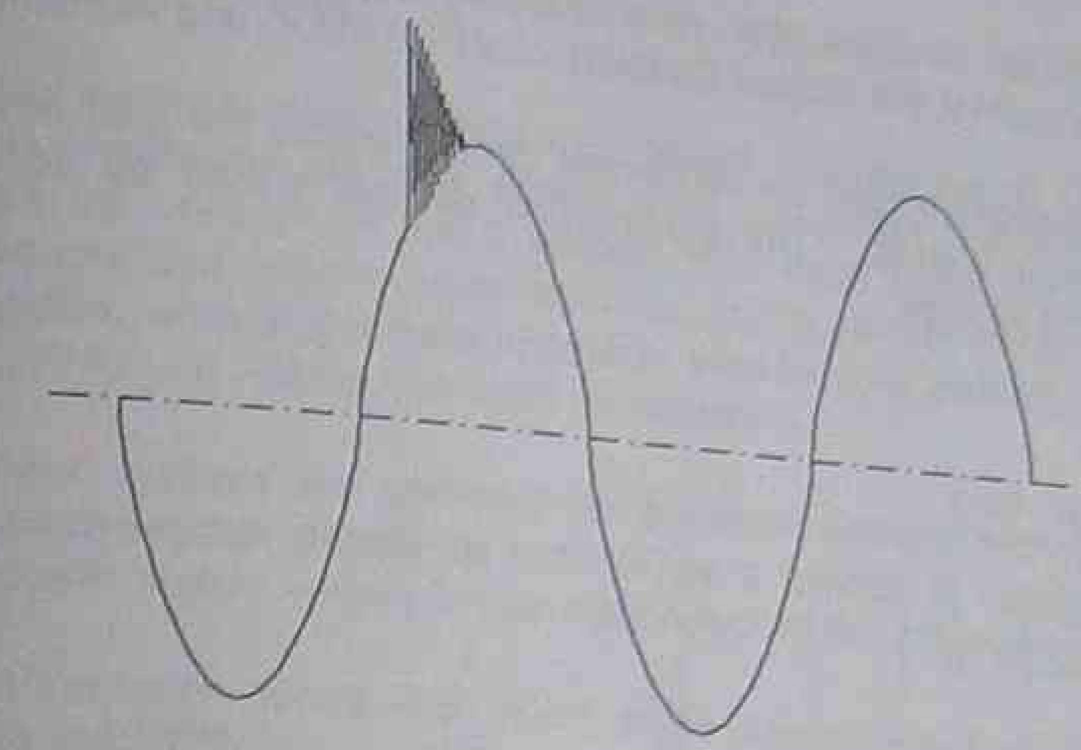


Figure 1.17 : Transient Overvoltage due to Switching an Inductive AC circuit

Transient overvoltages due to switching are not restricted only to AC circuits. Switching transients also occur in DC control circuits, even at voltages as low as 24 Volts.

For example, in modern control systems, where PLC outputs are often used to control field devices such as relays, contactors, solenoids and other highly inductive devices, switching transients of substantial voltage (200-300 Volts peak-to peak) are quite common. While these magnitudes of voltage are well within the designed insulation levels of the outputs and should not normally result in any equipment failures, the high frequencies associated with these multiple restrikes can be coupled into the electronic circuits of the output cards and interfere with digital communications, microprocessor sequences and data storage memories.

Transient over-voltages, whether caused by lightning or switching, can affect electronic equipment in the following ways :

- **Disruption of Normal Operation**
  Although no physical damage may appear to occur, the logic levels in digital systems and communications circuits can be disrupted, causing data loss, data corruption, unexplained communications 'hang-ups' (requiring re-setting), processor lock-ups (requiring 're-booting') and/or spurious tripping of protection devices. These problems all result in frustrating *downtime* and a lack of confidence in the integrity of the control system.
- **Degradation of Components**
  This problem is more serious because long term exposure to voltage and current stresses will degrade the electronic components, reduce their useful lifetime and eventually will result in equipment failure ..... more *downtime!!!*
- **Damage to Equipment**
  Severe transient over-voltages can sometimes result in immediate damage to the power supplies or I/O cards of the electronic equipment of the control system ..... more *downtime!!!*

Consequently, some form of suppression is highly recommended on control circuits which switch inductive loads, even small control relays. Switching inductive loads can significantly reduce the lifetime of the switching relay contacts.

The following figures illustrate the recommended suppression techniques, which are commonly used to protect the *Output Contacts* of a PLC in DC and AC control circuits.

The suppression devices should be connected directly across the load device, close to the source of the stored energy. The suppression devices should be adequately rated to absorb the switching energy.

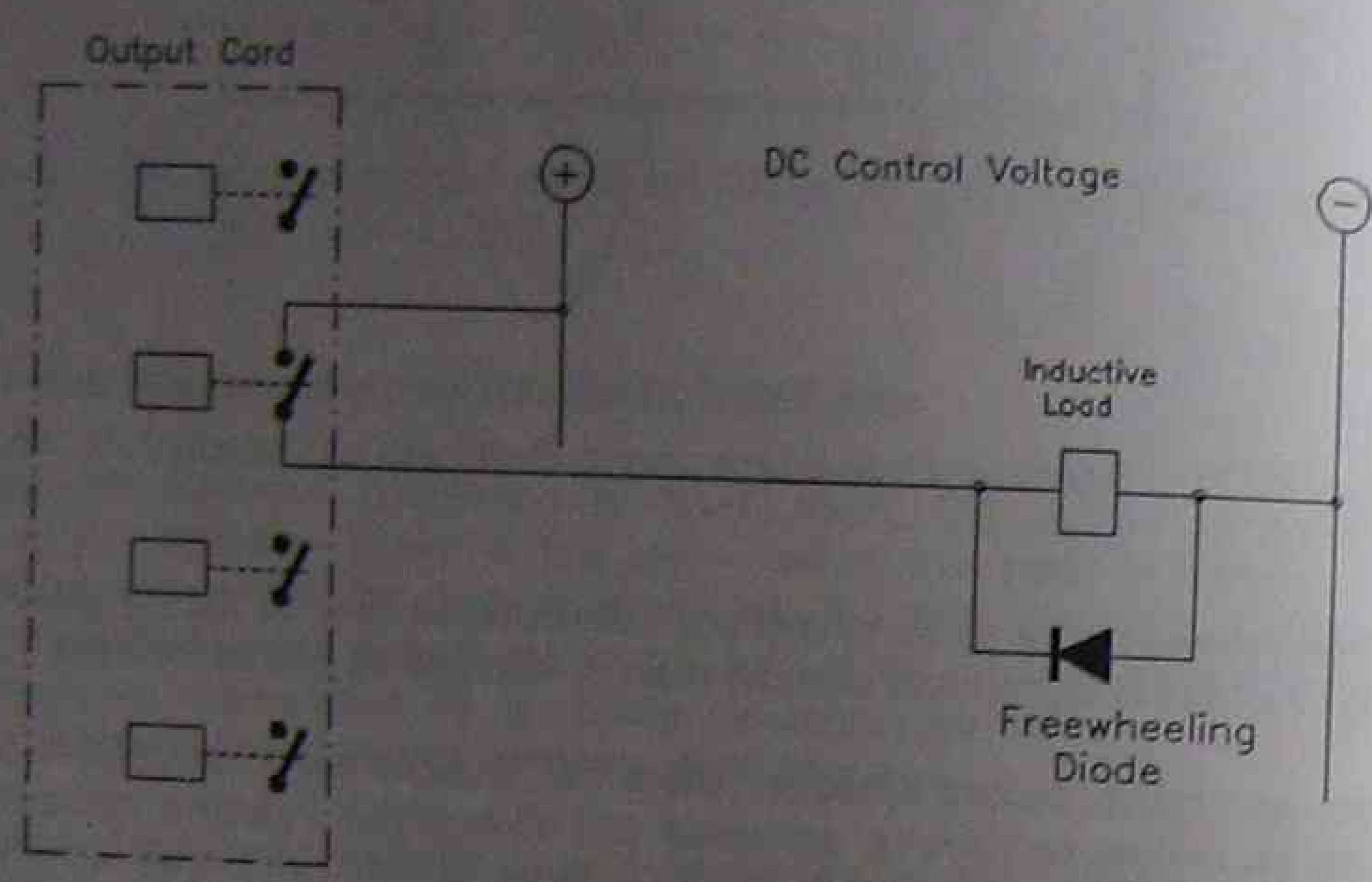


Figure 1.18 : Typical Suppression Techniques for DC Control Circuits

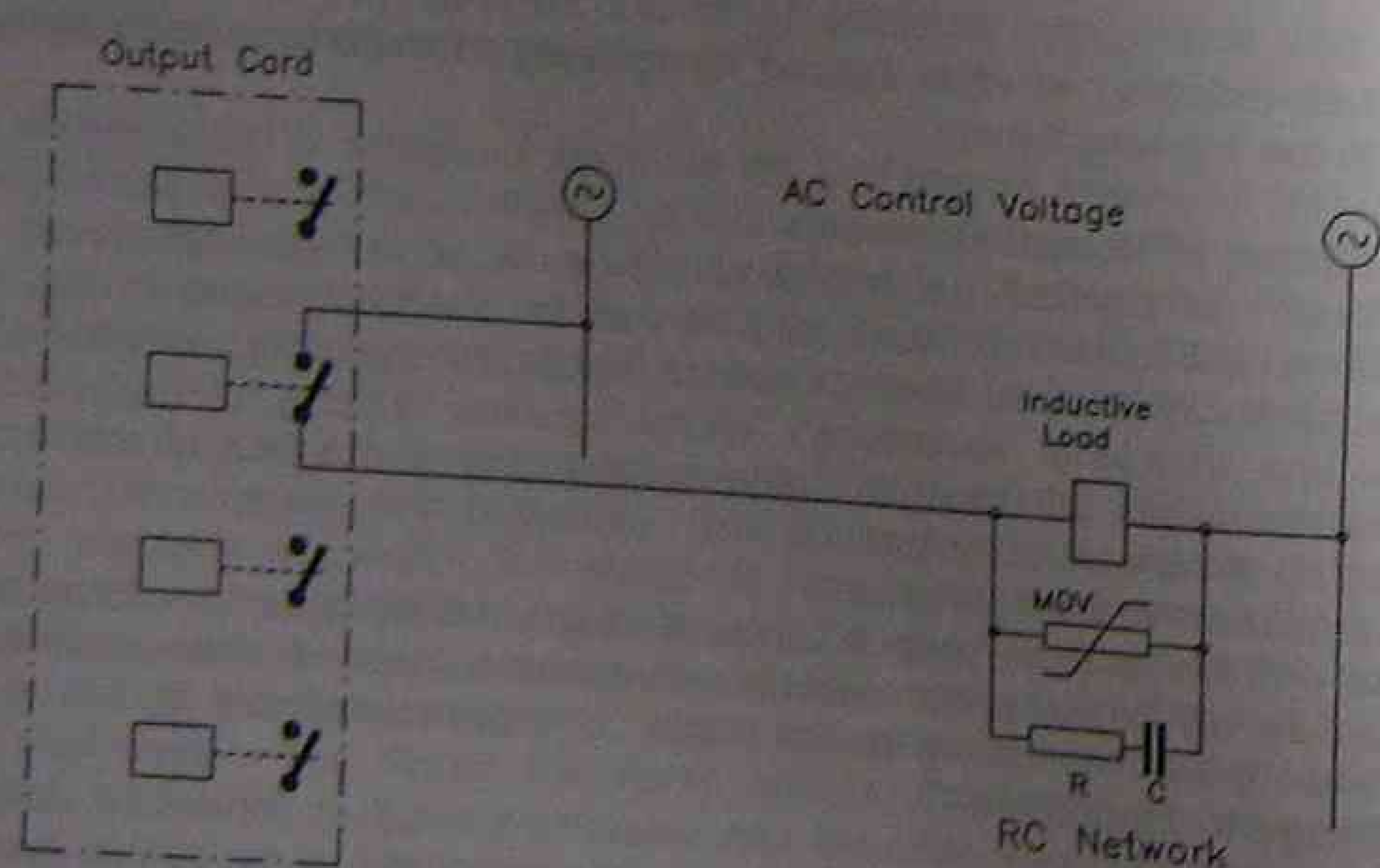


Figure 1.19 : Typical Suppression Techniques for AC Control Circuits

1.7 Power System Faults

An electrical power supply system comprises a network of transmission lines, transformers, cables, etc which convey the electrical energy from the power generation station to the users. To isolate the voltages of the 3 phases from each other and from the ground, insulation must be provided around the conductors. In the case of transmission lines, air is used as the insulation, while in the case of cables, transformers, motors, etc, material such as Resins, XLPE, PVC and Rubber are used for insulation.

Most modern power systems are operated as 3-phase systems with the neutral of the transformers connected either directly to earth or via a resistor or reactor. The continued operation of the power supply system is then dependent of the integrity of the insulation.

When there is an insulation failure, high *short circuit* currents will flow in the power supply conductors. If the insulation failure results in a short circuit between phases, this is known as a *phase fault*, and when the short circuit takes place between the phase and earth, it is known as an *earth fault*.

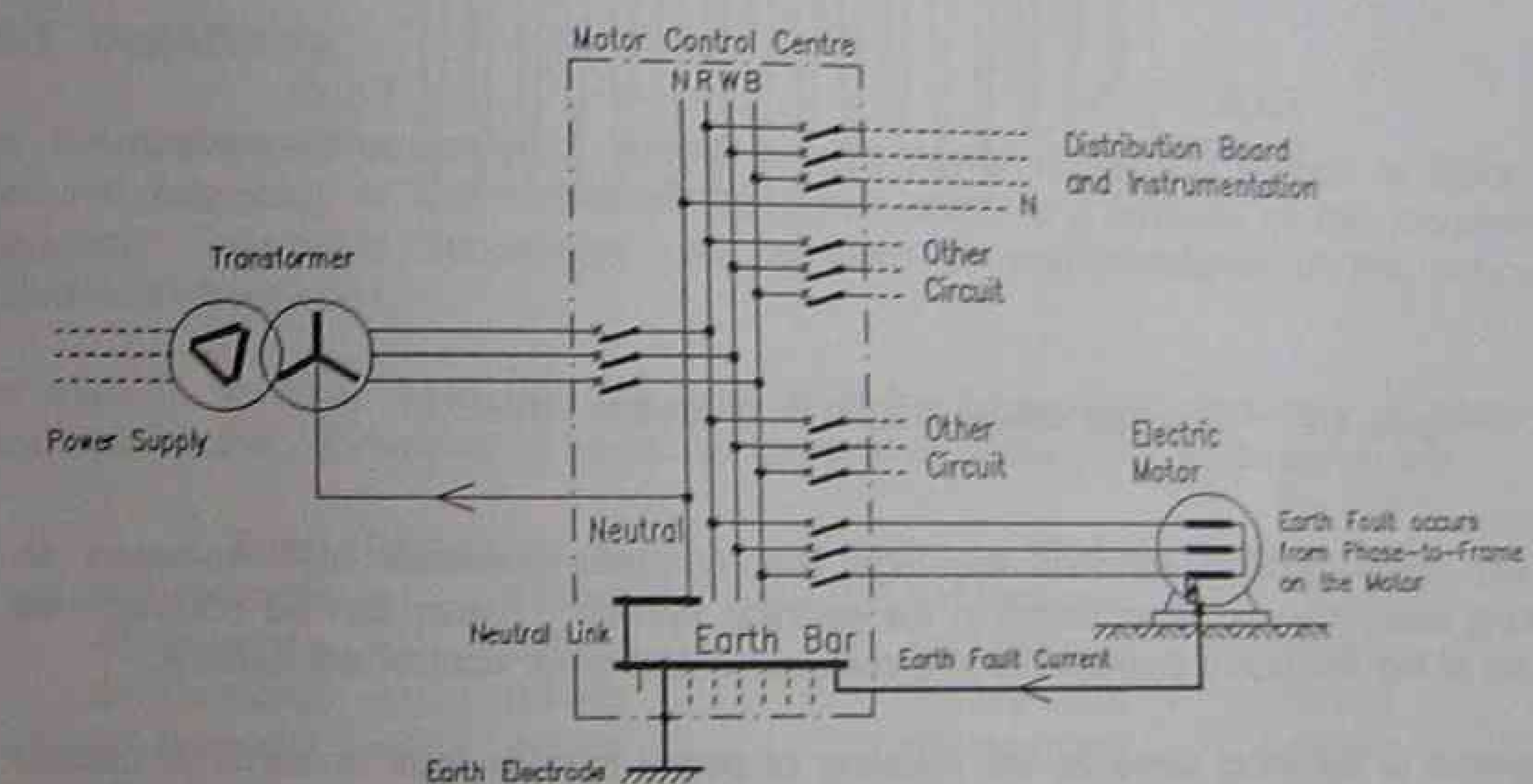


Figure 1.20 : The current path for a typical Earth Fault in an industrial plant

It is not practical to design a power supply system so as to completely eliminate the possibility of insulation failure or faults. Faults will and do occur, however infrequently. During these fault conditions, high 50Hz fault currents flow in the power supply cables and, in the case of an *earth fault*, into the local earthing system and back to the neutral point of the transformer.

Special equipment is normally installed to detect these disturbances and to automatically initiate corrective measures. These electronic detection devices are known as *protection relays* or simply as *Protection*. The protection relays do not prevent faults, but their main purpose is to safeguard the continuity of supply by identifying the location of the fault and quickly switching out the faulty component or section of conductor. The speed of fault detection and switching varies, depending on the type of protection and the type of fault. Fault interruption is typically from 0.1sec to 1.0 sec.

At the instant that the fault occurs, there is a high rate of change of current magnitude in the power supply, from normal load current to fault current. There is also a sudden high current flowing into earthing system. This high current persists for a period until the fault is identified and cleared by the protection system. At the instant that the fault is interrupted, there is a another high rate of change of current magnitude down to zero. The magnitude of the fault current depends on the impedance in the fault path, which comprises the source impedance at the point of supply and the impedance up to the point of the fault.

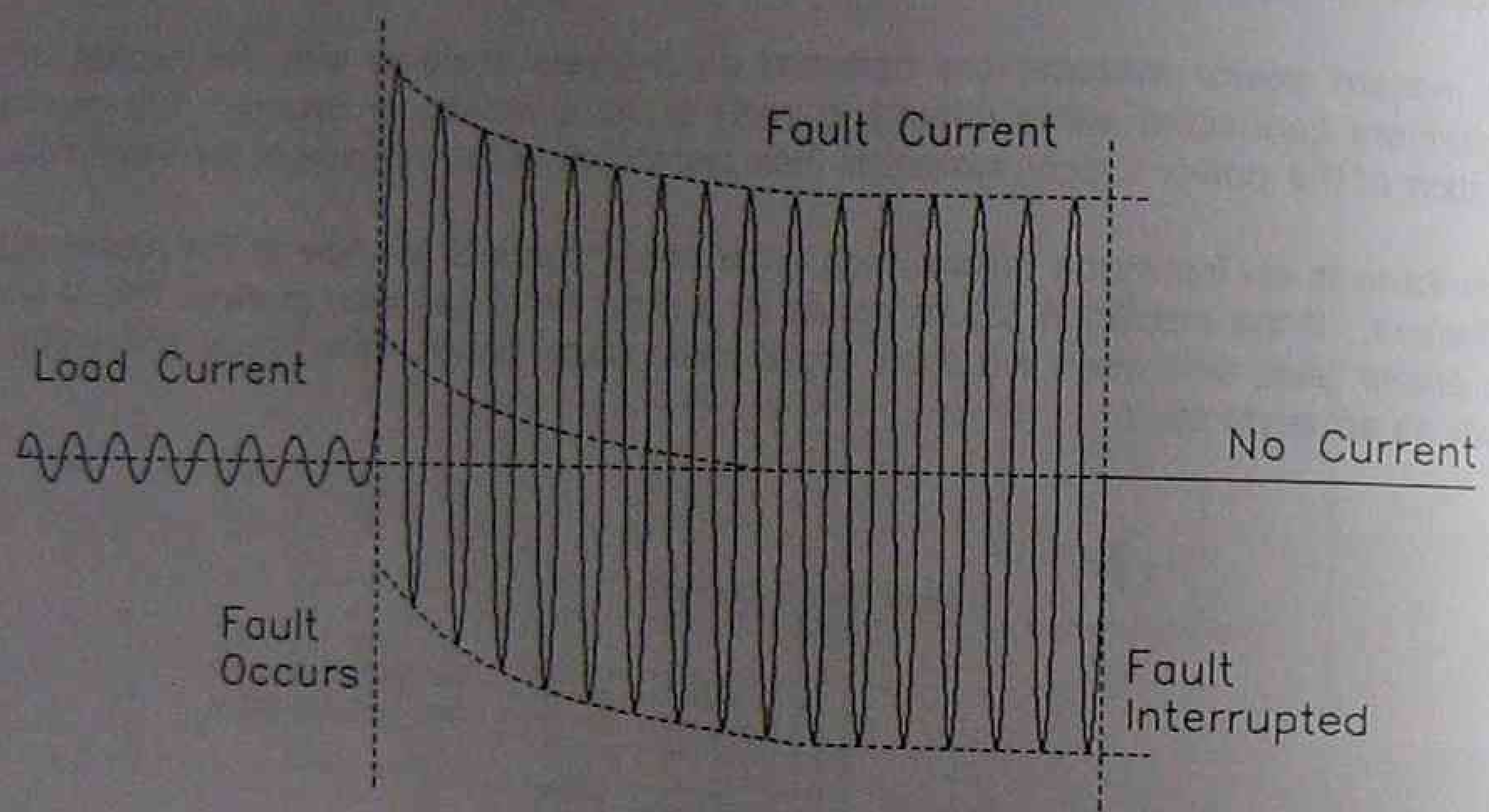


Figure 1.21 : A typical power system fault current waveform

As with high lightning currents, the high fault currents generate high voltages at the earthing electrode and other points in the earthing system. These can be coupled into the circuits of the electronic instrumentation, computers and other control equipment.

Compared to lightning currents, the coupling of power system fault currents is usually not as severe even though they often reach 50kA and are usually present for relatively long periods of time. The reasons for this lower coupling are as follows :

- Power system fault currents are predominantly *50Hz currents.* Therefore, the inductance in the fault path does not result in voltages as high as with lightning.
- In contrast to lightning, power system faults are usually local events that affect a relatively small area.

1.8 Harmonic Interference

In industrial applications and in building air conditioning systems, the use of power electronic converters for the speed control of electric motors has increased substantially over the past decade and have become a significant portion of the connected load. Modern industrial process control makes extensive use of variable speed drives to achieve the required level of automation. As the technology develops, there is a noticeable trend towards more and more variable speed drives.

Converters comprise various combinations of diodes, thyristors, transistors or other non-linear devices which draw a non-sinusoidal current and distort the AC voltage in the power supply system. Harmonics are not confined to the converter busbar but will affect equipment in other parts of a plant and the interconnected power system. They cause additional losses in other items of plant and are a major *source of electrical interference.* Harmonic distortion can be looked upon as a type of electrical pollution in a power system and are of concern because they can affect other connected equipment. As with other types of pollution, the source and magnitude of the harmonic distortion should be clearly understood in order to effectively deal with this problem.

1.8.1 Definitions

The ***fundamental frequency*** of the AC electric power distribution system is 50Hz. A *harmonic frequency* is any sinusoidal frequency which is a multiple of the *fundamental frequency.* Harmonic frequencies can be **even or odd multiples** of the sinusoidal fundamental frequency.

The multiple, that the harmonic frequency is of the fundamental frequency, is called the ***Harmonic Order.*** Examples of harmonic frequencies of the 50Hz fundamental are :

Even Harmonics		Odd Harmonics	
2nd harmonic =	100Hz	3rd harmonic =	150Hz
4th harmonic =	200Hz	5th harmonic =	250Hz
6th harmonic =	300Hz	7th harmonic =	350Hz
8th harmonic =	400Hz	9th harmonic =	450Hz
etc		etc	

A **Linear** electrical load is one which draws a purely sinusoidal current when connected to a sinusoidal voltage source, eg. resistors, capacitors and inductors. Many of the traditional devices connected to the power distribution system, such as transformers, electric motors and resistive heaters, have linear characteristics.

A **Non-linear** electrical load is one which draws a non-sinusoidal current when connected to a sinusoidal voltage source, eg. diode bridge, thyristor bridge, etc. Many power electronic devices, such as variable speed drives, rectifiers and UPSs, have non-linear characteristics and result in non-sinusoidal current waveforms or *distorted waveform.* An example of a periodic *distorted waveform,* which repeats itself 50 times a second, is shown in Figure 1.22

1.8.2 The Analysis of the Harmonic Distortion

The technique used to analyse the level of distortion of a periodic current waveform is known as Fourier Analysis. The analysis method is based on the principle that a distorted (non-sinusoidal) periodic waveform is equivalent to, and can be replaced by, the sum of a number of sinusoidal waveforms, which are :

- A sinusoidal waveform at fundamental frequency (50Hz)
- A number of other sinusoidal waveforms at higher *harmonic frequencies*, which are multiples of the fundamental frequency.

The process of deriving the frequency components of a distorted periodic waveform is achieved mathematically by a technique known as the Fourier Transform. Microprocessor based test equipment, which are used for harmonic analysis, can do this very quickly using an "on-line" technique known as an FFT (Fast Fourier Transform).

The example below illustrates a distorted voltage wave comprising a fundamental wave and a 3rd order harmonic wave, or simply the *3rd Harmonic*, which is a 150Hz sinusoidal waveform (3 x 50Hz). The total RMS value of the distorted current is calculated by taking the square root of the sum of the squares of the fundamental and harmonic currents. In this example, the summation can be done separately for the 2 different phase relationships.

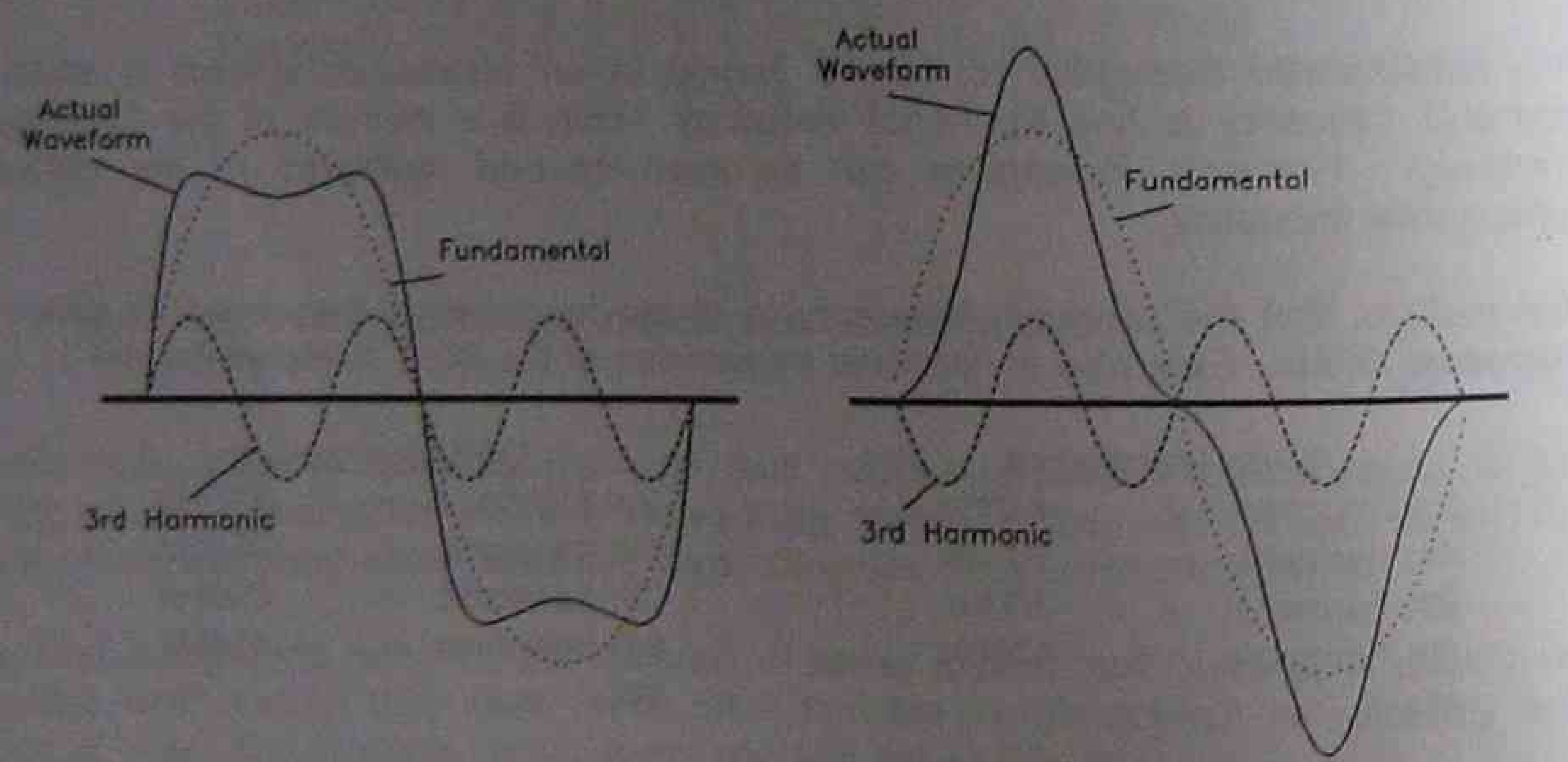


Figure 1.22 : Distorted AC Waveform - Fundamental plus 3rd Harmonic

Harmonic distortion of the current waveform is relatively easy to recognise as a distorted waveform, which is repetitive at the fundamental frequency of 50Hz. Random noise does not have this repetition. The signature of odd and even harmonics are as follows :

- **Odd Harmonics** are present when the negative half cycle is an exact repetition of the positive half cycle, but in the negative direction. Alternatively, odd harmonics are present when the first and third quarters are similar and the second and forth quarters are similar.
- **Even Harmonics** are present when the negative half cycle is NOT a repetition of the positive half cycle. Another characteristic of even harmonics is that the first and forth quarters are similar and the second and third quarters are similar. It is not common to find even harmonics in an industrial power system.

1.8.3 The Sources of Harmonic Distortion in the Power Supply System

The major sources of harmonic distortion in an industrial power supply system are :

- **Power Electronic Converters for Speed Control of Motors**
  The largest contributors of harmonic distortion in a modern power supply system are the converters associated with AC and DC variable speed drives. These are predominantly 6-pulse systems. The characteristic harmonics in this type of converter are 5th, 7th, 11th, 13th, 17th, 19th, etc.
- **Other Industrial Converter Systems**
  In modern industrial plants, non-linear power electronic circuits are used for many other applications such as industrial rectifiers for a wide range of applications, industrial heaters, induction furnaces, arc furnaces, "soft" starters for electric motors, battery chargers, uninterruptable power supplies (UPS), electroplating plants, etc.
- **Transient harmonics generated by devices such as transformers or capacitor banks during energisation.** Transformer magnetising inrush currents typically include 2nd, 3rd and 4th harmonics.

Since power electronic converters in **Variable Speed Drives (VSDs)** are the most common source of harmonics in industrial power systems, this discussion on harmonics will be based mainly on VSDs. The level of the harmonic distortion generated by VSDs depends on a large number of variables, some of which are often difficult to quantify, such as :-

- The magnitude of the current flowing through the converter
- The configuration of the power electronic circuit (6-pulse, 12-pulse, etc),
- The characteristics and impedances of the connected power supply system

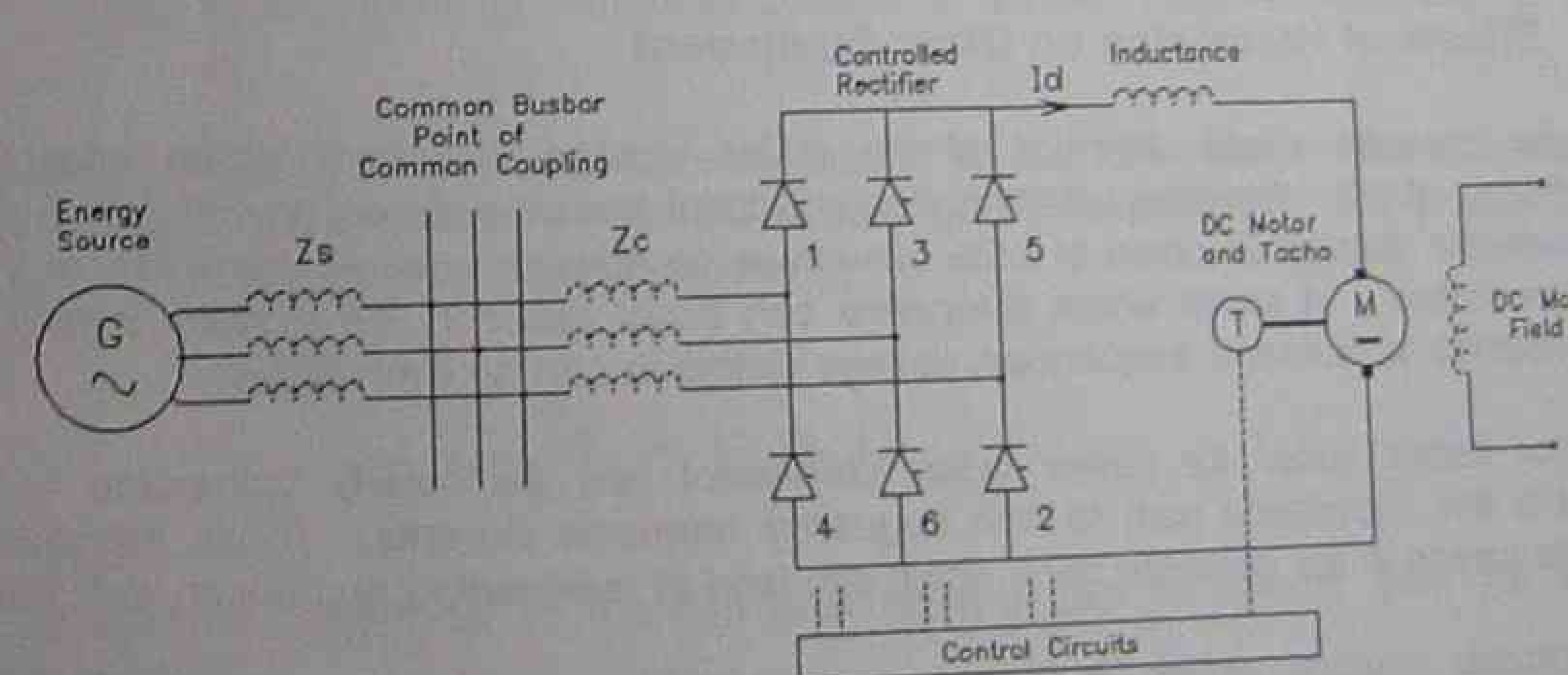


Figure 1.23 : The Sources of Harmonic Currents in a DC Converter

The main reason why power electronic converters draw harmonic currents is that the current is ***discontinuous*** in each phase. The main producer of harmonics in both AC and DC variable speed drives is the rectifier bridge connected to the AC power supply. From a harmonics point of view, it does not matter if the rectifier bridge comprises thyristors (controlled rectifier) or diodes (uncontrolled rectifier) ..... they both behave similarly. In the rectifier bridge, only two thyristors (or diodes) are conducting at any one time and the periods of conduction pass from one thyristor (or diode) to the next. Over the period of one cycle of fundamental frequency, each of the 3 phases of the power supply carries a pulse of positive current for a period of 120° and a pulse of negative current for a period of 120°.

These discontinuous phase currents combine on the DC side to result in a rippled DC current, which is usually smoothed by a choke in the DC circuit. Consequently, the rectifier can be considered to be a **source of harmonic currents**, which flow back into the power supply network impedance.

Power electronic converters do not generate all the possible harmonics, only certain harmonic currents. The harmonic order and magnitude of the harmonic currents generated by any converter depends on the following factors :-

- The Pulse Number (**p**) of the converter. The pulse number is the number of DC pulses produced at the output of the rectifier during one cycle of the supply voltage. The order of the harmonic currents that will be present can be predicted mathematically and is given by the formula :

$$n = k.p \pm 1$$

where :
- n order of the harmonics present
- k integers 1, 2, 3, ...
- p pulse number of the converter

- The magnitude of the load current, I_d on the DC side of the rectifier part of the converter affects the magnitude of the harmonic currents.
- The magnitude of the load voltage, U_d on the DC side of the rectifier part of the converter affects the load current.

1.8.4 Effects of Harmonics on Other Equipment

Harmonic currents cause distortion of the mains voltage waveform which affects the performance of other equipment and creates additional losses and heating. For example, a total harmonic voltage distortion of 2.5% can cause an additional temperature rise of 4°C in induction motors. In cases where resonance can occur between the system capacitance and reactance at harmonic frequencies, voltage distortion can be even higher.

Capacitor banks (used for power factor correction) are particularly vulnerable. They present a low impedance path to high frequency harmonic currents. These increase the dielectric losses in the capacitor bank which can lead to overloading and eventual failure.

Transformers, motors, cables, busbars and switchgear supplying current to converters should be derated (over-dimensioned) to accommodate the additional harmonic currents and the extra losses associated with the high frequency "skin-effect". Experience has shown that the current rating of transformers, cables, etc feeding 6-pulse converters must be derated by roughly 10% of the converter current and those feeding 12-pulse converters by roughly 5% of the converter rated current.

The electronic equipment used for instrumentation, protection and control are also affected due to the interference coupled into the equipment or communications cables. This affects the reliability and performance of the control system.

The mains supply current contains currents at the following harmonic frequencies :

$$f_n = (k.p \pm 1) \times f_1$$

where :
- f_n frequency of the nth harmonic component of current
- f_1 fundamental frequency of the supply voltage (n = 1)
- k integers 1, 2, 3, ...
- p pulse number of the connected converter

The following table summarises the harmonic currents that will be present in the following converter connections.

Converter Connection	Pulse Number p	Order of Harmonics n
1-phase, fullwave	2	3,5,7,9,11,13......
3-phase, halfwave	3	2,4,5,7,8,10.......
3-phase, fullwave	6	5,7,11,13,17,19....
Double 3-phase, fullwave one shifted 30°	12	11,13,23,25....

Figure 1.24 : Order of Harmonics present for different Converter Connections

The magnitude of the harmonic currents depend on the active power drawn by the load, which is directly proportional to the DC current I_d. For example, for a 3-phase, 6-pulse converter, the fundamental current is given by :-

$$I_1 = \frac{\sqrt{6} x I_d}{\pi} = 0.78\ I_d$$

The theoretical magnitude of the harmonic currents can be derived from the following simple formula :-

$$I_n = \frac{I_1}{n}$$

where :
- I_n the nth harmonic component of current
- I_1 the magnitude of the fundamental component of current
- n order number of the harmonic

For example, the theoretical magnitude of the harmonic currents in the mains, generated by a 3-phase 6-pulse power electronic converter will be :

- 5th Harmonic (250Hz) : 20.0% of fundamental current
- 7th Harmonic (350Hz) : 14.3% of fundamental current
- 11th Harmonic (550Hz) : 9.1% of fundamental current
- 13th Harmonic (650Hz) : 7.7% of fundamental current
- 17th Harmonic (850Hz) : 5.9% of fundamental current
- 19th Harmonic (950Hz) : 5.3% of fundamental current
- 23rd Harmonic (1150Hz) : 4.3% of fundamental current
- 25th Harmonic (1250Hz) : 4.0% of fundamental current
- .... etc .... etc

These theoretical values are based on ideal commutation and a ripple free load current on the DC link. These ideal conditions do not exist in practice and the magnitude of the harmonic currents depend on the design of the DC link filter and the type of converter. Manufacturers take great care to optimise these filters to keep harmonic currents as low as possible. The commutation improves the current waveform by reducing the higher frequency harmonics. The harmonic currents are also affected by the power system reactance, which tends to decrease them. Australian Standard AS 2279 Part 2 gives typical practical values based on measurement, which are generally lower than the theoretical values. However, the ripple in the DC link current tends to increase the 5th, 11th, 17th, ... harmonics and reduces the 7th, 13th, 19th, ... compared to the theoretical values. Figures published by a manufacturer for a 6-pulse converter confirm this. In practice, the theoretical values can be used as *worst case* values.

In practice, the total RMS current drawn by a variable speed drive is the square root of the sum of the squares of the harmonic currents.

For example, in a variable speed drive application, assume that the current drawn by the 3-phase 6-pulse rectifier at fundamental frequency (50Hz) is 100Amps. Using the theoretical values of harmonic currents listed above, the following harmonics and their current values will be :

- 20Amps (20%) at the 5th harmonic current (250Hz)
- 14.3Amps (14.3%) at the 7th harmonic current (350Hz)
- 9.1Amps (9.1%) at the 11th harmonic current (550Hz)
- etc ..... (ignoring harmonics above the 25th harmonic order)

Consequently, the magnitude of the total RMS current drawn by the VSD will be :

$$I_{RMS} = \sqrt{I_1^2 + I_5^2 + I_7^2 + \ldots + I_{25}^2}$$

$$I_{RMS} = \sqrt{100^2 + 20^2 + 14.3^2 + \ldots + 4^2}$$

$$I_{RMS} = 104.1 \text{ Amps}$$

1.8.5 Acceptable Levels of Distortion in the Mains Supply System

In the mains supply system, harmonic voltage distortion is the consequence of the flow of harmonic currents through the impedances in the power supply circuit connected to the converter. A typical power supply system at an industrial or mining plant consists of a source of AC power generation, which can either be a local generating station in a small system or a power station at the other end of a transmission line or transformer in a large system. The impedance between the "ideal" generator and the main busbar is usually referred to as the source impedance Z_s of the supply system. Additional impedance, usually comprising cables, busbars, transformer, etc. exists between the main busbar and the converter busbar and is the cable impedance Z_c, as shown in Figure 1.23.

The flow of current to a variable speed motor is controlled by the converter. The current is non-sinusoidal due to the non-linearity of the converter and the generation of harmonic currents. The flow of distorted current through the power distribution and supply system produces a distorted volt drop across the source and distribution impedances in series. Other equipment, such as electric motors or even other consumers can be connected to the main busbar. Consequently, this busbar is referred to as the ***Point of Common Coupling*** (PCC).

The voltage at the PCC will be distorted to an extent depending on the magnitude of the distorted current, the magnitude of the impedances and the ratio between them. The source impedance can easily be calculated from the system fault level and this is commonly used as the criteria for the permissible size of converter load. A high fault level means a low source impedance and vice versa. If the source impedance is low, then the voltage distortion will be low. The distribution impedance must be calculated from the design details of the distribution system. A high distribution impedance will tend to reduce the voltage at the point of common coupling but increase it at the converter connection terminals. This voltage distortion can cause interference with the electronic trigger circuits of the converter and give rise to other problems if it becomes too high.

If the magnitude and the frequency of each harmonic current is known, a simple application of Ohm's law will give the magnitude of each harmonic voltage and the sum of them will give the total distorted voltage.

From AS 2279-1991 Part 2, the *Total Harmonic Distortion (THD)* of voltage and current are given by the following formulae. Generally it is sufficient to use values of n up to 25.

$$U_T = \frac{100}{U_1}\sqrt{\Sigma_{n=2}^{n=\infty} U_n^2} \ \%$$

$$I_T = \frac{100}{I_1}\sqrt{\Sigma_{n=2}^{n=\infty} I_n^2} \ \%$$

where :

U_T	Total harmonic voltage distortion
I_T	Total harmonic current distortion
U_1	Fundamental voltage at 50Hz
I_1	Fundamental current at 50Hz
U_n	nth harmonic voltage
I_n	nth harmonic current

The acceptable level of harmonics in industrial power supply networks are clearly defined in Table 1 of the Australian Standard AS 2279-1991 Part 2 : *Disturbances in Mains Supply Networks*. Briefly, limits are set for the level of Total Harmonic Voltage Distortion, which are acceptable at the **Point of Common Coupling (PCC)**. The application of these standards requires the prior calculation of harmonic distortion at all points in the system before the converter equipment can be connected and, under certain circumstances, actual measurements of harmonic voltage to confirm the level of distortion.

1.8.6 Methods of Reducing Harmonic Voltages

The use of converters has many technical and economic advantages which will ensure their continued use in industrial and mining plants for many years ahead. In spite of the increase of harmonic distortion in power systems, their advantages far outweigh their disadvantages and their use will continue to grow.

As outlined above, harmonic voltage distortion at the Point of Common Coupling is the result of the flow of harmonic currents through the source impedance. On a *stiff* power system, where the source impedance is low, the voltage distortion will be low. On the other hand, the fault level will be high and the protection equipment will have to be rated accordingly. On a smaller power system, where the source impedance is high, the converter equipment should be connected as far downstream as possible away from the point of common coupling to effectively reduce the voltage distortion at the PCC. If this is not possible, an inductance (line choke) may be connected in series with the converter to effectively increase the impedance between the converter and the main busbar. Although this produces a high harmonic voltage drop and reduces the distortion at the PCC, the voltage distortion at the converter terminals will be high. Depending on the type of converter used, this can affect the converter control system. The line chokes need to be of special air core design and construction. A steel core cannot be used because this would produce excessive eddy current losses and the coils would overheat. For similar reasons, they should not be housed in steel cubicles but are usually left open and fenced off for safety. The inductance values are a few micro-Henrys but these can produce a significant inductive reactance at harmonic frequencies.

In general, there is not much that can be done to change the source impedance of a power system and, in difficult applications, the solution lies in the techniques to limit the source of the harmonic currents or to divert them to the system earth. There are two main methods of reducing harmonic currents :-

- The use of **multi-pulse converters**

  The use of converters of higher pulse numbers will greatly reduce the lower order harmonics. Alternatively, two converters of lower pulse numbers can be combined with a phase shift of 30° to produce a system of higher pulse number. Theoretically, 12-pulse converters will generate harmonic currents of the order (12k ± 1) and will not contain the 5th, 7th, 17th, 19th, ... harmonics. In practice, these do not disappear completely, due to slight differences in converter firing angles and unbalances, but are greatly reduced. The 5th harmonic current usually has the highest magnitude, so its elimination or reduction is desirable. This solution can be expensive.

When several similar converters, with controlled rectifiers, are connected to the same busbar, some cancellation of harmonic currents takes place due to phase shifts between the firing angle of converters running at different speeds. With PWM converters, with diode bridge rectifiers, very little cancellation takes place. The worst case should always be assumed for calculation purposes where the total current for each harmonic is the sum of the currents of the converters operating in parallel.

- The installation of **harmonic filters** close to the converter

  Harmonic currents may be diverted by means of shunt connected harmonic filters. The most common type of harmonic filters used in industry are series L-C filters with some damping resistance. Filters may be of relatively simple single-tuned construction, but are usually the more sophisticated (expensive), 2nd or 3rd order filters to provide a wider frequency band. The filter is tuned to a specific frequency so that its impedance is at a minimum at the tuned frequency. The harmonic currents generated by the converter equipment are short-circuited by the filter. The harmonic filter is "tuned" for a particular frequency when :

$$X_C = X_L$$

$$\text{or} \quad 1/jwC = jwL$$

One filter cannot provide filtering for a wide frequency range because it provides a sharp action for a narrow frequency band. Consequently, it is necessary to have more than one parallel filter to attenuate the troublesome frequencies. The filters are usually connected in delta (line-to-line) on a three phase system. The physical arrangement is similar to a conventional shunt capacitor bank and similar protection arrangements may be used.

The main problem with harmonic filters is that they can become detuned over a period of time for any one of the following reasons :-

- Changes in the filter capacitance due to age, temperature or failure of capacitance units within the bank.
- Changes in the inductance due to temperature and current
- Small changes in the system frequency

Since the overall reactance of the filter becomes capacitive at frequencies below the tuned harmonic frequency, resonance can occur between the filter bank and the power system inductance at fundamental or other lower frequencies. This possibility should be considered in the design of harmonic filter equipment to avoid resonance.

2

Chapter 2 : THE OBJECTIVES OF SITE EARTHING

2.1 The Objectives of Site Earthing

The main objectives of a good quality site earthing system are as follows :-

- To avoid physical damage to buildings and equipment due to direct or indirect lightning strikes and power system fault surges. The earthing system must provide a safe path for lightning and fault currents to flow into the body of the earth.
- To provide a safe working environment for personnel even during lightning strikes and power system faults. The "touch potentials" at metallic enclosures should be below the voltage level at which personal injury can take place.
- To provide shielding and an alternative path for induced currents to reduce the effect of coupled noise on electronic equipment.
- To provide an equipotential platform on which electronic equipment can operate and be safely interconnected without fear of large differential voltages, even when the equipment may be located in several buildings, separated by some distance.

Many aspects of the first objective were covered in Chapter 1. The second objective is covered in considerable detail in AS 3000-1991 : SAA Wiring Rules and is well known to most electrical engineers, technicians and particularly electricians. The third objective will largely be covered in Chapter 3, but will be expanded on in this chapter. The last objective is the more difficult to achieve and is the main subject of this chapter.

2.2 Categories of Earthing

Several different categories of earthing are commonly referred to in the context of earthing for industrial sites, large buildings and power supply installations. These are :

- Neutral Earthing
- Safety Earthing
- Signal Reference Conductor Earthing
- Screen Earthing

2.2.1 Neutral Earthing

Neutral earthing refers to the earthing of the **neutral point of the transformers for the power supply** to buildings, industrial sites, etc. Distribution transformers are usually connected in the delta-star (Dyn11 or Dyn1) configuration, with the neutral point on the secondary side solidly earthed to the substation earth electrode.

From a power supply point of view, ***neutral earthing*** is particularly important to prevent over-voltages on the phase conductors of the 3-phase power supply system during fault conditions. The neutral earth also provides a return path for earth fault currents, which

Although it is connected to earth at or near the transformer, the neutral is often isolated from earth at all other locations in the power supply system. In a balanced 3-phase power system, the neutral should ideally carry little or no current. But in practice, the neutral provides a path for a wide variety of 50Hz currents, resulting from single phase loads, and harmonic currents (mainly 3rd) from power electronic equipment, etc. In addition, the transformer is often a considerable distance from the building containing the electronic equipment. Consequently, the neutral can be a generous source of conducted noise.

Most electronic instrumentation and control equipment is powered from a single phase supply, so there is potential for conducted noise to gain entry to the electronic circuits via the neutral, unless it is isolated in some way through the power supply. In practice, it is more common to have a problem with a "noisy neutral" than with a "noisy earth".

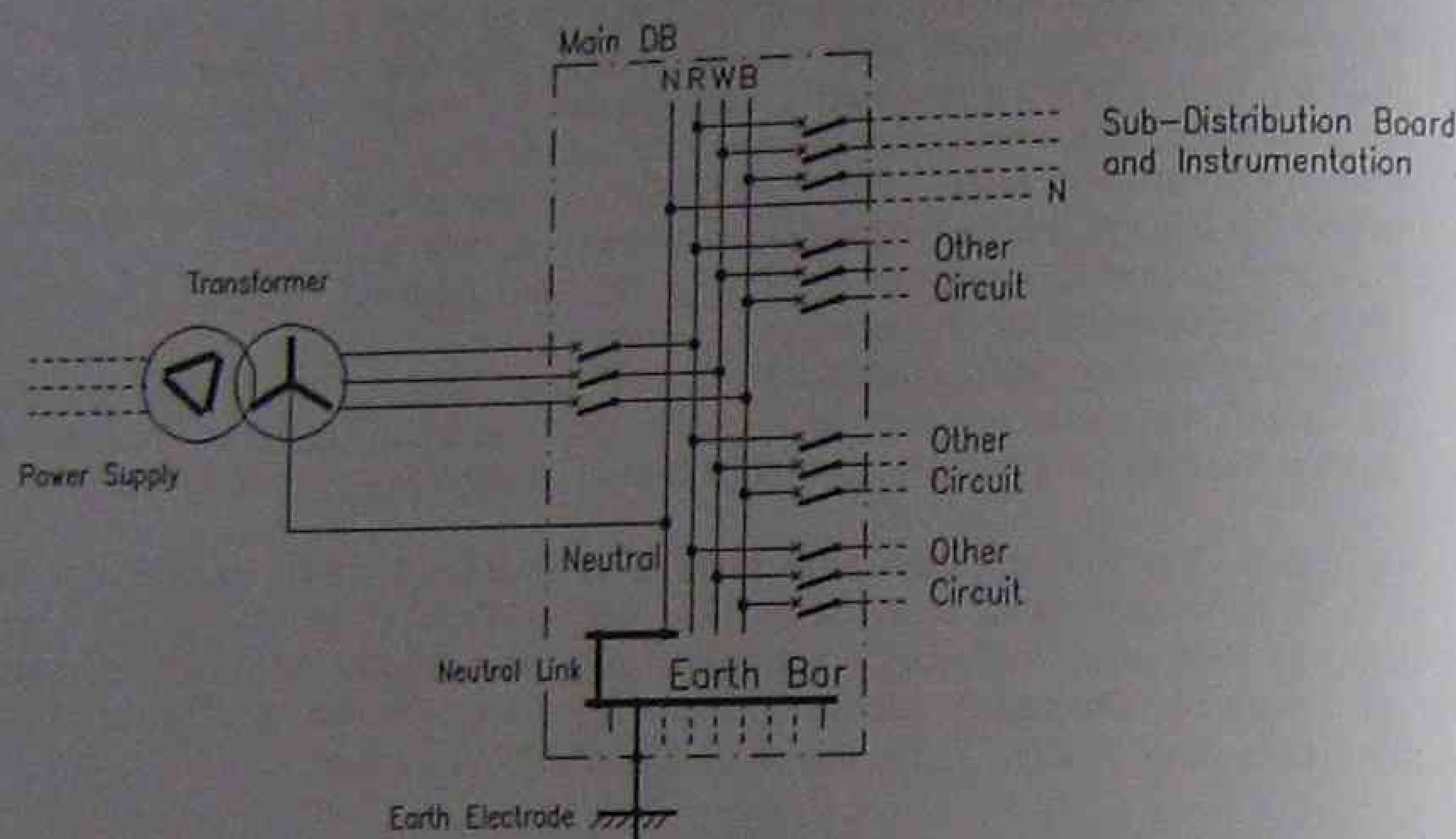


Figure 2.1 : Earthing of the Neutral of the Secondary Winding of the Transformer

(Note : An earthing system known as MEN (Multiple Earthed Neutral), where the neutral is earthed at several locations, is often used for domestic power supplies. This system is seldom used in industrial applications and will not be covered in any detail in this course. Refer to AS 3000-1991 : SAA Wiring Rules).

2.2.2 Safety Earthing

Safety Earthing is covered in considerable detail in AS 3000-1991 : SAA Wiring Rules and will not be covered in great depth here.

Essentially, most electrical equipment, such as electric motors, switchgear, control panels, distribution boards, motor control centres, etc are located inside metal enclosures. If one of the phase conductors accidentally makes contact with the enclosure, it would become "alive" for the period until the fault were detected by the protection and isolated. This situation represents a considerable safety hazard to personnel standing next to or touching the "live" piece of equipment.

Consequently, all exposed metalwork should be solidly connected to a safety earth conductor, which is further bonded to the building earth electrode (recommended) or bonded to an earth conductor provided by the supply authority. (Refer to AS 3000-1991 : SAA Wiring Rules).

All other metallic components such as cable ladders, cable trays and conduits should also be connected to the safety earth system. Consequently, these should be made electrically continuous across all joints and terminations and care must be taken to ensure that, where these metallic cable support and screening systems terminate at a distribution board or metallic enclosure, electrical continuity between them is ensured.

The symbol that will be used to indicate a Safety Earth is as follows :

This symbol represents the third conductor (green/yellow) in a single phase supply cable.

2.2.3 The Signal Reference Conductor

The earthing of the signal reference conductor has little to do with personnel safety, touch potentials or protection of equipment against lightning. Any decision to earth the signal reference conductor **should be made purely from the point of view of noise immunity.**

The purpose of the signal reference conductor is to provide a common reference plane for the small voltages associated with electronic equipment. This is particularly important if the equipment is required to transfer signals to other remote electronic equipment or if electronic devices are connected together by data communications cables. Some common reference plane needs to be established between them.

Galvanically introduced noise is directly related to the manner of earthing the signal reference conductor. Galvanically introduced noise can be minimised by earthing the signal reference conductor at **one end only**. There will still be some capacitive coupling at the non-earthed end, but this can be reduced by using a screened cable. This implies that balanced differential signal transmission, with the signal reference conductor earthed at one end only, is less noisy and preferable. However, the **signal reference conductor should NOT be confused with the cable screen**, which can sometimes be earthed at both ends.

Some practical examples of earthing of the signal reference conductor are outlined in the following three figures.

Figure 2.2 shows a typical serial data connection between two PCs using an unbalanced EIA/RS-232 connection. For simplicity, only the two data lines are shown (pins 2 and 3 on a 25-pin DB-25 connector). The third conductor is the signal reference conductor (common), which is connected to pin-7 in the comm-port. Internally, pin-7 is connected to the PC chassis, which in turn is connected to earth via the yellow/green safety earth connection in the power supply cable.

The two PCs are clearly galvanically coupled and, in addition, the earth loop via the signal reference conductor provides access for "noise" currents to flow through the cable. This problem would be aggravated if the two PCs are some distance apart and powered from different distribution boards. In this case, the electrostatic screen may as well be earthed at both ends, because the screen will carry some of the noise current and will also provide some protection from electromagnetically coupled noise. This type of connection, although common with PCs, is NOT recommended for reliable plant control systems.

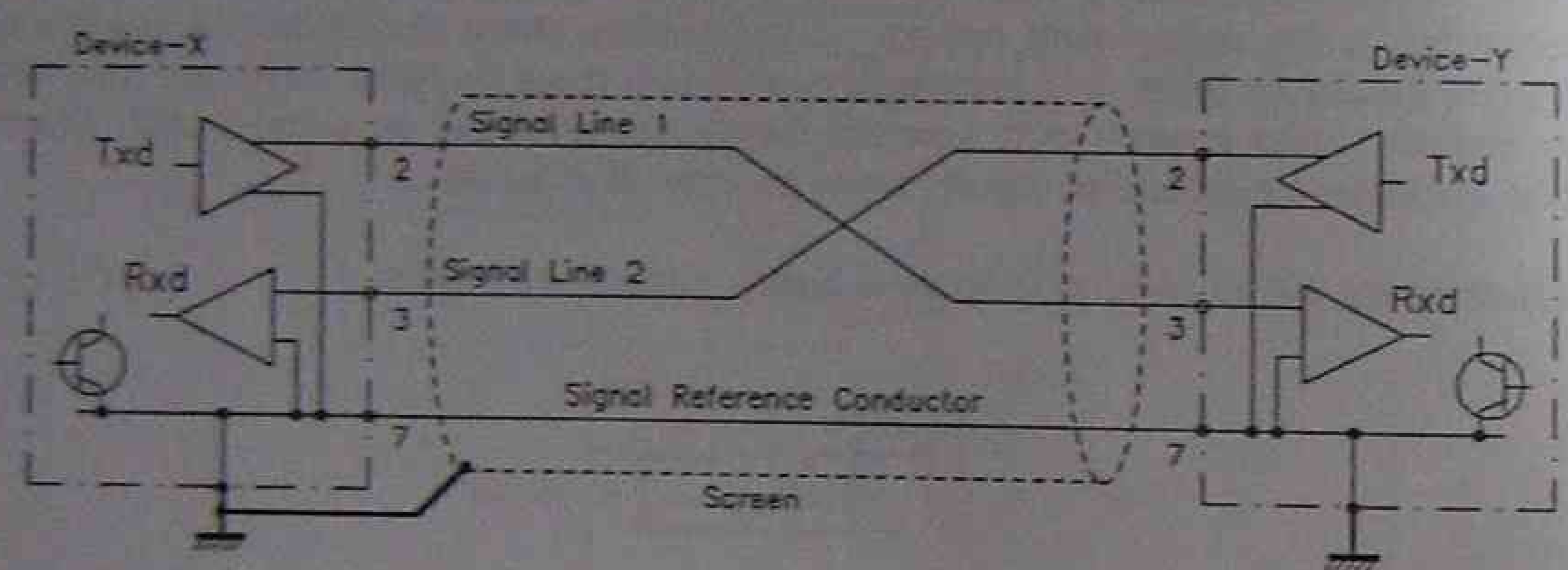


Figure 2.2 : EIA/RS-232 Serial Data Communications Link between two PCs using a Screened cable with the signal reference conductor earthed at both ends via Pin-7 on the Serial Port.

To avoid the earth loop problem, the signal reference conductor should be earthed at one end only and additional measures taken to avoid coupled noise. For example, the well known EIA/RS-422 and EIA/RS-485 interface standards have been developed for industrial environments and are often used with PLCs for industrial control. These standards use the balanced differential connection for bi-directional communications. In this connection, the signal reference conductor is still required between the two (or more) ends, to provide a common reference plane for the electronic equipment at the two ends .... but it is earthed at one point only. A typical connection is shown in Figure 2.3.

By earthing the signal reference conductor at one end only, the possibility of external currents circulating between the two ends via this conductor and introducing noise is removed.

Note that the screen earthing is a separate issue .... and will be covered in the next section. The electrostatic screen should be earthed at one end only, while the electromagnetic screen should be earthed at both ends.

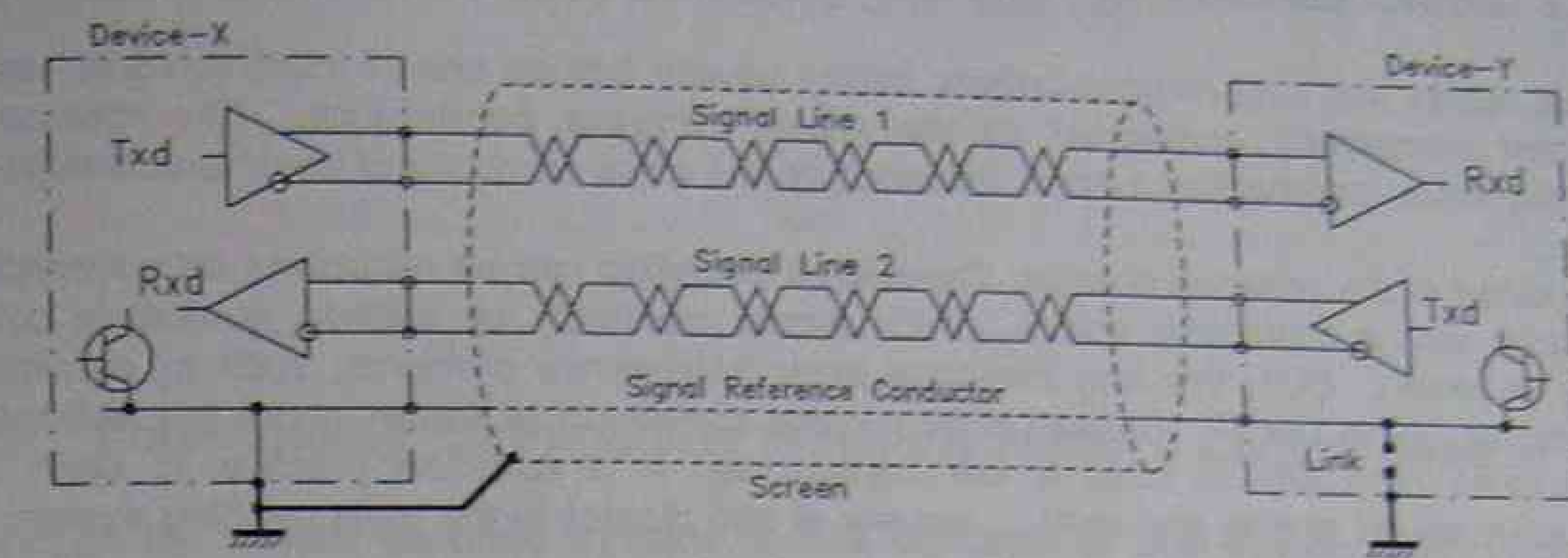


Figure 2.3 : EIA/RS-422 Serial Data Communications Link using a Screened Twisted Pair (STP) cable with the signal reference conductor earthed at one end only.

Another typical connection is the co-axial LAN connection or video connection. Here the electronic signal reference is connected to earth at both ends, the two ends are isolated from each other via a transformer. Once again, the electrostatic screen should be earthed at one end only, while the electromagnetic screen should be earthed at both ends. This is covered in the next section.

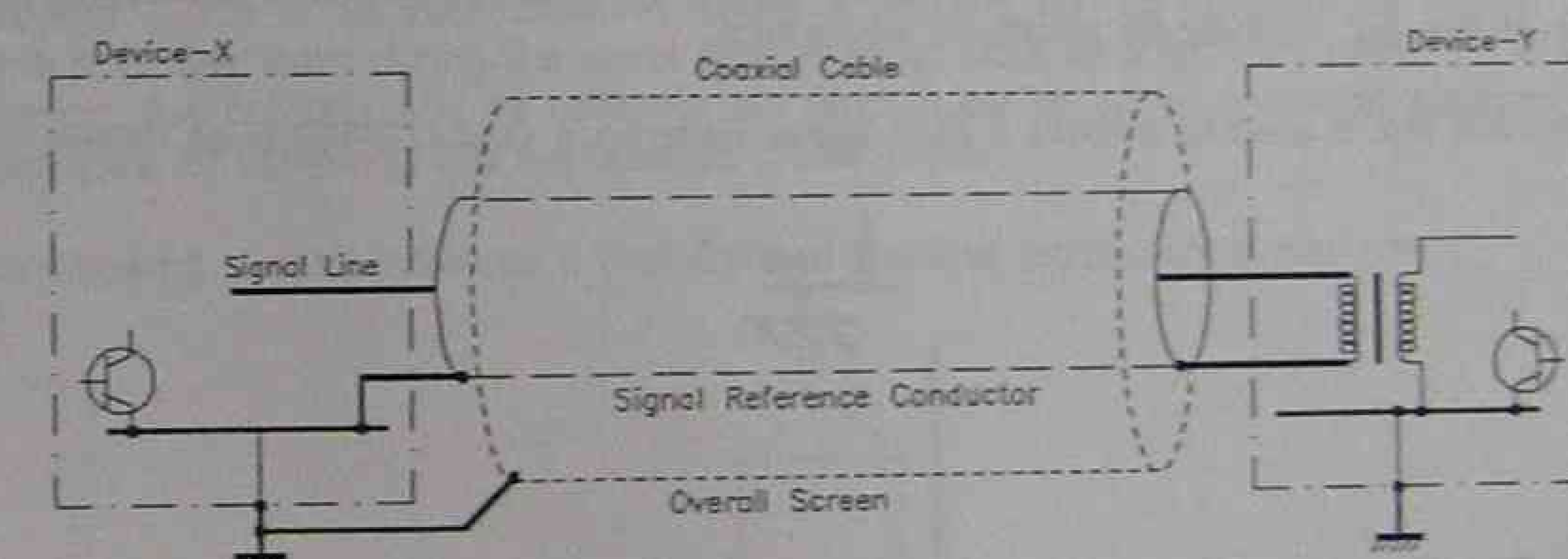
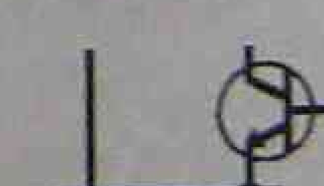


Figure 2.4 : LAN Data Communications Link with Co-axial cable

The symbol that is used to indicate a Signal Reference Conductor is as follows :



The inclusion of the transistor symbol emphasises that electronic circuitry is connected to this reference conductor. This is important for surge protection and noise immunity considerations.

2.2.4 Screen Earthing

Signal cables and data communications cables usually include one or more screens, *which are not electrically connected to the signal carrying conductors*. The method of earthing these screens has a major influence on the noise immunity of the interconnection.

As outlined in the previous chapter, ***Capacitive coupling*** can be minimised by surrounding the cable with a conductive screen, which should preferably be earthed at multiple points along its length. BUT, this may introduce other interference problems, such as circulating currents or "earth loops". Consequently, unless something is known about the alternative earth paths (KNOWN to have a low impedance), it is common practice to earth the conductive shield at **one end only** .... usually at end closest to the main earthing system.

As outlined in the previous chapter, ***Inductive coupling*** can be minimised by providing a conductive path (or paths), running parallel to the signal conductors, which is earthed at both ends AND at any other convenient locations. Suitable screening materials are metallic conduits, cable trays, cable ducts, cable ladders, etc.

The most important thing about screen earthing is that something MUST be known about the other alternative bonded paths between the two electronic devices .....
screen earthing must be coordinated with the rest of the earthing system.

From a screening point of view, the ideal environment for electronic equipment is within an equipotential surface on which the equipment is solidly bonded. This is usually approximated by a grid of conductors on or within the equipment room floor. In IEC 1024-1993, this is referred to as the Zero Signal Reference Grid (ZSRG) and represents ideal "state-of-the-art" earthing for electronic equipment.

The symbol that is used to indicate a Zero Signal Reference Grid (ZSRG) is as follows :

2.2.5 The Protective Earth

Another important concept is the **Protective Earth**, which is relevant to the installation of Surge Protection Units (SPUs). A SPU needs to divert surge currents and is usually solidly bonded to ***one of the above earths***, depending on the installation :

- If the Surge Protection Unit is mounted at a building entrance, then the *building earth* is used as the protective earth.
- If the Surge Protection Unit is mounted at a stand-alone item of equipment, then the *safety earth* is used as the protective earth.
- If the Surge Protection Unit is used in a zero signal reference grid (ZSRG) environment, then the *ZSRG* is used as the protective earth.

The symbol that is used to indicate a Protective Earth is as follows :

2.3 Coordinating Earthing and Shielding within a Control System

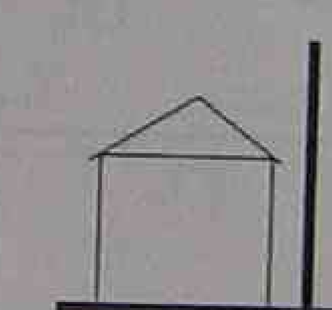
Although the **overall earthing system should be seen as one system**, the relationship between the different earths, defined above, is important to ensure adequate protection of the electric power system itself, the protection of operators and users, the protection of the electronic control equipment and the shielding of this equipment against noise.

It is also important to note that the behaviour of the earthing system will be different for various frequency ranges. For the first two types of earth, the 50Hz behaviour is probably most important. For the rest, frequencies from 50Hz up to the MHz range should be considered.

2.3.1 The Well Earthed Building

Before continuing, an additional symbol is introduced that represents a ***Well Earthed Building***. This is an ideal situation where a building and its contents all remain at the same potential, even during the worst type of surge such as a lightning strike. In this ideal situation, the building and its contents are said to be on an equipotential platform. The techniques for achieving this are outlined in this section.

The following symbol indicates a Well Earthed Building (equipotential platform) :



2.3.2 The Problem with Earth Coordination

The fundamental problem with earth coordination is the difference in voltage between items of electrical equipment during major surges, such as earth faults and lightning strikes. To illustrate the problem, assume that some electronic control equipment is situated within each of two buildings A and B, which are situated some distance apart. Initially, the earths of the two building are NOT intentionally connected, except through the body of the earth. The earth resistances of the two buildings are designated as R_A and R_B.

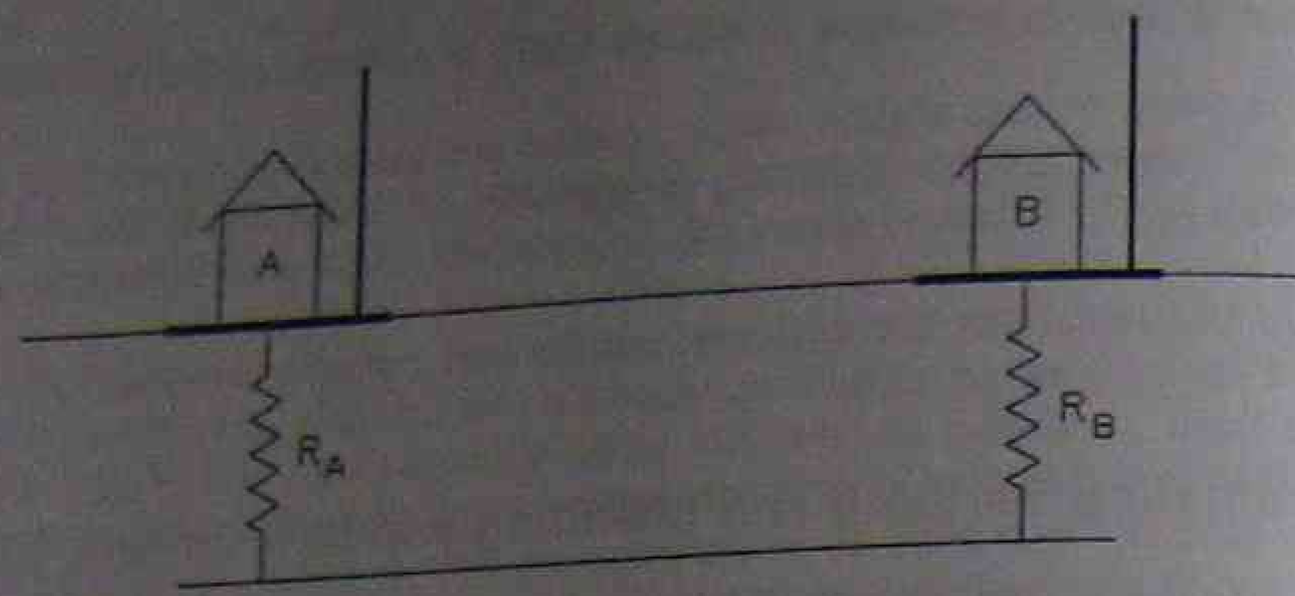


Figure 2.5 : Two separately earthed buildings A and B – no cable connection.

If building-A is struck by lightning (a very large current source) the building-A earth potential $V_A = I.R_A$ will rise to a large value relative to "true earth" reference potential V_{ref}. Since building-B has not been struck, no current flows through R_B the building-B earth potential V_B will remain at the earth reference potential V_{ref}.

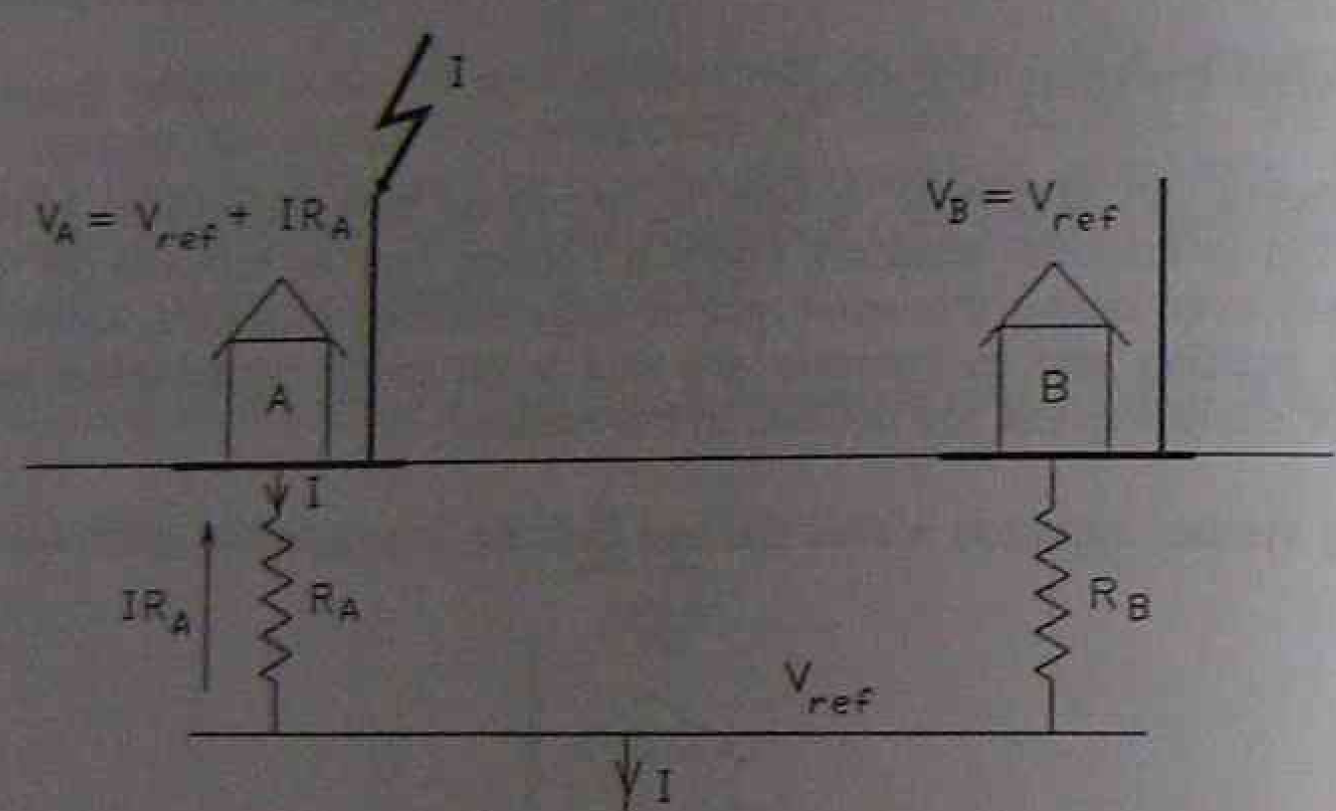


Figure 2.6 : Two separately earthed buildings A and B – no cable connection. Building-A struck by lightning

In this example, the existence of a large voltage difference between the earth bars of buildings A and B is irrelevant because they are not electrically connected in any other way. However, if a power cable or signal cable is run between the two buildings, the rise in potential at the building-A end of the cable, relative to building-B, could be several hundred kV and this could cause damage to the electrical equipment installed at either of the two ends of the cable.

The question is .... how should this problem be overcome?

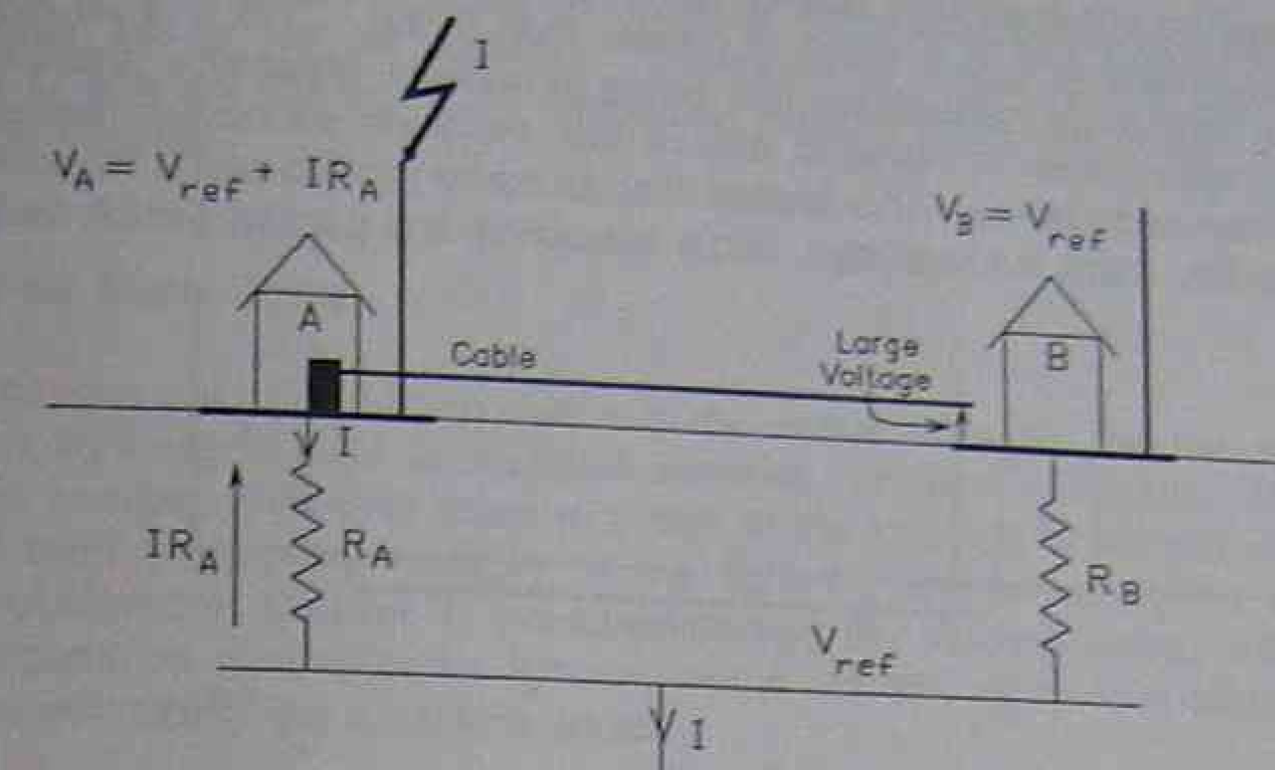


Figure 2.7 : Two separately earthed buildings A and B – WITH cable connection Building-A struck by lightning

The problem and solution is very similar to the easily visualised situation where a ship must transfer some cargo to another ship floating nearby in heavy seas. What should be done to ensure that the cargo transfer can take place without damage to the ships or the cargo? This is the well known ***Two Ships Analogy.***

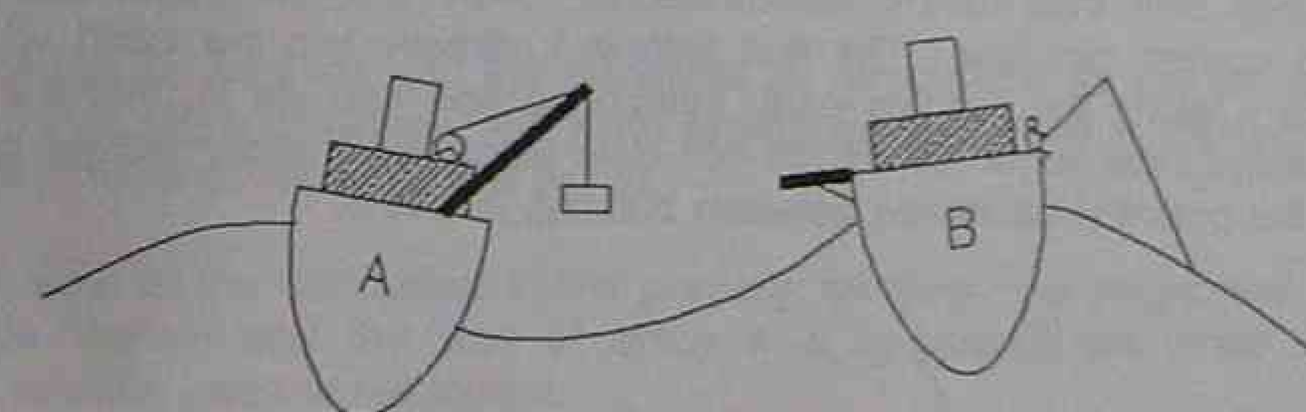


Figure 2.8 : The Analogy of the Two Ships

One solution would be to clamp both ships firmly to the sea bed to prevent them moving relative to one another during the transfer operations. Although possible, this is NOT a practical solution.

Another solution would be to clamp the two ships together with as many ropes and chains as possible to prevent ***relative movement*** between the two ships during the cargo transfer operations. This is a far more practical solution and is the technique commonly used in these situations. Although this solution does not prevent all relative movement, it is reduced to small manageable magnitudes.

This solution is similar to what has been found practical for **building and plant earthing**. To avoid large potential differences between the earths of separate buildings, their earths must be tightly interconnected through as many conductive paths as possible.

Usually, this can be achieved with copper conductors (trench earth ... with cross-sectional area of at least 50mm² and to a depth of greater than 0.5m). This is a far more practical and successful solution in comparison with trying to achieve impossibly small values of R_A and R_B. Every effort must be made to ensure that the earth connection between the two buildings is of **low impedance**. This implies that as many parallel paths as possible should be used .... conduit, cable ladders/trays, cable armouring and parallel trench earths.

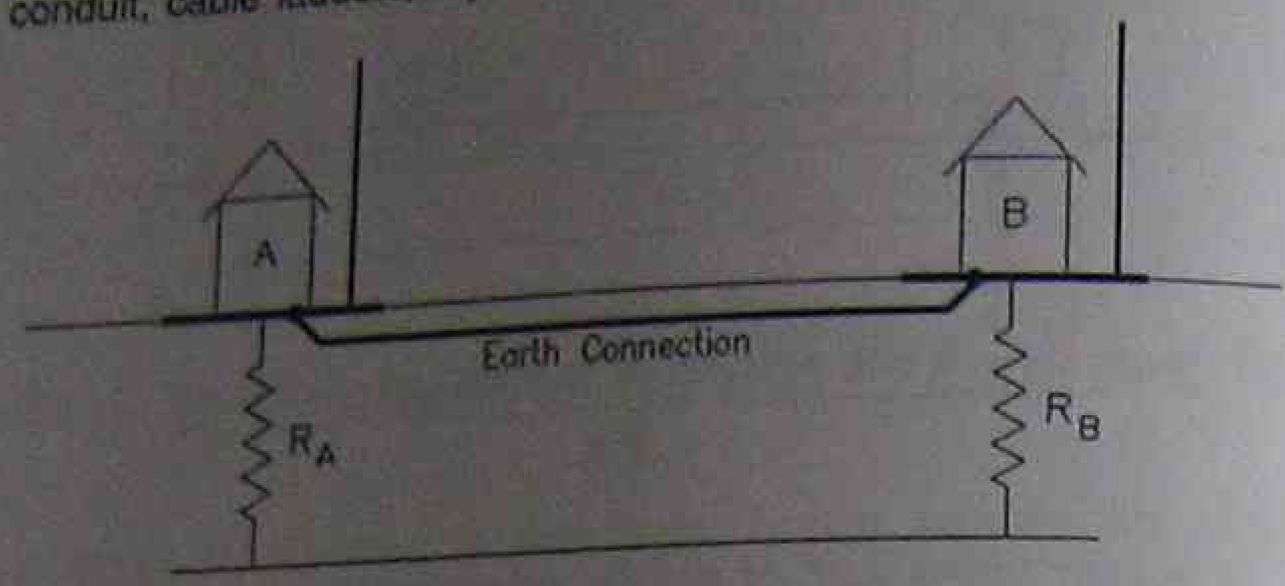


Figure 2.9 : The Earth Interconnection between Two Buildings or Structures

2.3.3 The Importance of a Low Resistance Earth

The above examples may have suggested that R_A and R_B need not be low values. This is not necessarily true. Earth resistance should always be as low as practically possible.

To clarify this, the aspect of current division must be considered. In the example above of the two buildings with their earths interconnected, there are *two paths* along which the lightning/surge current can flow. The first path is I_1 directly into the earth via R_A and the second path is I_2 along the building earth interconnection and via R_B into the earth. The larger the current I_2, the larger will be the volt drop along the interconnecting cable and the larger will be the potential difference between building A and B.

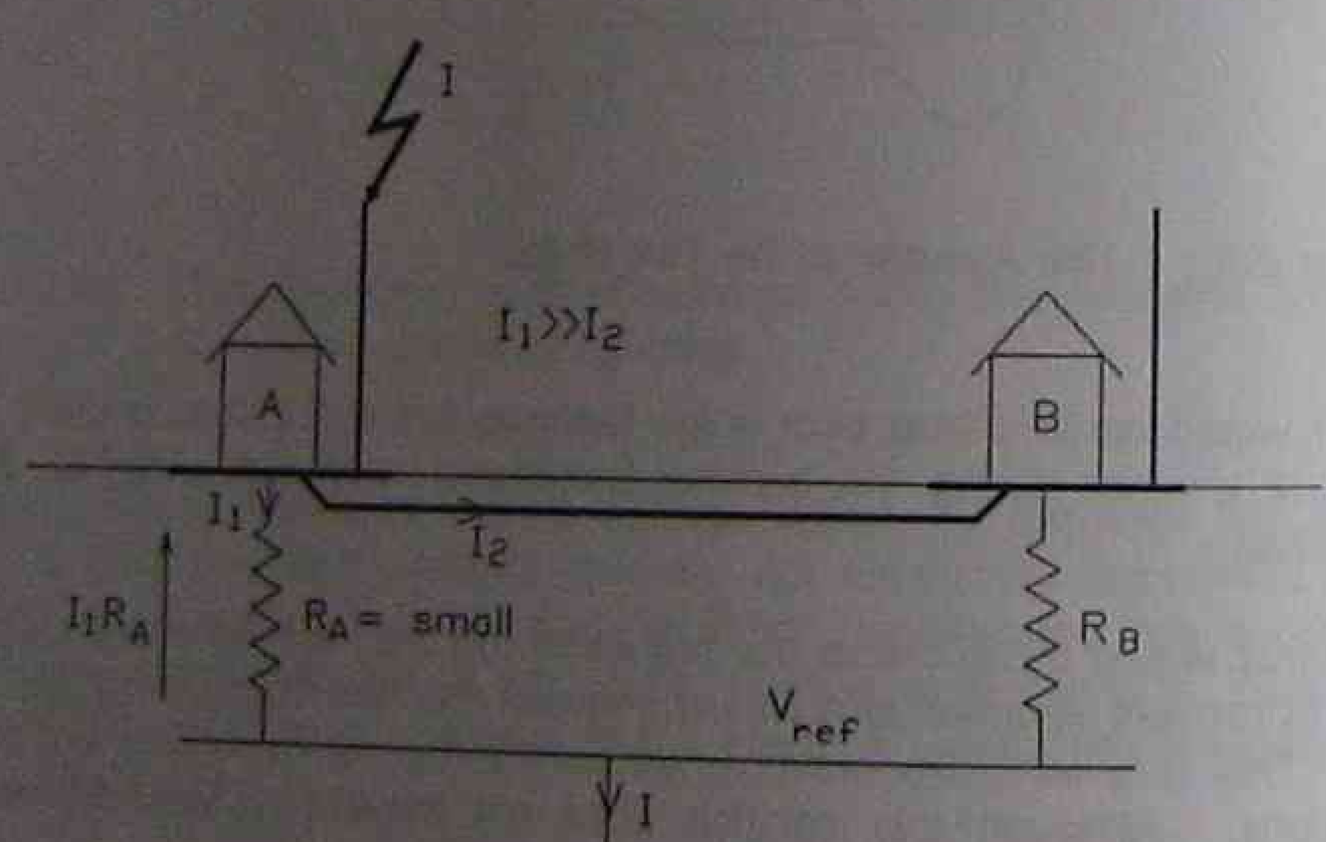


Figure 2.10 : The Importance of a Low Earth Resistance

To minimise the current flow I_2 along the building earth interconnection, the values of R_A and R_B should be as low as possible. Consequently, most of the current should be encouraged to flow into the local (low resistance) building earth with as low a building earth voltage V_A as possible.

2.3.4 The 50 Metre Rule

By interconnecting the two building earths in the above example, the net earth resistance seen by the lightning current is reduced because the two resistances R_A and R_B are connected in parallel. However there is a limit to the lowering of the net earth resistance due to the finite propagation velocity of the lightning current along the interconnecting cable. As explained in Chapter 1, the *inductance* of the interconnecting cable is the most important impedance parameter for lightning surge current, which is a steep fronted wave and behaves something like a ±10kHz wave.

If the two buildings are sufficiently far apart, such that it takes the lightning current 10μs to make the round trip (there and back), then for the first 10μs of the lightning stroke the resistance R_B does not contribute to the net earth resistance seen by the lightning current.

This has led to the "rule of thumb" known as ***The 50m rule*** :

> ***When determining the earth resistance seen by the lightning current, consider only earth electrodes within 50m of the prospective point of strike.***

2.4 The Earth Electrode

Codes of practice on earthing and the standards all recommend as low an earth resistance as possible. For safety purposes, the earth resistance should be < 10Ω and many supply authorities recommend values as low as 1Ω.

However, in view of the discussion in the previous sections, the shape and dimensions of the electrode system and the way in which it is connected are more important than achieving a specific value of resistance.

From the viewpoint of lightning protection, a single integrated structure earth electrode system, as opposed to the concept of a separate 'clean' earth, is preferable.

The four most common types of earth electrode are as follows. These are covered in more detail in Appendix B.

- Vertical driven rods
- Ring trench earth around the perimeter of a structure
- Radial conductor electrodes (crow's foot)
- Foundation reinforcing steel electrode

Considerable care must be exercised in selecting the correct type, size and material for earth electrodes. Guidance is given in both the national (AS 1768-1991) and international standards (IEC 1024.1-1990). Tables have been included in Appendix B which summarise these recommendations. IEC 1024.1 recommends that earth electrode should be made of copper or steel with copper ≥ 50mm² and steel ≥ 80mm².

2.4.1 Trench Earths vs Driven Rods vs Foundation Reinforcing Steel

Ideally, earthing systems for buildings should include both driven rods (> 16mm diameter copper rod driven vertically into ground to depth of more than 2m) and trench earths (buried copper conductor with minimum cross-sectional area of $50mm^2$ and depth of 0.5m). The reason is that the advantages of both methods are then combined.

The main advantages of vertical driven rods are :

- Higher soil ionisation for lightning surges resulting in a smaller final earth resistance. This is a slow effect (about 5μsec).
- Provides access to more moist (and hence lower resistivity) soil at deeper levels. However, very long rods do not necessarily mean much lower impedance. The inductance needs to be considered as well.

The main advantages of trench earths are :

- Lower transient impedances for lightning surges (ratio of voltage to current during transient conditions) as a result of the two parallel paths at the connection point. This is an immediate effect.
- Provides easier installation in presence of rocky ground

The steel reinforcing in the building foundations should not be ignored as method of making a very good earth connection. Concrete is hygroscopic (absorbs moisture) and thereby ensures a good electrical connection between the steelwork and the surrounding soil. Building regulations generally exclude the use of reinforcing bars (rebars) for the conduction of currents. However, this exclusion is specifically aimed at the use of reinforcing bars (rebars) for the conduction of power frequency (50Hz) currents. This does not necessarily apply to the effects of natural phenomena such as lightning or EMI. When lightning strikes a building, the building regulations will not prevent a portion of the lightning current flowing in the rebars!

In any earthing system, a combination of the various types of electrodes to suit the local conditions is usually most appropriate.

- The lower surge impedance of trench electrodes is an advantage during the first stages of lightning current discharge.
- The soil ionisation associated with spike (rod) electrodes provides a lower earth resistance in the later stages of lightning current discharge.
- Each metallic electrode placed in the soil, such as the driven rods, trench earth and building reinforcing, when connected in parallel, will contribute to a lower overall earth resistance.

A situation sometimes arises where a building inadvertently has two earthing systems, for example, a power/safety earth and separate low impedance electronics earth ("clean" or "instrument earth"). When lightning strikes, most of the lightning current will take the shortest path and will flow into the low impedance earth. For this reason, amongst others, all earth electrodes should be interconnected to form a single equipotential earth platform.

2.4.2 Site Building without an External Lightning Protection System

A situation often arises where a building, which does not have an external LPS (Lightning Protection System), must be included into the site equipotential platform.

If a power supply earth or safety earth exists at the building and it meets the requirements of a lightning protection earth (< 10Ω) then this earth should be used as the bonding point of the LPS (Lightning Protection System).

If no earth point exists at the building, then either one should be installed or the building metalwork should be bonded and used as the bonding point for the lightning protection.

2.5 Steps in Designing an Earthing System for a Structure

The following step-by-step approach to site earthing can be followed in most cases :

Step 1 : **Install the Trench Earth**

- Bury a trench earth around the perimeter of each building.
  - Depth of trench earth : > 0.5m
  - Distance from building : not closer than 1m from the walls (or in building foundation)
  - Preferred earth conductor : Copper, $\geq 50mm^2$ or dia $\geq$9,5mm (or 30x3mm, or 50x3mm copper strip), building reinforcing steel
- For a mast, a "crow's foot" trench earth arrangement is preferred with length of radials $\geq$30m and number of radials $\approx$8.
- For a small structure, at least two down conductors, each connected to its own earth electrode (driven rod) should be used.

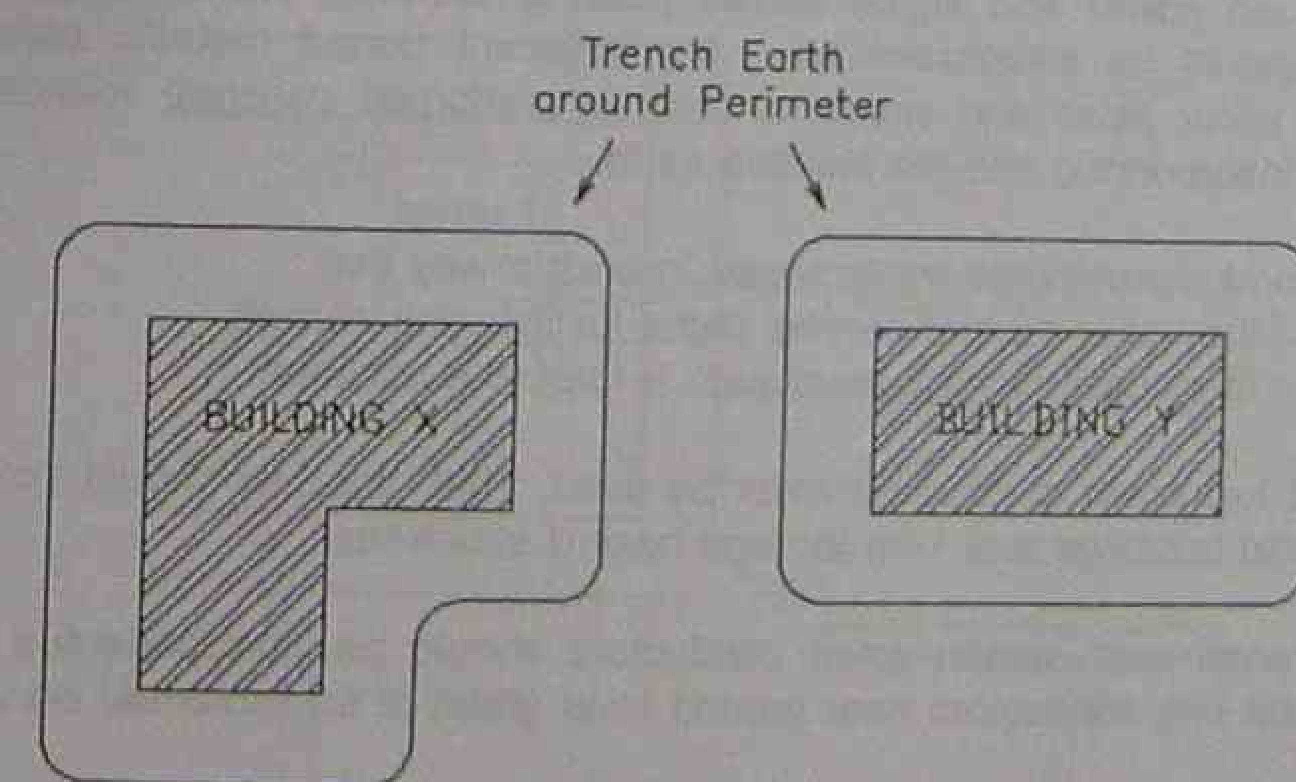


Figure 2.11 : Install Trench Earths around perimeter of Buildings

Step 2 : Install Driven Rods

- Place additional driven rods at regular intervals along the trench earth.

  - Recommended distance between driven rods : 2 to 10 times rod depth ($\leq$10m)
  - Depth of driven rods : 2m to 3m (exceeding 2,5m in only very special cases)
  - Preferred rod material : Copper, galvanised steel or stainless steel (minimum 50mm^2)

- A trench earth electrode can be used without additional driven rods.

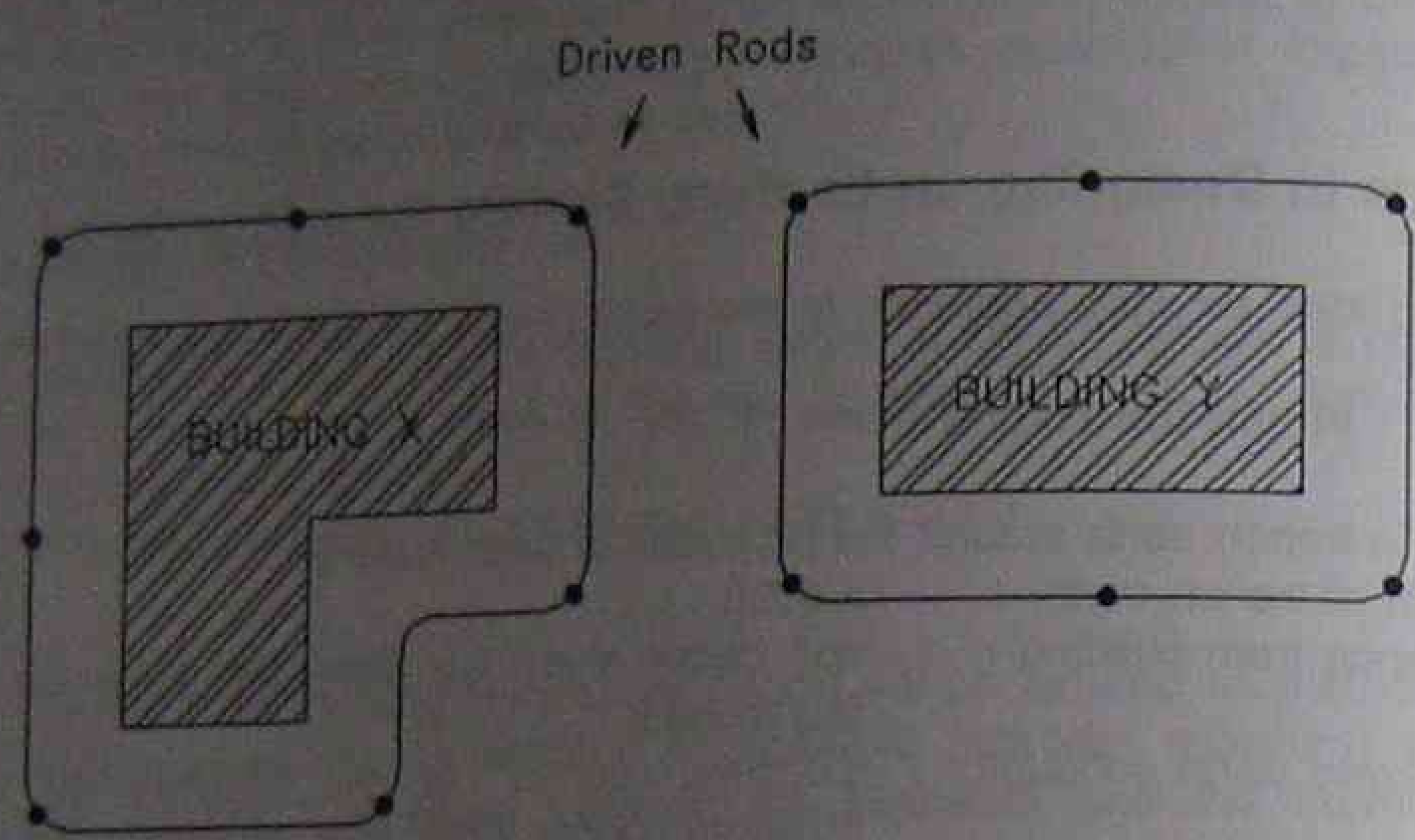


Figure 2.12 : Install Driven Rods in combination with Trench Earths

Step 3 : Bonding of the Earth Electrode to other Components

- If there are power and signal cables passing between the buildings, the building earths should be interconnected. Any adjacent buried metallic objects such as metallic water pipes and structural steel in reinforced concrete foundations should also be incorporated into the building earth.

- Down conductors should be arranged in such a way that :
  - they offer several parallel paths for lightning current
  - the length of the current path is kept to a minimum

- At least two down conductors must be used. Their spacing should not exceed 25m for normal buildings and 10m for high hazard structures.

- If no trench earth exists, down conductors should be interconnected by means of horizontal ring conductors near ground level (point of equipotential bonding).

- Natural components, such as I-beams, metal sheeting, pipes, re-enforcing can form part of the down conductor, provided they are bonded to the air terminal. Horizontal ring conductors are not necessary in metal frame or reinforced buildings.

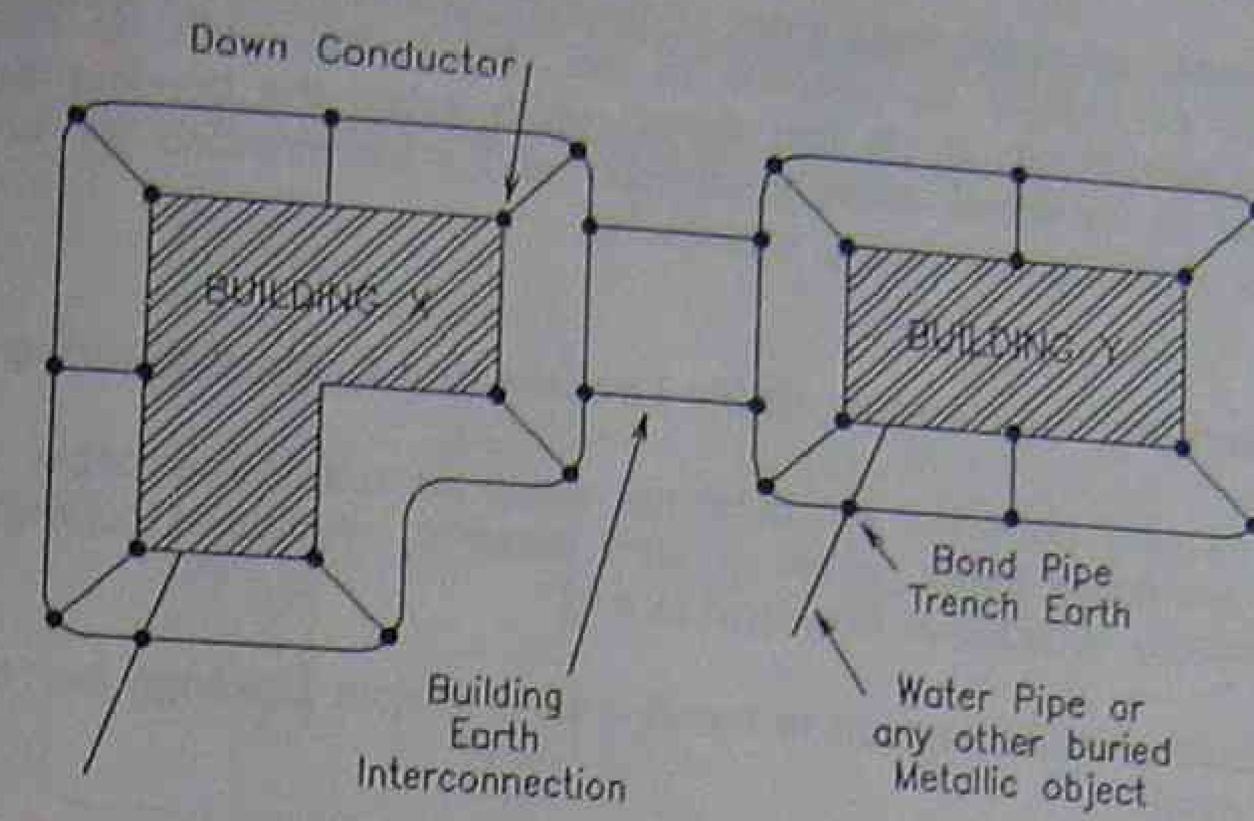


Figure 2.13 : The addition of Bonding between Buildings and Structures

Step 4 : Define Bonding Bars for Equipotential Bonding

- Define bonding bars for equipotential bonding at each building where more than one point of entry exists, ensure that bonding bars are themselves interconnected.

- Bond any external metalwork to the building earth (metal walkways, chimneys, framework).

- The bonding bar should be connected as closely as possible to the earth electrode as well as building metalwork, reinforcing, etc.

- Use bonding material dimensions in accordance with IEC 1024.1–1990.

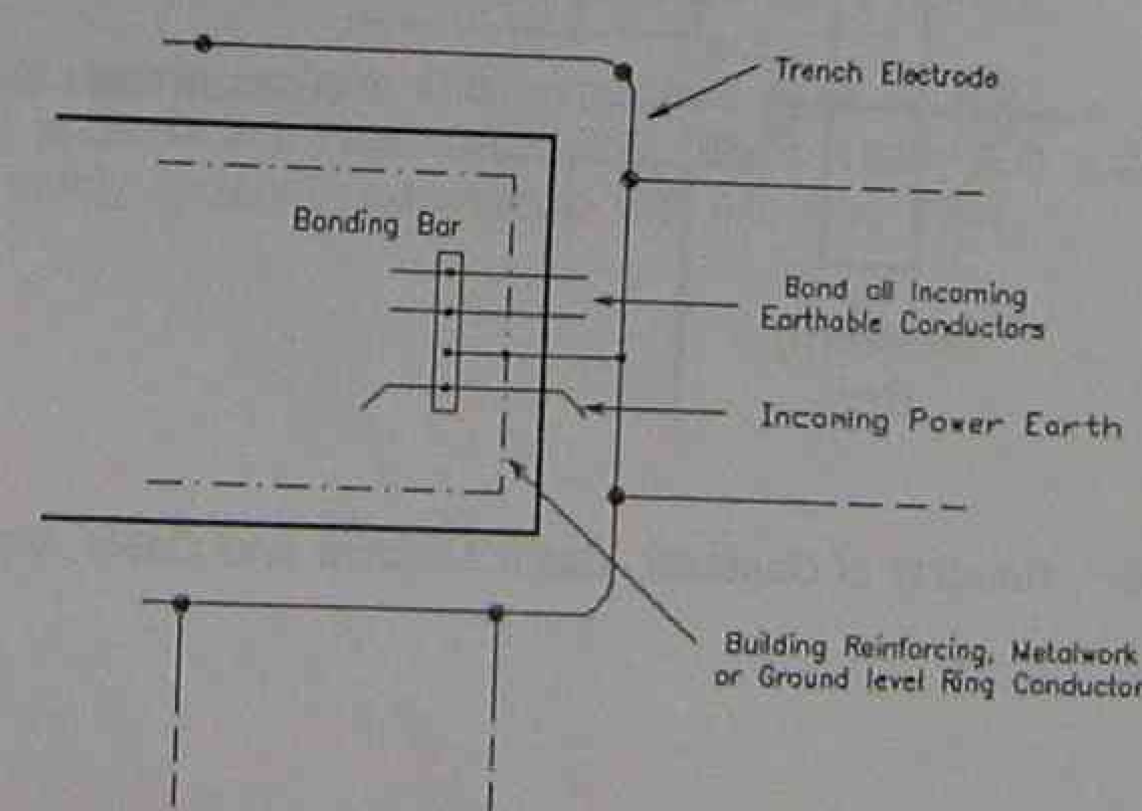


Figure 2.14 : Definition of bonding bars for equipotential bonding

- When power and signal lines enter at different locations the bonding bars should be connected as closely as possible to the ring trench earth as well as building metalwork/reinforcing. If no ring trench earth exists the bonding bars should be connected to individual earth electrodes and interconnected by an internal ring conductor (building reinforcing, metalwork)

Step 5 : Bonding the Conduit, Cable Ladders and Cable Armouring

- Cables running between the buildings must be run inside cable ducts such as conduit, armoured cable, cable support systems, reinforced concrete ducts which are electrically continuous from end to end.
- Cable ducts must be bonded to bonding bars at both buildings (= 16mm² copper or 50mm² steel).
- It is recommended that power and signal lines enter the structure at the same location.
- Cable runs between buildings should be near to ground level and preferably buried.

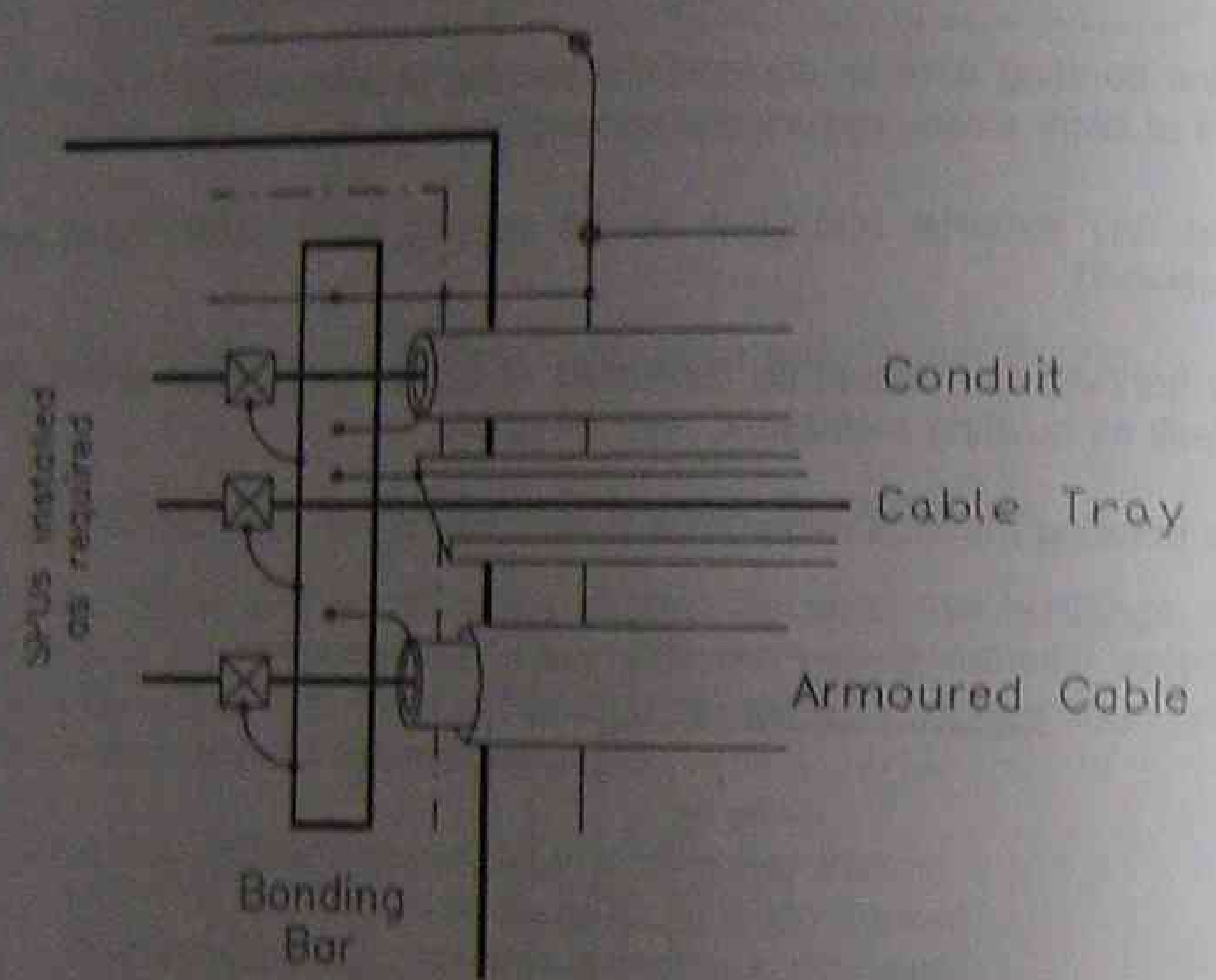


Figure 2.15 : Bonding of Conduits, Cable Ladders and Cable Armouring

Step 6 : Bond all Metallic Components inside the building to the Bonding Bar

- Metallic components inside the building must be bonded to the bonding bar

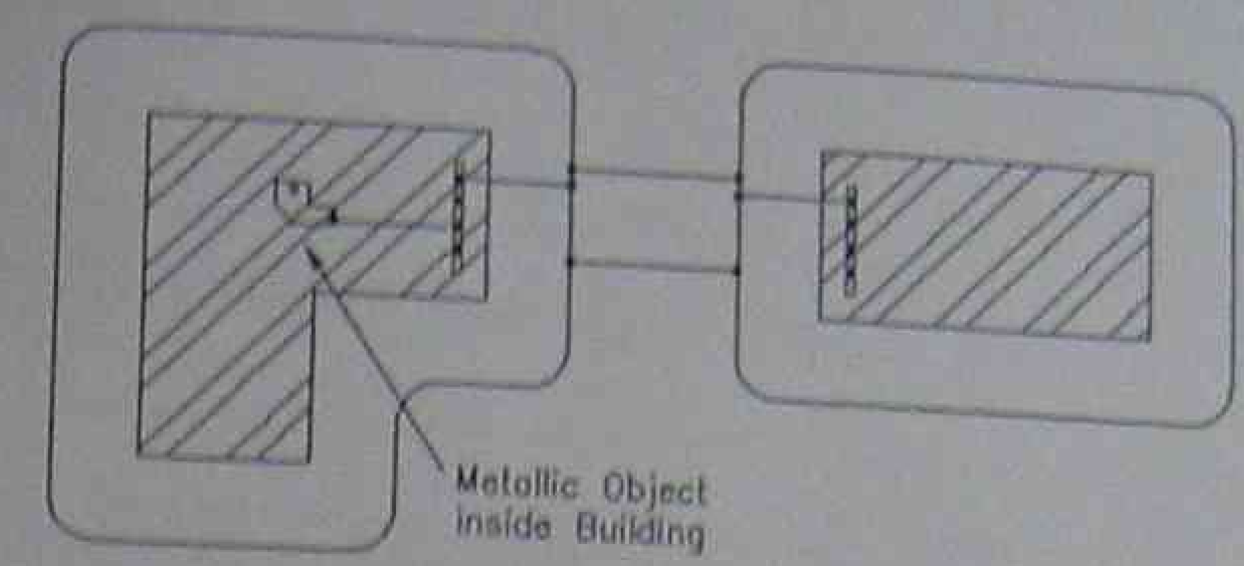


Figure 2.16 : Bonding of Metallic Objects inside a Building to the Bonding Bar

2.6 Concluding Comments on Site Earthing

- The overall objective in designing building earthing is to create a ***single equipotential platform*** on which electronic equipment can safely operate.
- Minimising the earth resistance is less important than ensuring that during a lightning strike all buildings rise in potential equally so that there is no differential voltage between the earths of adjacent buildings. This would stress signal and power cabling running between the buildings.
- To avoid large currents through the building earth interconnections the individual building earth resistance should still be a low value (< 10Ω).
- Bonding of metallic objects and conductors must be done in accordance with the standards such as AS 1768-1991, IEC 1024.1-1990, IEC 1024.1.1-1993 and the electrical safety system in accordance with AS 3000-1991.

Blank Page

Chapter 3 : **COUPLING OF INTERFERENCE INTO THE ELECTRICAL SYSTEM**

3.1 Introduction

It is not practical to completely eliminate disturbances, which are associated with lightning surges, power system faults and harmonics, from the electronic equipment. The cable installation and the treatment of the cable screens, armouring and earthing have a major influence on the level of interference, particularly when electronic equipment is connected over long distances in a noisy industrial environment.

This chapter covers the mechanism by which the surges are coupled into the electronic circuits and how the coupling can be minimised by the correct design of the earthing and shielding system. However, the discussion in this section is limited to lower frequency fields, such as those produced by lightning events, switching surges, fault currents and other mains frequency phenomena such as harmonics. This analysis does not cover RFI.

The analysis is valid where the wavelength of the disturbance field is longer than twenty times the length of the conductors under consideration.

Frequency	Wavelength	Length of Conductor
(1) 50Hz	6000km	300km
(2) 10kHz	30km	1.5km
(3) 1MHz	300m	15m
(4) 10MHz	30m	1.5m

(1) Power System phenomena (faults, harmonics, switching, etc)
(2) Lightning phenomena
(3) & (4) RFI

The surges and interference can be coupled into the electronic control system via one or more of the following three mechanisms :

- Galvanic (resistive) coupling – direct electrical connection
- Capacitive (electrostatic) coupling – electric fields
- Inductive (magnetic) coupling – magnetic fields

However, before analysing the mechanism of interference coupling, it is necessary to review the main differences between "unbalanced" and "balanced differential" signal lines. This will highlight the substantial difference in noise immunity between these two techniques. The methods of earthing the signal reference conductor are also different for the two connections.

3.2 Unbalanced and Balanced Signal Lines

3.2.1 Unbalanced Signal Connection

In simple data communications systems, such as those using the EIA/RS-232 interface standard, the connection is said to be "unbalanced" because only one conductor carries the signal voltage, with reference to a "common" signal reference conductor. In American terminology, this common wire is sometimes called the "signal ground".

The Figure 3.1 shows an example of an EIA/RS-232 interface connection between two devices comprising a transmit channel, a receive channel and two "control lines" (often called "handshaking" lines).

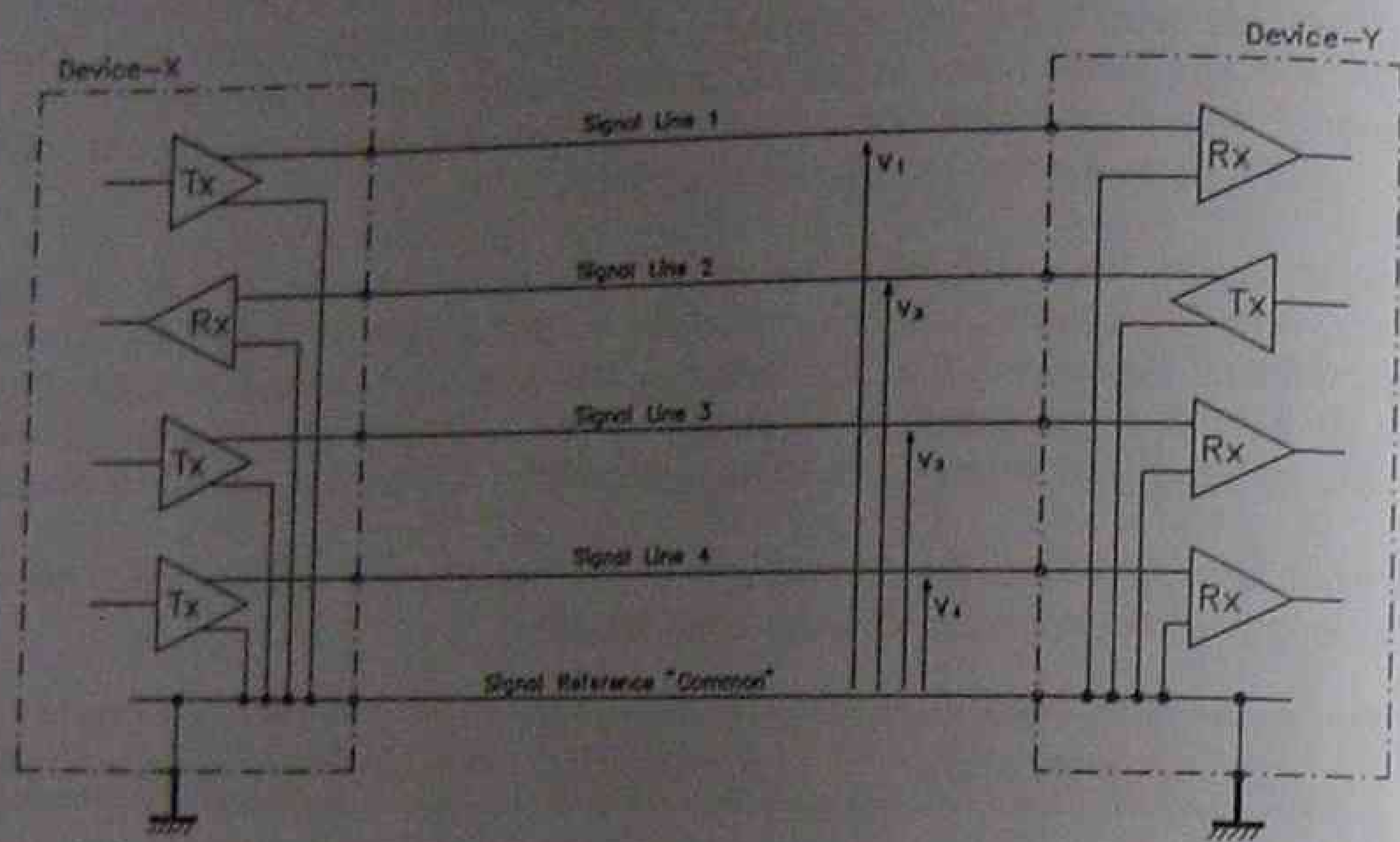


Figure 3.1 : Data Communication using the Unbalanced Signal Connection

In the EIA/RS-232 unbalanced connection, the data signal is the voltage between the signal conductors and the common signal reference conductor, for example V_1, V_2, V_3 and V_4 in the figure above. The signal reference conductor is simultaneously shared by the signals on several channels. Theoretically, unbalanced data transmission should work quite well if the signal currents returning on the common are small. In practice, it does ... but it is used mainly for communication links over relatively short distances (15m to 100m for RS-232) and at relatively low data speeds (up to ±100kbps). This current in the common depends on a number of factors, such as the line driver voltage (5V to 25V for RS-232) and the resistance of the receiver (3k to 7k for RS-232). The volt-drop on the common conductor then depends on its series resistance and inductance.

There are two main problems with the unbalanced connection :

- The common signal reference conductor is not a perfect reference point, because it has characteristics similar to the other conductors, i.e. resistance, inductance and capacitance. So for long communication distances, the common conductor does not have the same "zero" voltage at all points along its length or at its ends. In this way, the signal from one channel can be partially coupled to another channel through the impedance of the common. This is known as "impedance coupling".

- This configuration is also more susceptible to ***coupled noise*** than the balanced connection described below, because the effects of electrostatic and electro-magnetic coupling cannot be reduced by twisting the signal lines together. Although the conductors in unbalanced cables are generally spiralled together, each channel has only ONE conductor associated with it, so twisted "pairs" are not practical. Consequently, the signal voltage will have other externally induced voltages superimposed on it.

The signal voltages measured at the receiver end of the cable is the sum of :

- The original signal voltage from the line driver
- The externally coupled noise voltage
- The volt drop associated with the common signal reference conductor

An overall screen, usually earthed at one end, can be used to shield this type of cable from electrostatic coupled noise.

3.2.2 Balanced Signal Connection

Data communication interfaces, such as those using the EIA/RS-422 or EIA/RS-485 interface standards, require **two** conductors for each signal. The signal voltage for each channel is the ***voltage difference*** between the two signal wires (e.g. V_{AB}), hence its name .... balanced differential system. Although a balanced connection still requires a reference conductor to provide a common reference for the two (or more) electronic devices at the ends of the signal cable, this reference conductor is NOT used for signal transfer.

- **Differential (Transverse) Mode Voltage**
  This is the voltage measured between two signal conductors, which are isolated from the *signal reference conductor* ("common") ..... this is the "Signal Voltage".
- **Common Mode Voltage**
  This is the voltage measured between the signal conductor and *signal reference conductor* ("common").

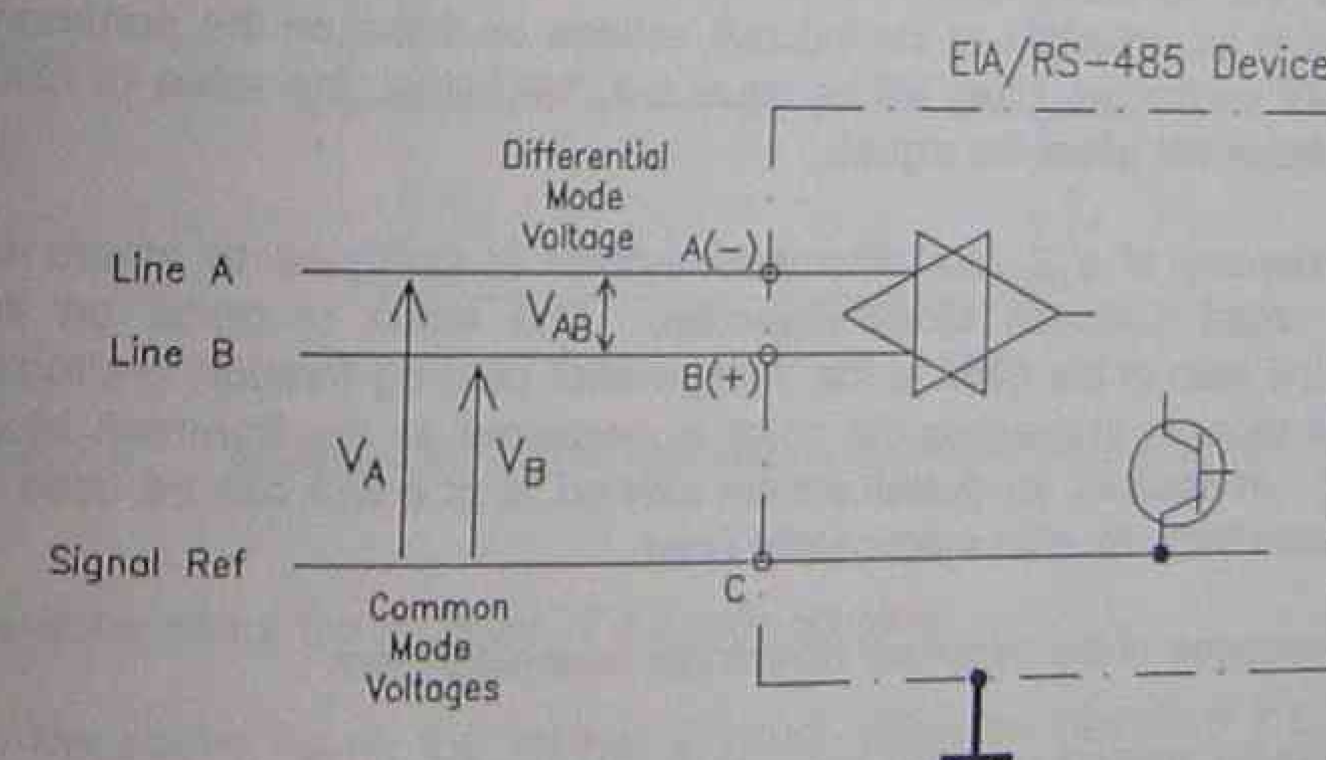


Figure 3.2 : The Differential Mode and Common Mode Voltages

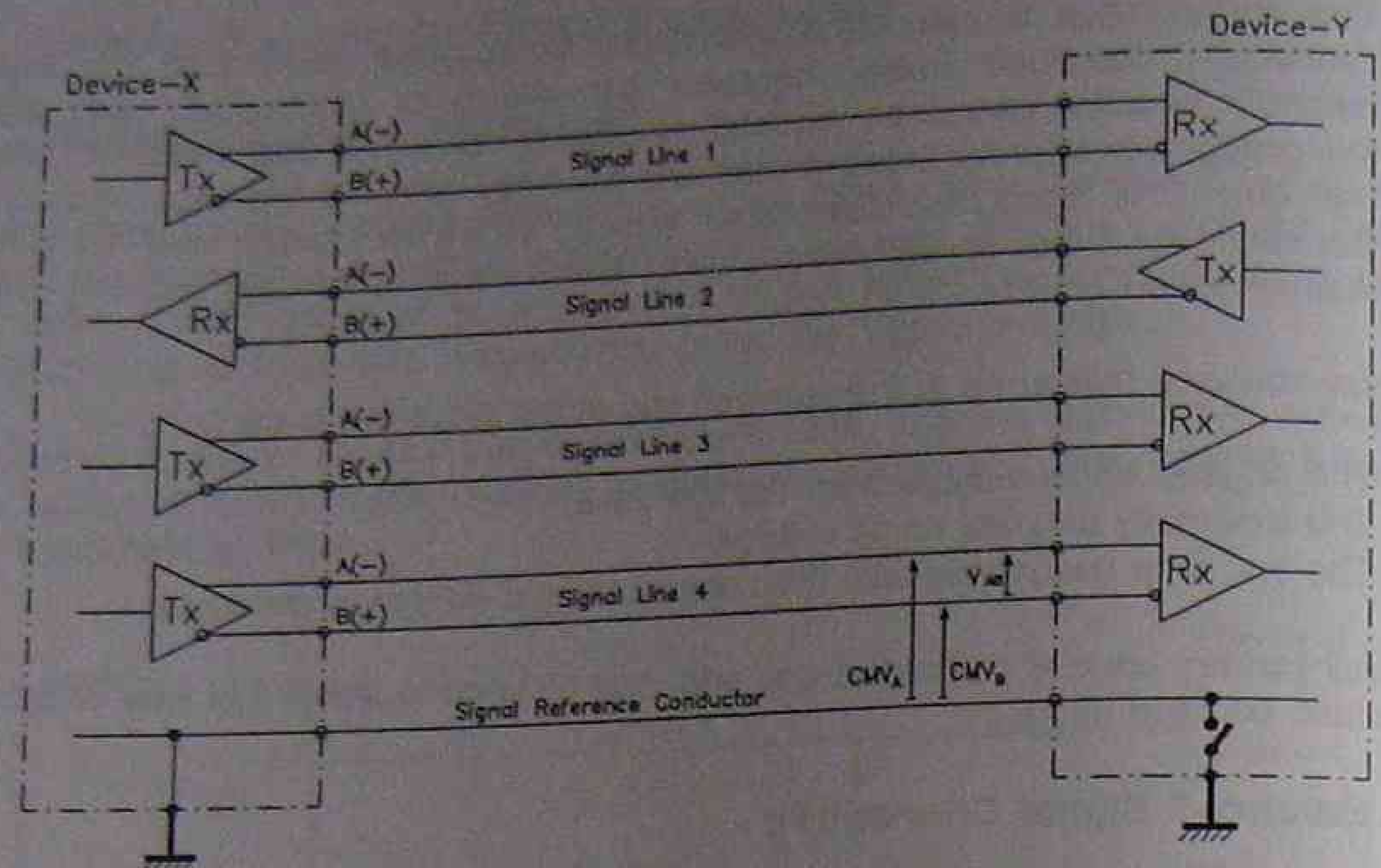


Figure 3.3 : Data Communications using a Balanced Signal Connection

This type of connection permits a **higher rate of data transfer over longer distances with higher noise immunity**. So the balanced differential connection is the preferred method for data transfer in industrial applications, where noise can be a major problem.

The successful transfer of voltage signals across a balanced interface, in the presence of noise, is based on the assumption that the two signal conductors have similar characteristics and will be affected equally by noise, voltage drops, etc. It does not mean that noise does not exist near the balanced differential connections .... some systems use unshielded twisted pairs (UTP). The voltage on both conductors should rise and fall together, but the differential voltage (V_{AB}) should be largely unaffected. The voltage between the signal conductor and the common reference conductor is called the Common Mode Voltage (CMV) and this is an indication of the induced voltage or noise on the communication link. Ideally, the CMV on the two wires will be equal but, the higher the value of CMV, the more likely that the noise will affect the signal.

The receiver circuitry of a 2-wire differential system is designed to ignore or reject the CMV and is called Common Mode Rejection. The effect of noise on the signal is measured as the ratio of the CMV to the Voltage after passing through the receiver and the success of the receiver in rejecting the noise is measured as the Common Mode Rejection Ratio (CMRR). In addition, an overall screen earthed at one end can be used to shield the signal conductors from coupled electrostatic noise.

The main advantages of the balanced differential connection are :

- There is no resistive coupling between the separate signal channels.
- The pairs associated with each signal channel can be twisted together to reduce the effect of coupled noise due to electric and magnetic fields.

The main disadvantage is that a balanced differential system requires two conductors for every signal channel. Consequently, cables can be more expensive.

3.3 Galvanic Coupling

Galvanic coupling occurs when there is a direct connection between an electric circuit, which is generating the interference, and the electric circuit of the affected equipment. For example, galvanic coupling occurs when a portion of the lightning current actually flows through a signal cable connecting two electronic devices. This can occur where the signal "common" of an unbalanced interface is earthed at both ends, which is not unusual. The RS-232 serial data communications ports on an IBM-PC are connected in this way.

Figure 3.4 shows two electronic devices (e.g. two PCs) located at different locations in an industrial plant and connected together by means of an RS-232 cable. Assume that a lightning strike causes a large surge current to flow through the earthing system close to device-X. With the inductance (L_e) of the earth connection and the resistance (R_e) of the earth electrode itself, a large voltage V_x is established at the enclosure of device-X.

From the figure, it is clear that there is an alternative path for a portion of the surge current to earth via the signal "common" reference conductor connected to device-Y. Depending on the surge impedance of the signal "common", a high voltage V_{xy} will appear across the signal line between device-X and device-Y as a result of the current flow. The development of this high voltage V_{xy} will have the following consequences :

- Definitely ... data communication errors
- Probably ... damage to the communication card/port in the two devices
- Possibly ... damage to the signal line "common" reference conductor, which connects the two devices

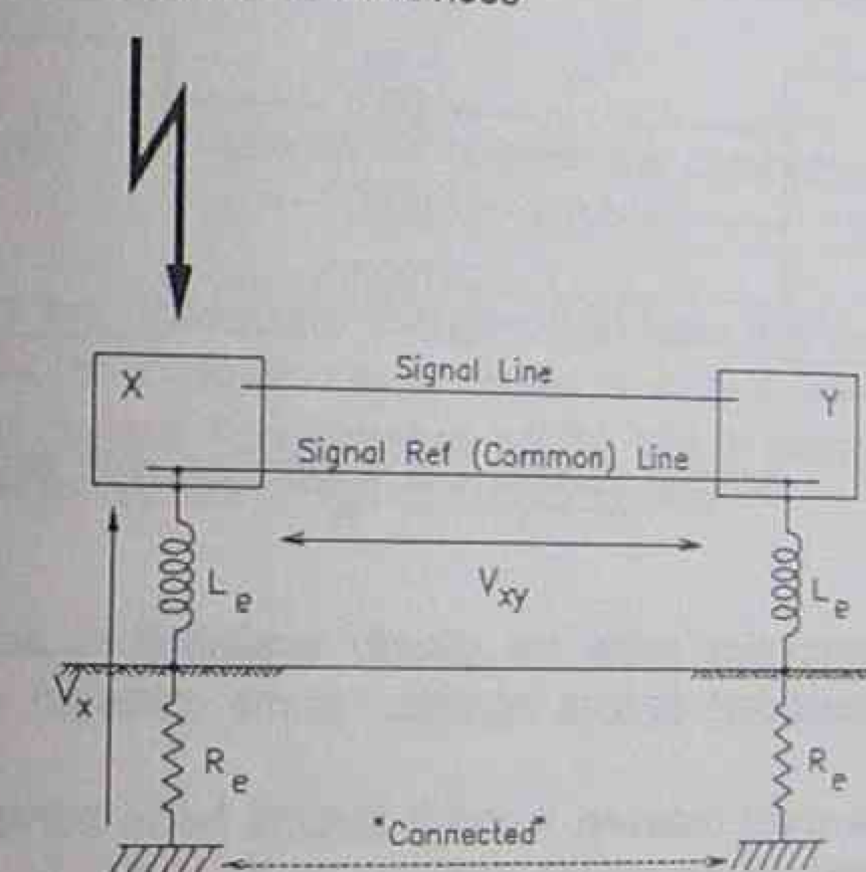


Figure 3.4 : Unbalanced signal connection between two Electronic Devices

What can be done about the problem of galvanic coupling .....

- From the above figure, the voltage V_x could clearly be minimised if L_e and R_e were made as small as possible. This is usually very difficult to achieve in practice.
- A better solution is the close bonding of the two pieces of equipment together with a heavy conductor so that the voltage V_{xy} appearing across the signal reference conductor is kept as low as possible. Bonding also provides an alternative path for any surge currents, which reduces the possibility of damage to the communication circuit and communication cable.

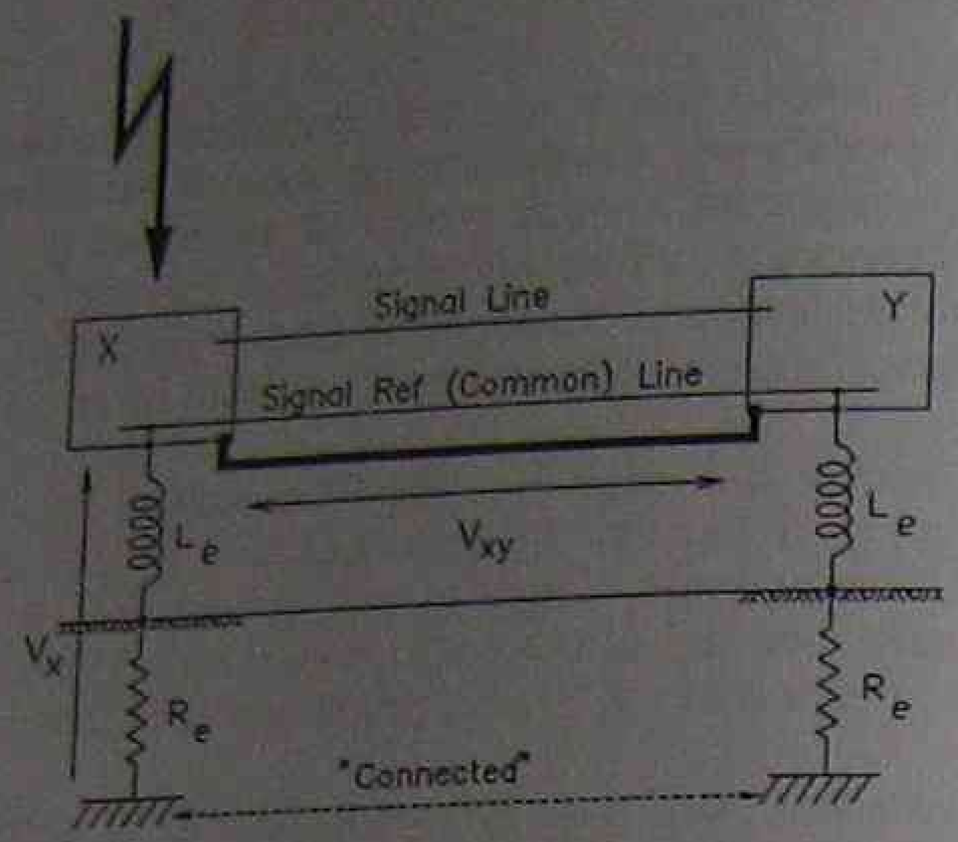


Figure 3.5 : Bonding devices X & Y together with a heavy conductor

- The impedance of the alternative path can be further reduced by replacing the single bonding conductor with multiple parallel paths. Alternative paths provide security and also reduce the effective impedance of the bonding connections.

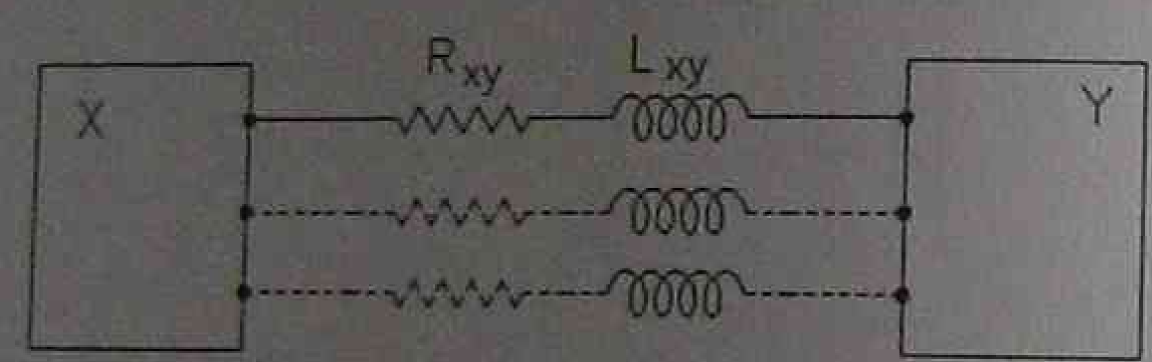


Figure 3.6 : Bonding devices X & Y together with several paths

Several materials and alternative paths are usually available to achieve the objective of closely bonding the two electronic devices together. Some common examples are :

- A continuous wide sheet between X and Y is ideal (wide band performance). This provides a very low inductance path
- Common examples of a good practical bonding components are cable trays, metallic conduit, steel wire armouring or other bonding conductors
- Alternative bonding paths between X and Y could also be implemented using structural steel work, which are part of the building

Close bonding will also provide shielding (low impedance path) for other noise and interference, such as harmonics, and improves the signal/noise ratio within the communication link.

Where the bond takes the form of a cable screen, such as armouring or conduit, the surge current flows on the outside of the screen and not in the signal lines. Surge Protection Units (SPUs) may still be needed to limit the voltage that exists between the signal lines and the inside of the screening materials.

3.4 Capacitive (Electrostatic) Coupling

Any two conductive metallic components separated in space will have an associated capacitance, which relates the charge on the conductors with the voltage difference between the two conductors. The capacitance increases with area (A) of the conductors and decreases with separation distance (d) between the conductors.

These variables are related by the following well known equation

$$Q = C\,V$$

where :
- Q is the charge on each conductor (depends on voltage)
- C is the capacitance between the conductors (depends on A and d)
- V is the voltage between the conductors

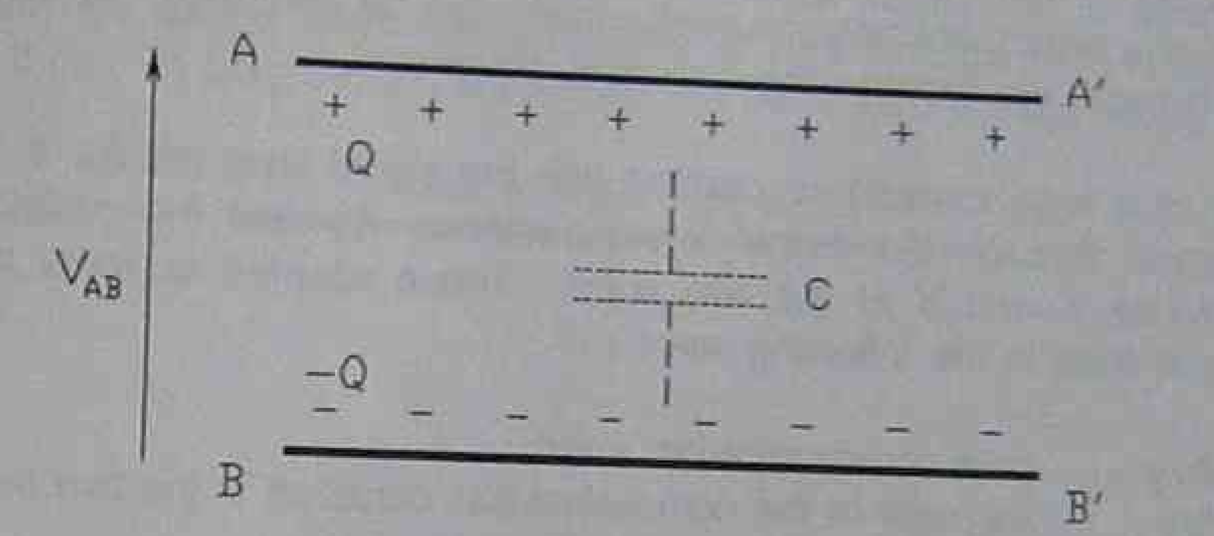


Figure 3.7 : Capacitance between two conductors AA' and BB'

If the voltage between the conductors changes, then there is a change in the charge on the conductors (movement of charge) which implies a current flow through the conductors. The magnitude of the current flow depends on the rate of change of the voltage. A high rate of change of voltage implies a high capacitive current.

$$I = C\,\frac{dv}{dt}$$

or

$$I = j\,2\pi f C\,V$$

where :
- I is the current flow
- f is the frequency of voltage change
- C is the capacitance between the two conductors
- V is the voltage between the two conductors

Figure 3.8 shows two electronic devices X and Y connected by a pair of signal conductors in an unbalanced connection. Conductor AA' is the source of the disturbance, such as an HV power cable running close to the signal cable connecting the two electronic devices.

If the voltage on the HV conductor AA' is changing at 50Hz with respect to the signal line, then from the equation above, a capacitive current will flow from AA' through the *coupling capacitances C_1 and C_2* into the signal line and back to source via the earthed "common" signal reference conductor. The current loop is completed via the earth.

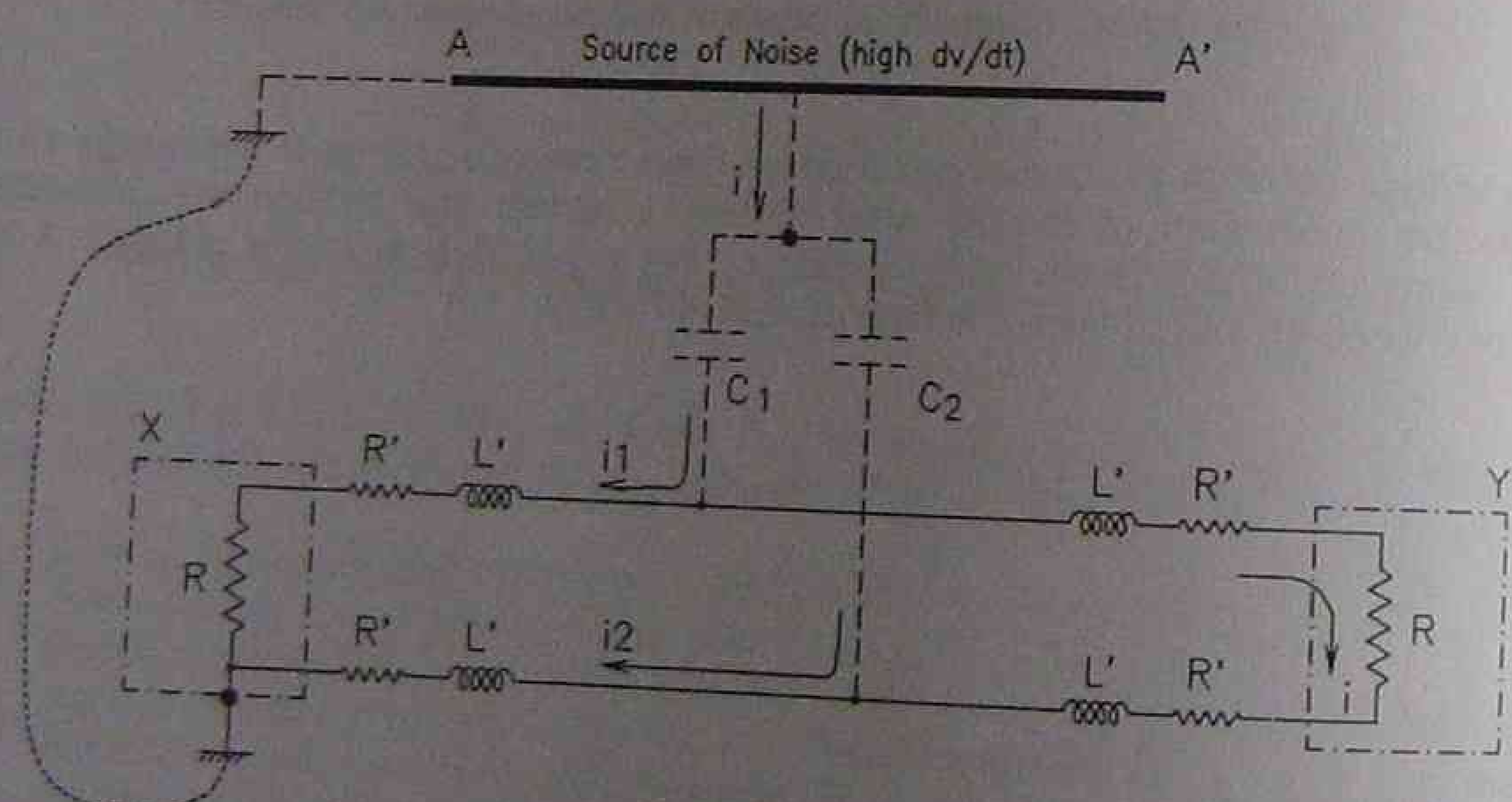
This mechanism is known as ***Capacitive Coupling***. From the above equations, the magnitude of the capacitively coupled current depends on the following :

- The rate of change of the interference voltage (dv/dt) of the source .... both Magnitude and Frequency
- Capacitance between the source and the signal lines. This in turn depends on :
  - the separation distance between the source to the signal lines
  - the distance over which the cables run in parallel

If the conductor AA' is the discharge path of a steep-fronted lightning strike (characteristic frequency of ±10kHz), the rate of change of voltage (dv/dt) is extremely high and, consequently, the electrostatically coupled current can be very high. In the worst case, this high level of current can damage the electronic equipment.

The coupling of a **high capacitive current** into the signal lines results in the development of high voltages through the signal line inductance (L) and the resistance (R) of the electronic devices X and Y at the two ends. These coupled currents and voltages will affect the signal lines in the following ways :

- Definitely ... data communication errors
- Possibly ... damage to the communication card/port in the two devices



where : R is the resistance of the terminal equipment
R' is the resistance of the signal line
L' is the self inductance of the signal line

Figure 3.8 : Mechanism of Capacitive Coupling

There are a number of practical techniques which can be used to reduce the effect of capacitive coupling. These are as follows :

- The noise due to electrostatic coupling can be reduced by reducing the capacitance between the source of the noise and the signal cable. Capacitance decreases with increasing separation between the source of the disturbance AA' and signal cable and reducing the area of overlap. This can be practically achieved by running signal cables along different routes to power cables, or where they need to cross, at right angles to each other.
- As illustrated in Figure 3.9, the use of an outer conductive screen (an envelope of conductive material around the signal conductors) will reduce capacitively coupled noise, **provided that the screen is connected to earth** to provide a path for the capacitive current. The coupled currents then flow through capacitance C to the screen and then to earth, instead of flowing through the signal conductors. Ideally, with both the shield and signal reference conductor connected to earth at one end, they would be at the same potential and a zero voltage difference would exist between them. In practice, the screen will not be at zero voltage along its length.

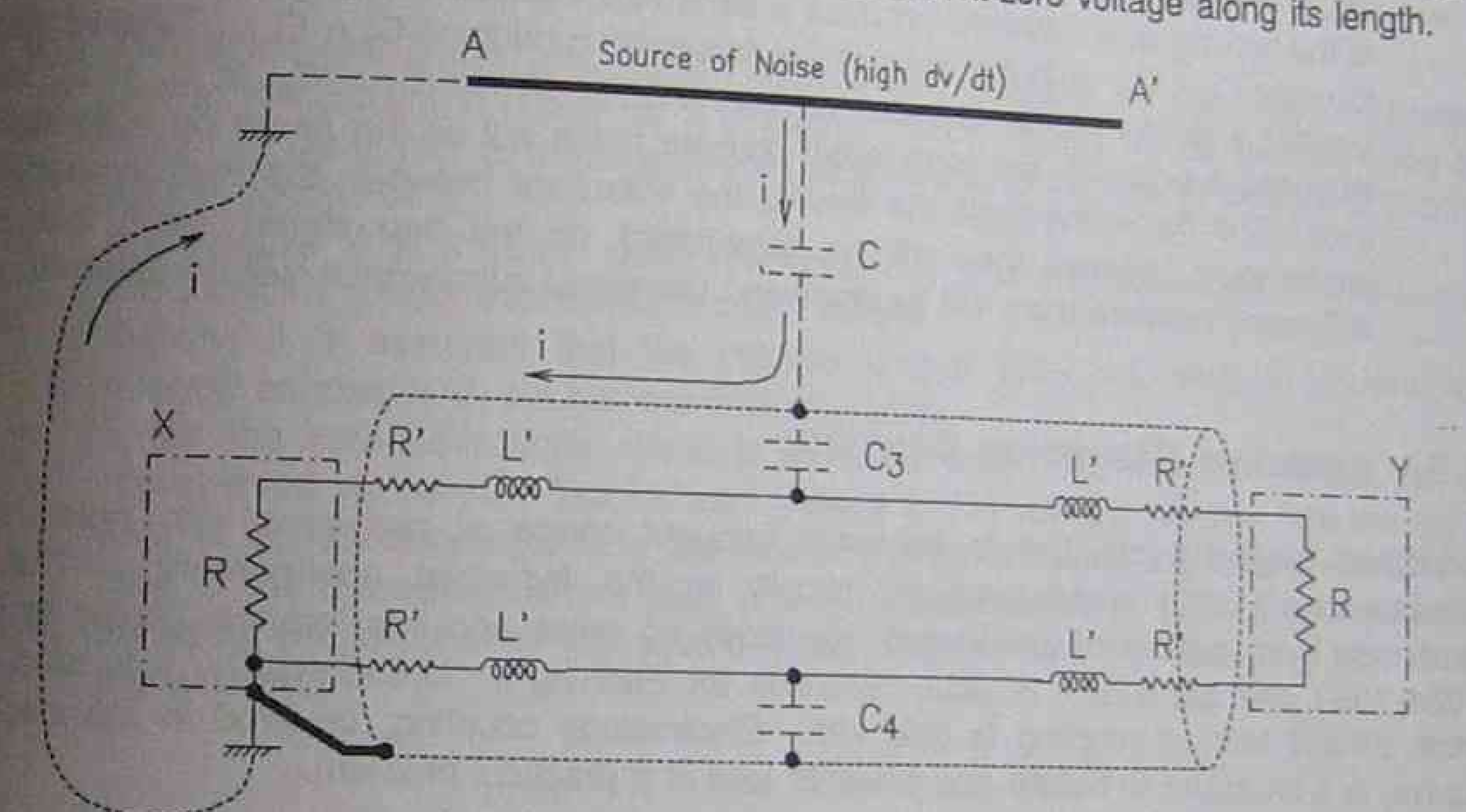


Figure 3.9 : Screening to avoid capacitive coupling

From Figure 3.9, it is clearly not necessary for both ends of the screen to be earthed to divert capacitive coupled noise to earth. In fact, earthing at more than one point can introduce other problems, such as earth loops during earth faults, which could damage the screen material or the earth connection of the drain wires. Consequently, **the electrostatic screen is usually earthed at one end only.**

However, when the screen is earthed at one end only, the capacitively coupled currents flowing through the screen impedance will result in a volt drop along the length of the screen. The screen voltage can, in turn, be capacitively coupled into the signal conductors via capacitance C_3 and C_4. Consequently, to keep this volt drop to a minimum, the screen should be made of a high conductivity material, such as copper or aluminium.

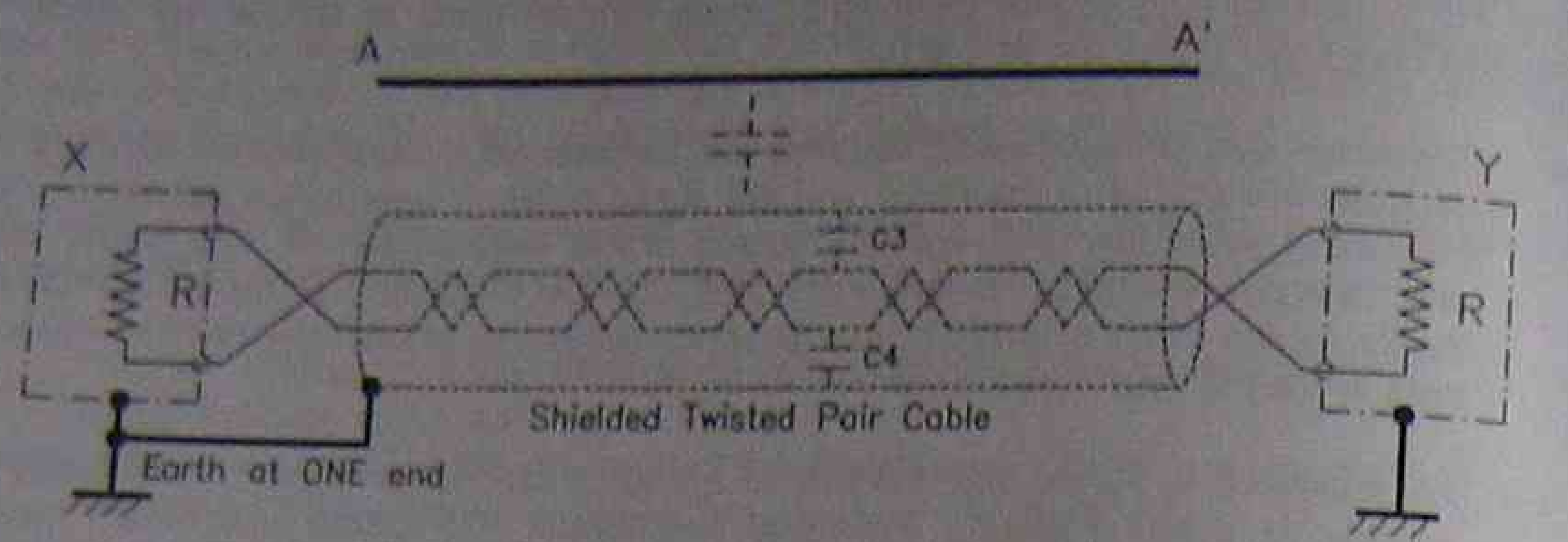


Figure 3.10 : Twisted Pairs also reduce capacitively coupled noise

- Using a **Balanced Connection** between the two terminal devices and the twisting of the two signal conductors provides a **balanced capacitive coupling**, which tends to make $C_1 = C_2$, or in the case of the screened conductor $C_3 = C_4$. Twisted pairs are not practical with an unbalanced connection. When $C_1 = C_2$ or $C_3 = C_4$ in a balanced connection, the capacitively coupled noise will be the same on both signal lines. The tighter the twist, the smaller the difference between the two conductors. Interference voltages may still be established on the two signal lines, but the *difference* between them will be small and the signal interference will be minimal.

3.5 Inductive (Magnetic) Coupling

Inductive (Magnetic) coupling is the most frequent cause of problems with noise and interference in data communications circuits in the industrial environment. This is confirmed by a number of well known references on noise and interference (Refer to IEC 1024-1993 and Bib 3.20 - St John "Grounds for Earthing"). Unfortunately, it is also the most difficult form of coupling to deal with. Electrostatic coupling, covered in the section above, is a lot easier to handle and presents less of a practical problem.

Amongst the main problems are the power frequency voltages (or its harmonics), which are coupled into the control and communication circuits from power cables, conduits, cable trays, etc running near to or parallel to the communication cables. Investigations have shown that about 80% of EMI (Electromagnetic Interference) problems are generated within the facility experiencing the difficulties. EMI can also enter electronic equipment directly from the power supply. Although this may not damage the circuits to the extent that they fail, data bits in digital circuits may be corrupted, resulting in data errors and delaying data transfer.

The mechanism of inductive (magnetic) coupling is as follows :

- Any conductor carrying current will produce a magnetic field around it. If there is an adjacent conductor, then a portion of this magnetic field will link with that conductor.
- In the figure below, the flux line a', produced by conductor A, does not link with conductor B. Flux line a" does link with conductor B (encircles conductor B) and is said to be "linking" or "coupled" with conductor B.

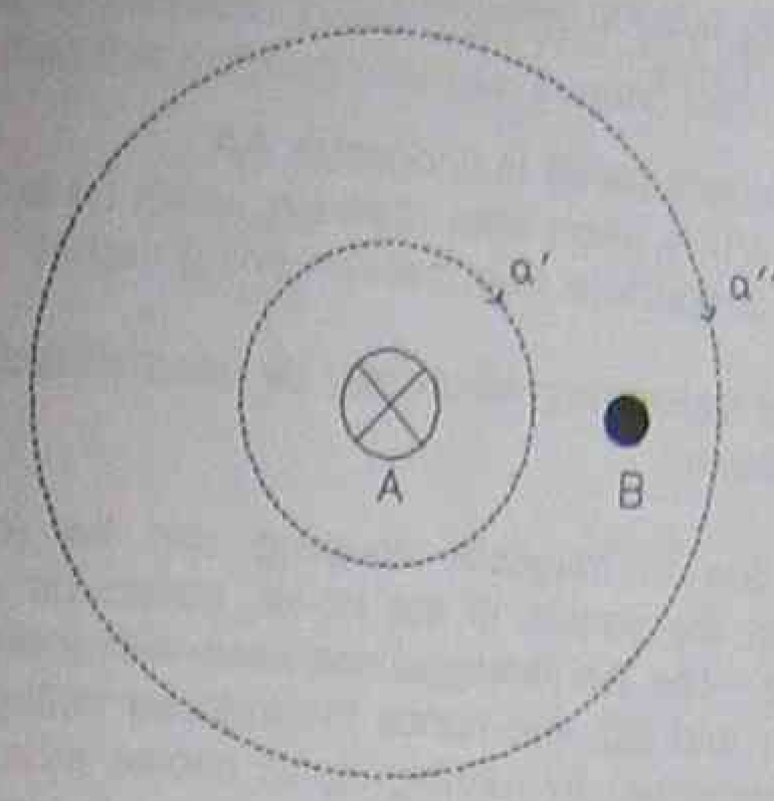


Figure 3.11 : Flux lines associated with current in conductor A

- ***Faraday's law*** states that, if the magnetic field produced by conductor A changes due to the current in conductor A changing, then a *voltage* will be induced along the length of conductor B which is directly proportional to the *rate of change* of the flux linking conductor B.
- If conductor A is a power cable and conductor B is a communications cable, then this induced voltage represents a noise voltage.
- Initially, it is assumed that the induced voltage does not result in current flow through conductor B, the communications circuit.
- Since the communications circuit is always a "loop", the complete circuit can be represented as below. The induced voltage (noise voltage) coupled into the signal loop is directly proportional to the *rate of change* of flux linking loop B-B'-C'-C-B (due to the disturbing current di/dt) and the *area enclosed by the signal loop*, and is inversely proportional to the square of the distance from the disturbing wire to the signal circuit.

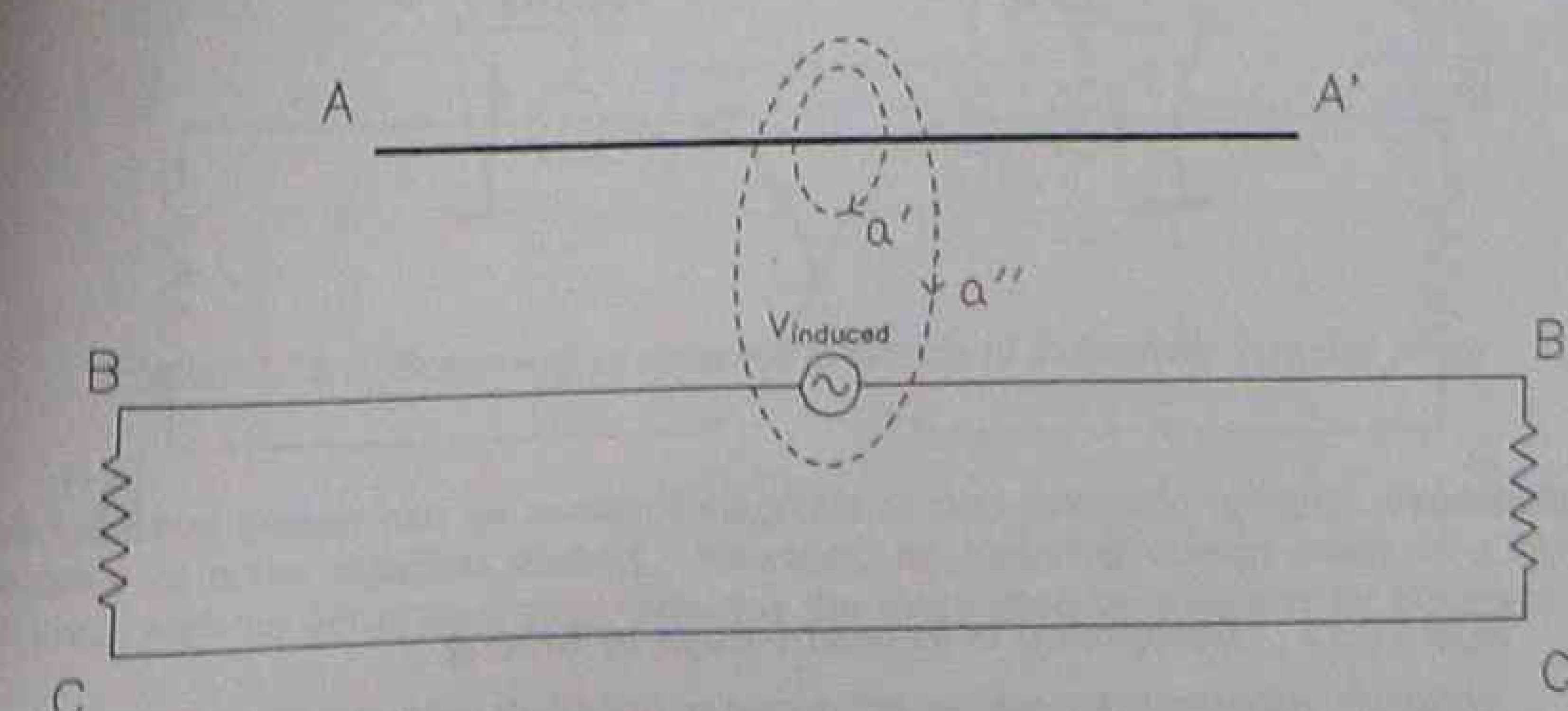


Figure 3.12 : Voltage induced into the signal wire by magnetic coupling

Figure 3.12 shows all of the factors necessary to introduce an error voltage into a signal line from an adjacent power cable :

- Rate of change of current (di/dt) in conductor AA'
- Signal loop BB'C'C with a given area (through which pass the lines of flux)
- A separation of the conductors from the disturbing signal

There are several practical techniques which can be used to reduce the effect of inductive coupling. These are as follows :

- The interference due to magnetic coupling can be reduced by increasing the separation between the source of the noise, conductor AA,' and the signal circuit loop B-B'-C'-C-B. The flux linkages decrease with increasing separation between the conductors AA' and BB' and hence the induced voltages are reduced. This can be practically implemented by running signal cables along different routes to power cables, or where they need to cross, at right angles to each other.

- Twisting of the two signal conductors reduces the effective circuit loop area ... the tighter the twist, the smaller the loop area and the lower the induced voltage. This technique is usually only practical with balanced differential connections. A further justification for twisting the two signal conductors together is that the polarity of the induced voltage will reverse with every twist. Hence the overall induced voltage over signal loop will tend to be zero ... assuming perfect symmetry of the twisted pair. This will reduce the noise level on signal lines which use the *balanced* connection.

This can be illustrated for a single twist as below :

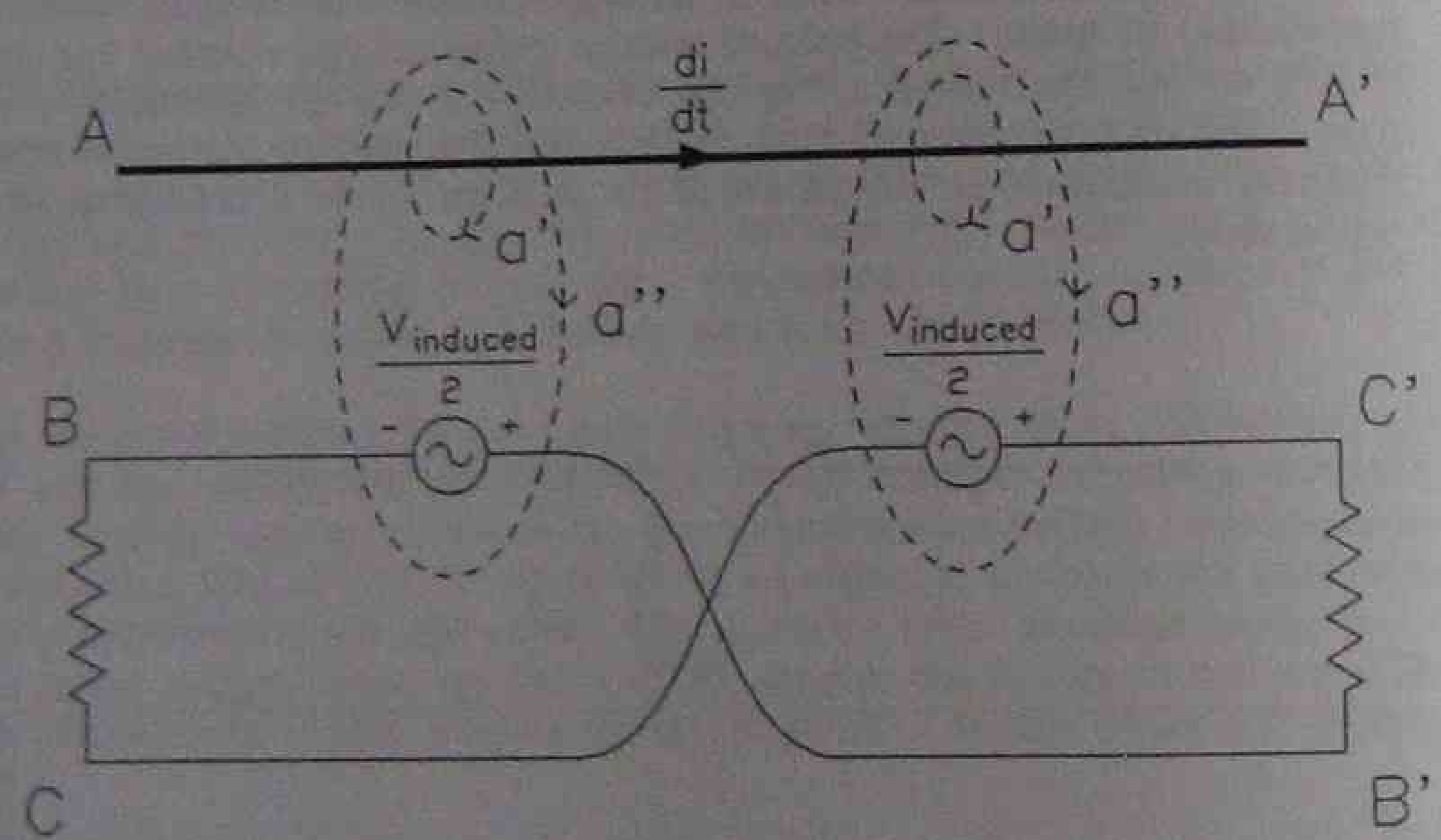


Figure 3.13 : Cancellation of induced voltage by twisting

Electrically, this is equivalent to the following and results in a zero net induced voltage, provided that the induced voltages in each loop cancel each other.

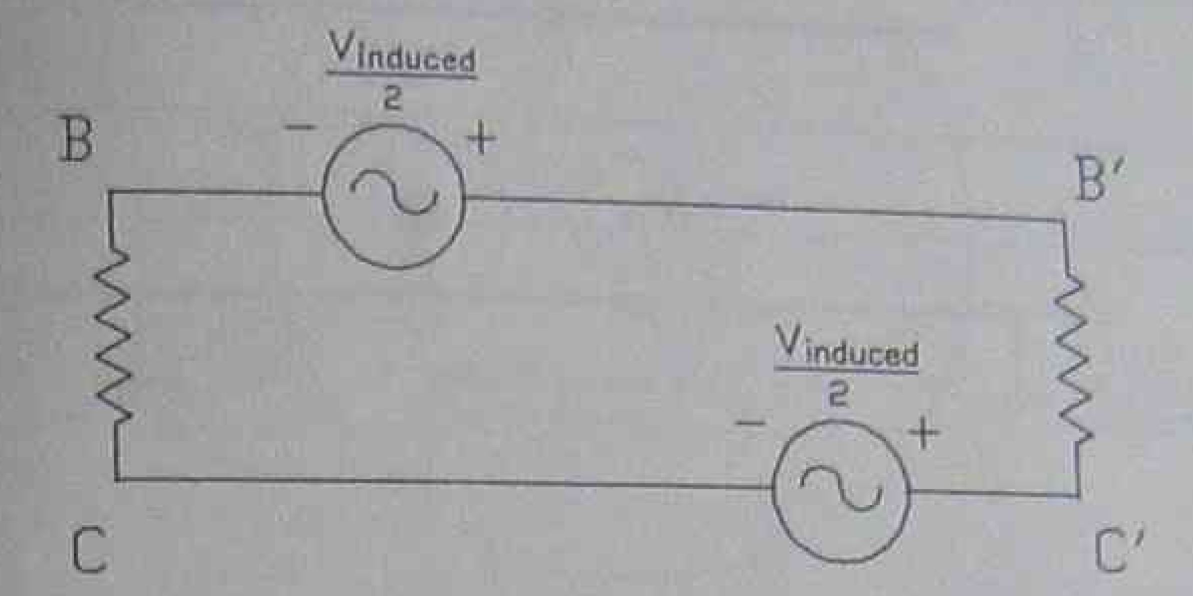


Figure 3.14 : Cancellation of induced voltage by twisting

- Magnetic coupling can also be reduced by installing a screen around the signal conductors to shield them from the magnetic field. However, to be effective, the inductive screen must be earthed at both ends to provide a path for a circulating current (i'), whose field will oppose the original magnetic field. This process is also assisted by the fact that the disturbing magnetic field produces eddy currents in the shield, which also oppose the original magnetic field.

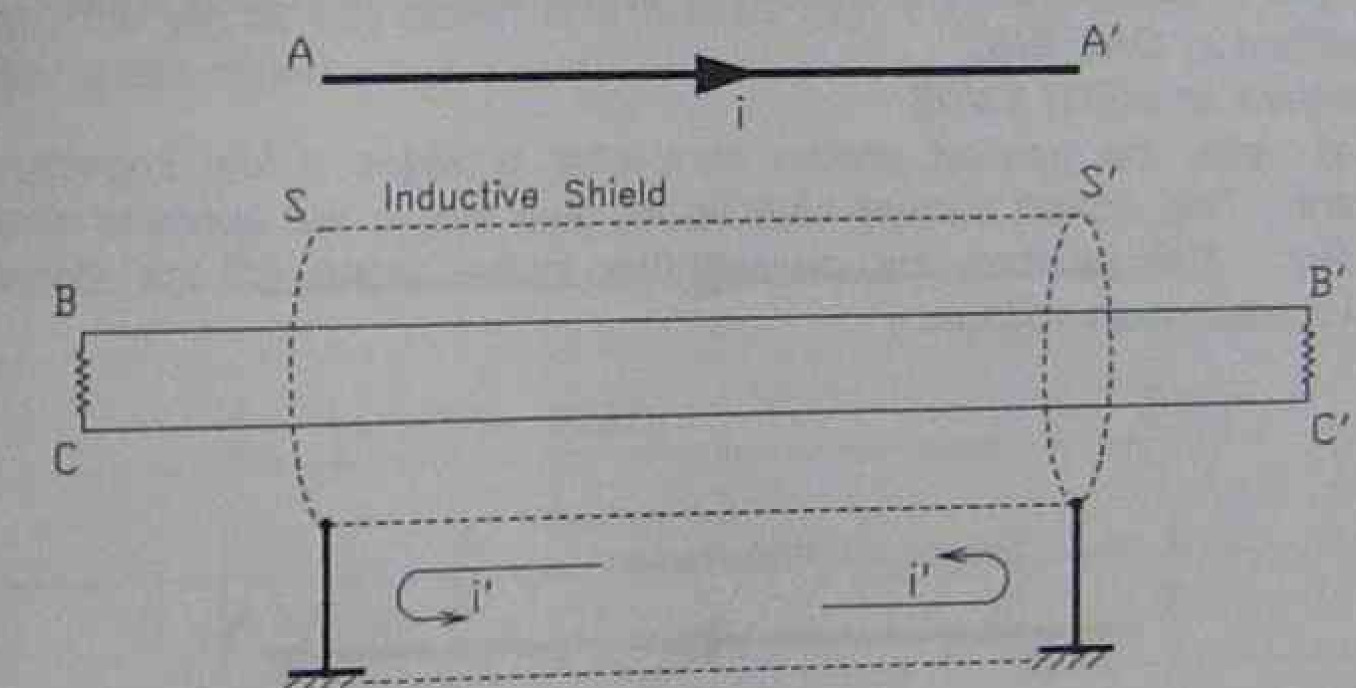


Figure 3.15 : Screening to reduce the effects of inductively coupled noise

The inductive screen can be made of magnetic or non-magnetic material, depending upon the level of noise rejection desired. However, an inductive screen made of a magnetic material, such as galvanised steel, provides the most effective shielding for magnetic fields.

The mechanism of inductive shielding is somewhat different to capacitive shielding.

In Figure 3.16, the effect of the current flow in the signal loop, caused by the induced voltages, will itself tend to reduce the magnetic field. This is based on ***Lenz's law***, which states that the *induced current* will have a direction such as to oppose the changes in the flux linkage.

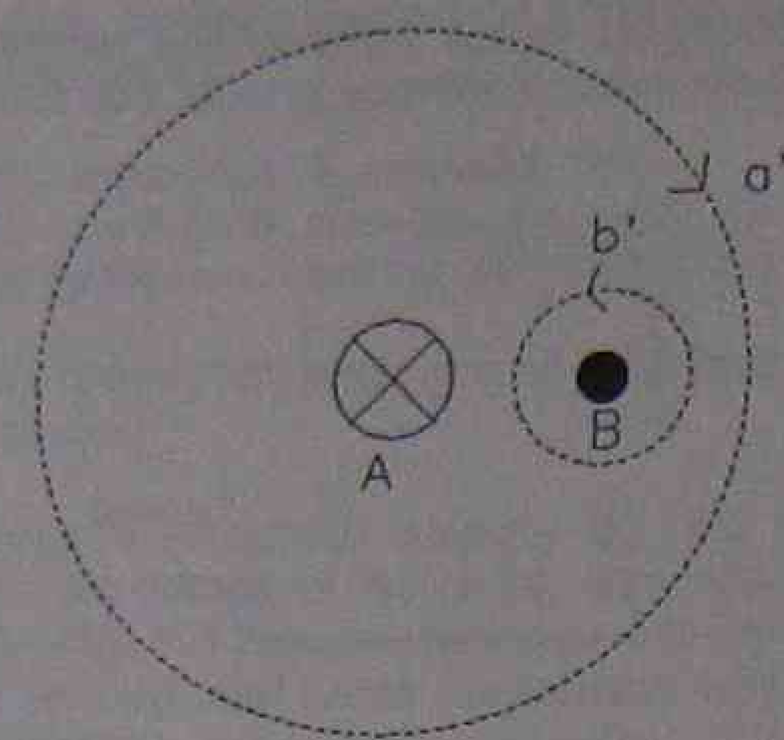


Figure 3.16 : Reduction of overall flux due to current in parallel conductor

For example, if the flux due to conductor A increases as a result of current increasing in conductor A, then the voltage in conductor B will increase resulting in an increase in the current in B. This change in current in conductor B will result in a flux b' which opposes the flux a''. This means that the net flux linking conductor B is reduced ..... and the voltage induced in conductor B is reduced, which is a desirable outcome.

The following two figures compare the situation where a parallel screen conductor is

- ***earthed at ONE END***
- ***earthed at BOTH ENDS***

In the second case, the parallel screen conductor provides a low impedance path for induced current. This screen current sets up its own flux in the opposite direction to the disturbance flux. This reduces the ***overall flux*** in the vicinity of the signal wires and reduces the induced noise voltage.

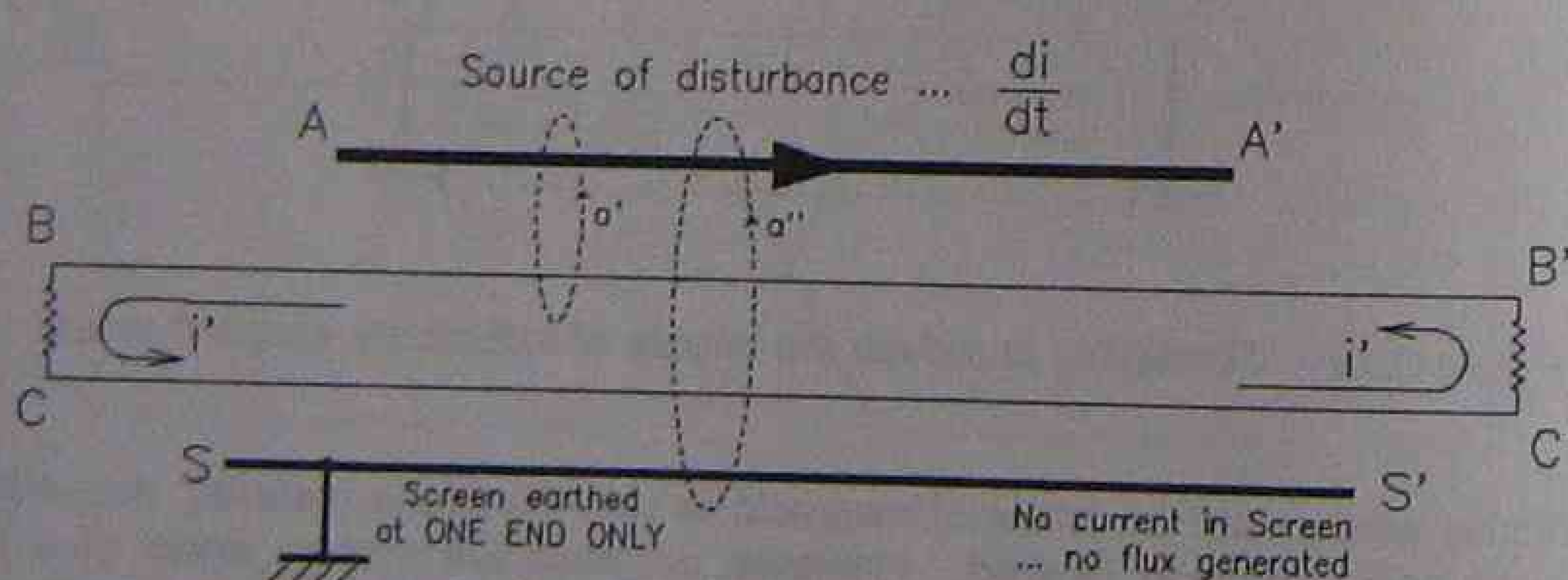


Figure 3.17(a) : Screen EARTHED AT ONE END ..... high induced noise

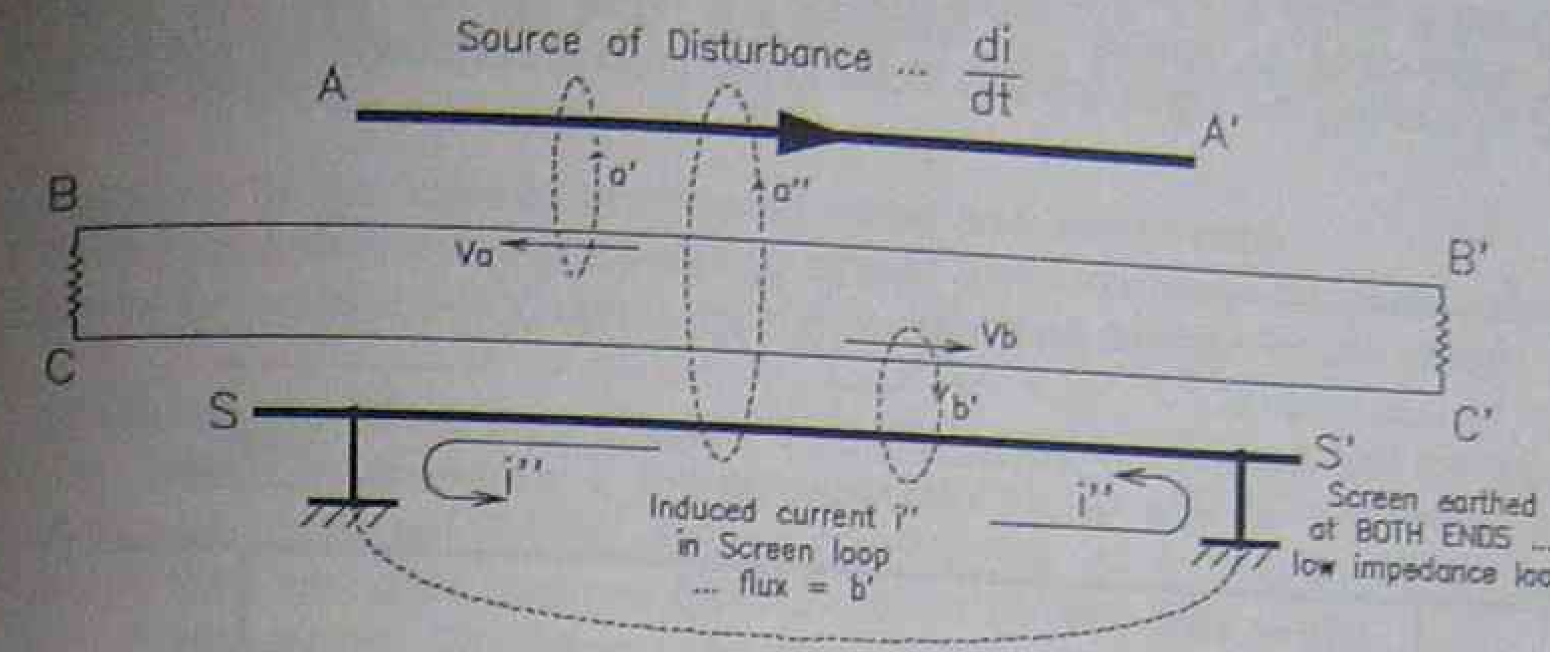


Figure 3.17(b) : Screen EARTHED AT BOTH ENDS ..... low induced noise

In practice, flux cancellation is achieved by passing the signal conductors, preferably a twisted pair, through a metallic conduit earthed at both ends. The induced current i', which flows through the screen or conduit, **reduces the flux linking the signal lines** BB' and CC' and thereby reduces the voltage induced in the signal conductor loop. In contrast to the situation with electric fields, it is essential that the inductive screen or conduit is **earthed at both ends** .... or at as many points along the way as possible. However, the inductive shield or conduit should NOT be part of the signal path.

If, in addition, the signal connection is a twisted pair, then the effect on the signal of any remaining flux is minimised.

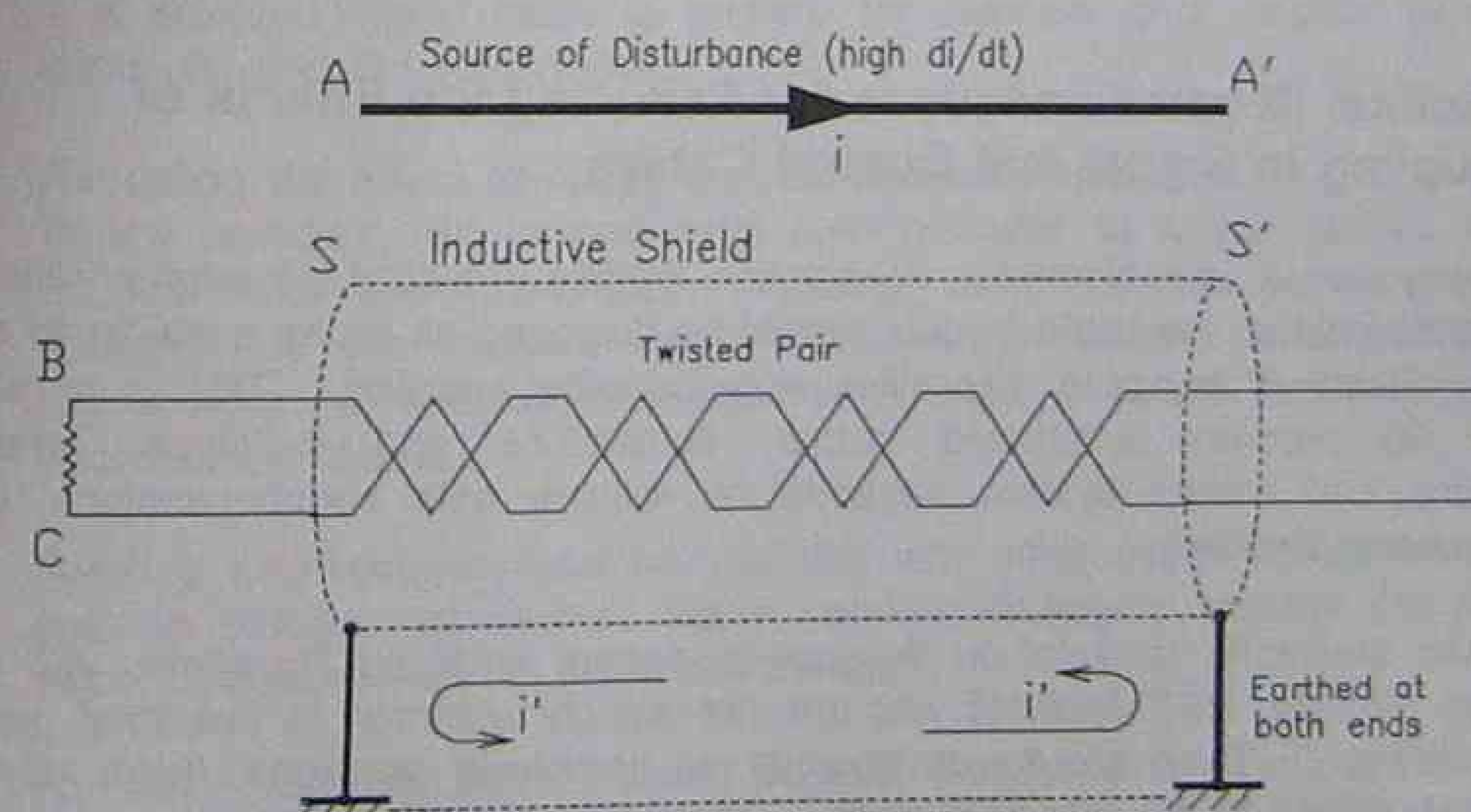


Figure 3.18 : Inductive screen earthed at both ends with balanced twisted-pairs

Even with the differential connection, there is a path for induced currents to flow through the stray capacitance to ground. To minimise this noise current, the loop area must be minimised by running the signal lines as close to the ground conductor as possible.

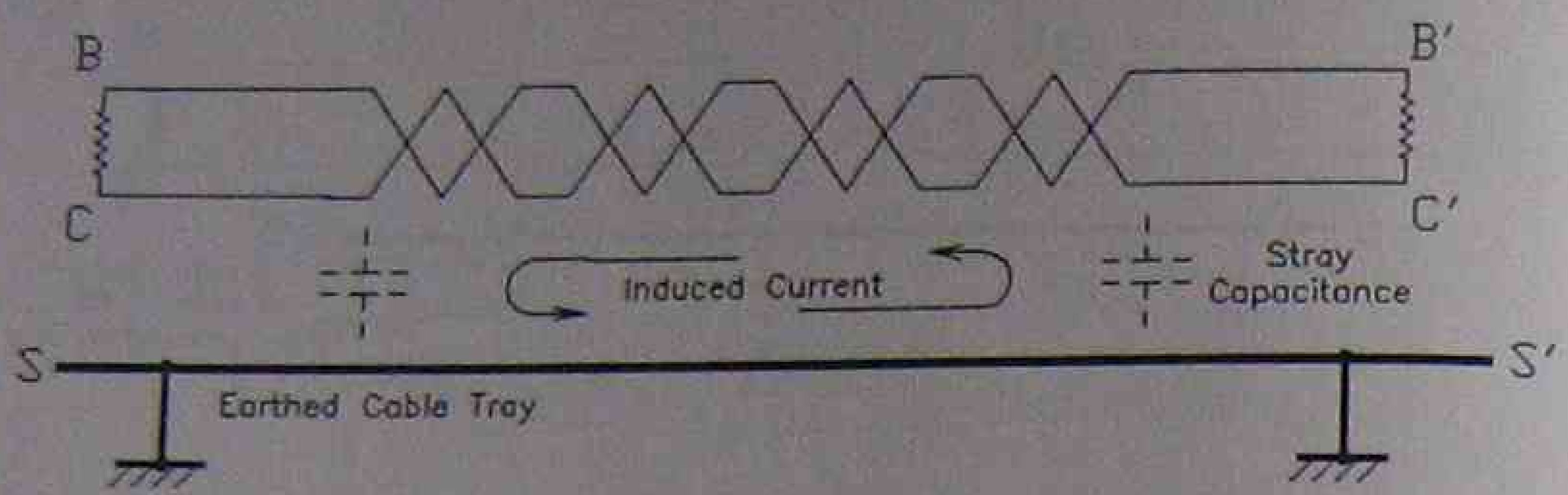


Figure 3.19 : Running cable close to earthed conductor or cable tray

Some important conclusions can be drawn from the analysis of the flux cancellation effect.

- If the source of the noise (e.g. power cables) is enclosed in conduit or armouring **earthed at both ends**, the induced current flow in the conduit will reduce the overall magnetic field outside the conduit or armouring.
- Running power cables along a metallic cable tray or ladder, which is earthed at both ends, will reduce the overall magnetic field in the vicinity of the cable.
- If a signal cable is run in a non-metallic (e.g. plastic) conduit, which is NOT recommended, a separate shield wire should be run along the conduit with the signal cable and it **must be earthed at both ends.**

3.6 Practical Recommendations for Reducing the Effects of Coupling in Signal and Control Cables

Where there is a combination of power, lighting, control, instrumentation and communication cables, the cable layouts should be designed as far as possible to avoid or reduce the effects of galvanic, capacitive and inductive coupling. This is of particular importance in modern automated plants, substations and buildings, where the measurement and control system depends on reliable data communications between several electronic devices.

Large power electronic devices on the power system such as Rectifiers, AC and DC Drives, Soft Starters, UPS systems, etc are increasingly common in industrial plants and modern buildings. They are major sources of **harmonic voltages (high dv/dt) and current high di/dt)** in the power system. Particular care should be taken when these devices are connected to the power supply system.

The following is a summary of the most important measures, which follow from the material covered in this chapter, to minimise the effects of noise and interference coupled into the electronic equipment.

(1) **Removal of the causes of coupled noise and interference.**
Where possible, the overall design should aim to achieve complete segregation of the power cables from control, instrumentation and communication cables.

(2) **Shielding the electronic circuits from the sources of noise and interference.**
(a) ***Galvanic Isolation*** : Where possible, try to use a differential connection standard, such as EIA/RS-422 or EIA/RS-485, in preference to an unbalanced connection standard, such as EIA/RS-232 or EIA/RS-565.
(b) ***Electrostatic Shielding*** : In cases where there is a possibility of high electric fields (due to high rate of change of voltage), capacitive shielding should be used, with the shield earthed at ONE end.
(c) ***Magnetic Shielding*** : In cases where there is a possibility of high magnetic fields (due to high rate of change of current) inductive shielding should be used, with the shield earthed at BOTH ends and also at other convenient locations.

ALL electrostatic shields should be earthed ... at least at one end.

For cables with multiple channels, each twisted pair should preferably have an electrostatic shield, which is electrically insulated from all other electrostatic shields along the entire length of the cable. Multiple channel cables should also have an overall electrostatic shield.

Where twisted conductors of a shielded cable must be exposed, for example at input/output terminals, the untwisted, unshielded length should be minimised.

If a shielded signal cable is broken, for example at a junction box, the shield continuity should be maintained.

(3) **Reducing the effect of coupled noise and interference.**
Where possible, use twisted pairs (±40 twists/m) to further reduce the effect of coupled noise and interference. Twisting results in less loop area for inductive coupling and also results in lower inductance per metre. Lower inductance allows higher frequencies to be transmitted over longer distances before signal distortion becomes significant.

Twisting also reduces inductive coupling with other signal conductors. The small spacing between the twisted signal conductors largely cancels the net magnetic fields associated with the conductor currents.

For these reasons, twisted signal conductors should be used wherever possible, which implies that balanced differential interfaces (e.g. EIA/RS-422 & EIA/RS-485) are preferable to unbalanced interfaces (e.g. EIA/RS-232).

If it is necessary to use an unbalanced connection with multiple conductor cable, such as an EIA/RS-232 cable, the conductors should have a general twist in the axial direction.

Unused conductors and electrostatic shields should be terminated. On multiple channel cables, half of the unused conductors and shields should be terminated at one end of the cable and the remainder at the other end of the cable.

Special three conductor twisted shielded cable is available for three-wire signals, such as potentiometer signals and dc power (+5V, -5V, common).

(4) **Ensure that the Earthing and Bonding has been correctly implemented.** See later chapters for complete details

Some overall practical recommendations are as follows .... :

Signal cable routes should be around rather than through high-noise areas. In cases where signal cables must unavoidably run parallel to power cables over long distances, it is recommended that:

- The communications cables should be laid as far from the power cables as possible at the outer extremes of the cable ladder or duct. The cable ladder or duct should be made from a conductive magnetic material, such as galvanised steel.
- If possible, the power cables should be laid up in trefoil to minimise the associated electromagnetic fields. Also, they should preferably be armoured.
- The cable trays/ladders should be specified with a magnetic barrier between the two types of cable. Enclosed steel ducts, steel conduits or steel barriers are suitable. The communications cables should be as close to the steel screen as possible.
- The cable tray/ladder, ducts, conduits and barriers should be electrically bonded together at every join. They should be earthed at least at both ends and at any other convenient locations.
- The communications cable should be a shielded twisted pairs, with the electrostatic shield earthed at one end. The screen continuity should be maintained at each termination point. Screens of individually screened cores, in the same cable, should be electrically isolated from each other, but continuous for each line through junctions.
- Where data cables cross power cables, the ideal angle is 90°.
- Optic fibre cables are increasingly attractive alternatives to copper conductors for data communications circuits in high interference environments. Fibre cables do not suffer from coupled noise or longitudinal voltage stresses.

3

Chapter 4 : ELECTRICAL SHIELDING

1.1 Introduction

The cable shields, which were mentioned in previous chapters, are only one of a wide variety of electromagnetic (EM) shields. In the context of industrial control, EM shields can also include the following components :

- Metallic equipment enclosures and cabinets
- The walls of equipment rooms
- Structural steel in steel buildings
- Reinforcing steel in reinforced concrete

These EM shields offer a greater or lesser degree of screening to electromagnetic interference, depending on the types of material used and the degree to which they are bonded to other components.

From an overall earthing point of view, the walls of a building, or of a control room, or of a metal enclosure (cabinet or panel) could be the designated as the equipotential boundary between zones of different electromagnetic environments. Ideally, all conducted surges should be "clamped" to earth ***before entering*** an environment of decreasing electro-magnetic interference (EMI).

The purpose of electrical equipment zoning is to define those specific areas where the electromagnetic conditions are similar.

4.2 Definition of Surge Protection Zones (SPZs)

Surge Protection Zones (SPZs) are also sometimes called Lightning Protection Zones (LPZs). The two terms are interchangeable. Surge Protection Zones (SPZs) are characterised by significant changes of the electromagnetic conditions at their boundaries.

Electromagnetic conditions are defined in terms of :

- Capacitive Coupling (Electric Fields)
- Inductive Coupling (Magnetic Fields)

Surge Protection Zones (SPZs) imply the following requirements :

- At the boundary of the zones, all metal penetrations must be bonded to earth.
- Screening measures must be introduced for electrical paths between zones
- Once a zone is defined, the electrical system must be designed, installed and maintained in such a manner that the zone definitions remain true.

Surge Protection Zones (SPZs) are defined as follows (IEC 1024) :

1. **Outdoors**

SPZ0_A : Area of direct lightning strikes .... and with
- unattenuated electromagnetic fields

SPZ0_B : Area of no direct lightning .... but with
- unattenuated electromagnetic fields

2. **Indoors**

SPZ1 : Area of no direct lightning .... but with
- currents on conductive parts and electromagnetic fields attenuated with respect to SPZ0_A and SPZ0_B

SPZ2 : Area of no direct lightning .... but with
- currents on conductive parts and electromagnetic fields attenuated with respect to SPZ1

SPZ3 : Area of no direct lightning .... but with
- currents on conductive parts and electromagnetic fields attenuated with respect to SPZ2

SPZ4 : etc

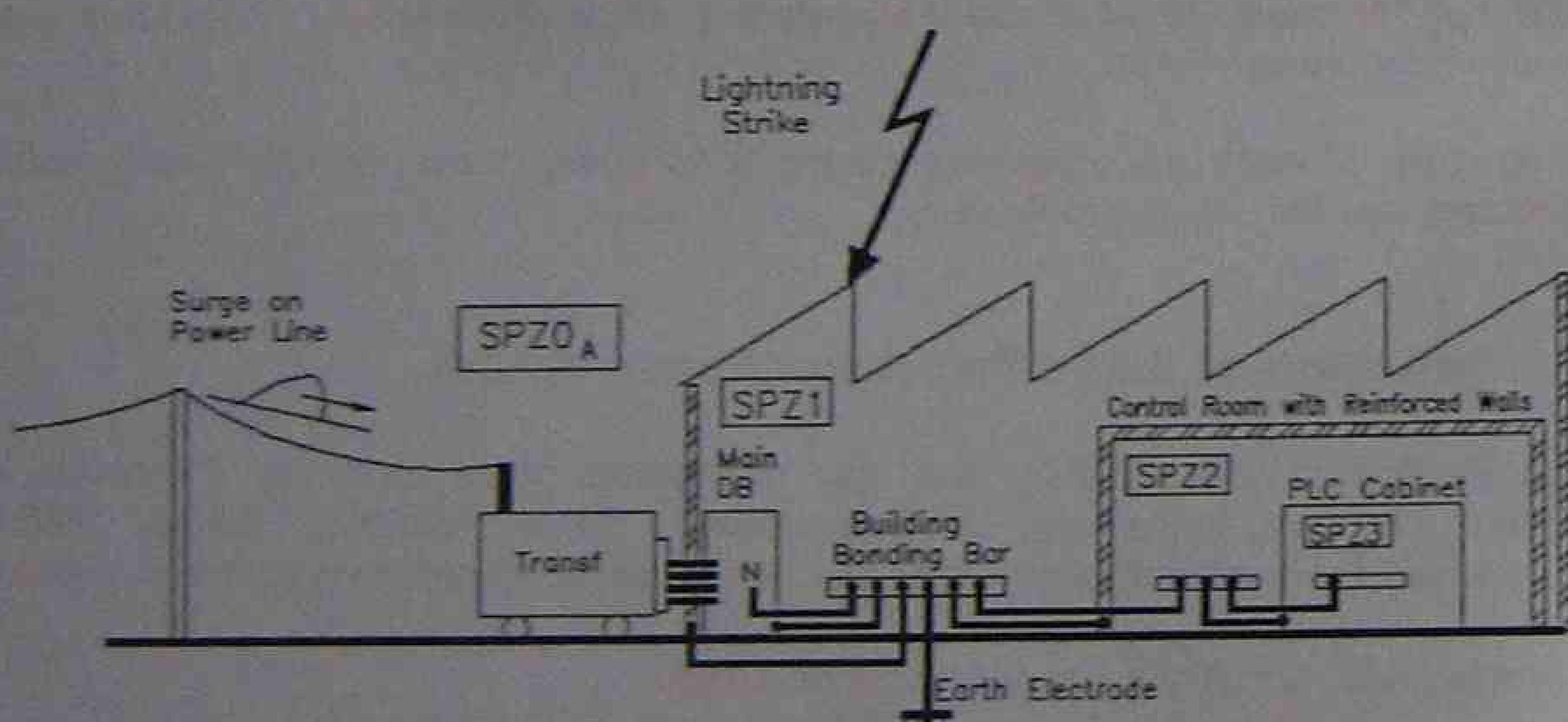


Figure 4.1 : Typical arrangement of the Protection Zones in a building

4.3 What Constitutes an Electromagnetic Shield

If the walls of a building were perfectly conducting, then they would form a Faraday cage, and differential voltages within the building would be limited to very low values, even though the potential of the building earth (and hence the building) relative to "true" earth may fluctuate dramatically due to currents in the earth electrode.

Achieving perfect conductivity of building walls would be extremely expensive and is usually not justifiable. So, the strategy is to provide shielding for individual items of electronic equipment. For example, the electronic equipment and the cables for the control system of an industrial plant are separately shielded. Special arrangements are usually also made for the control rooms and equipment rooms associated with an electronic control system.

4.4 Shield Design Criteria

A realistic objective is to achieve a ***nested shielding topology***, where the zone exterior to the building is the most harsh and, as progress is made towards the more deeply nested zones, the electromagnetic environment becomes more benign. This nested approach is only achievable if the shields between the inside and the outside zone are not violated through incorrect terminations and earth connections.

Figure 4.2 shows an example of a signal cable running from outside a building to a PLC Cabinet deep within the building. In this example, it is assumed that the signal cable is inside a galvanically continuous steel conduit or steel wire armour (SWA). To reach the PLC, the cable first needs to penetrate the outer building wall, then pass into an equipment room and then finish up in a PLC cabinet containing the PLC rack and possibly some other sensitive electronic equipment. Four zones (0 to 3) are shown in this Figure.

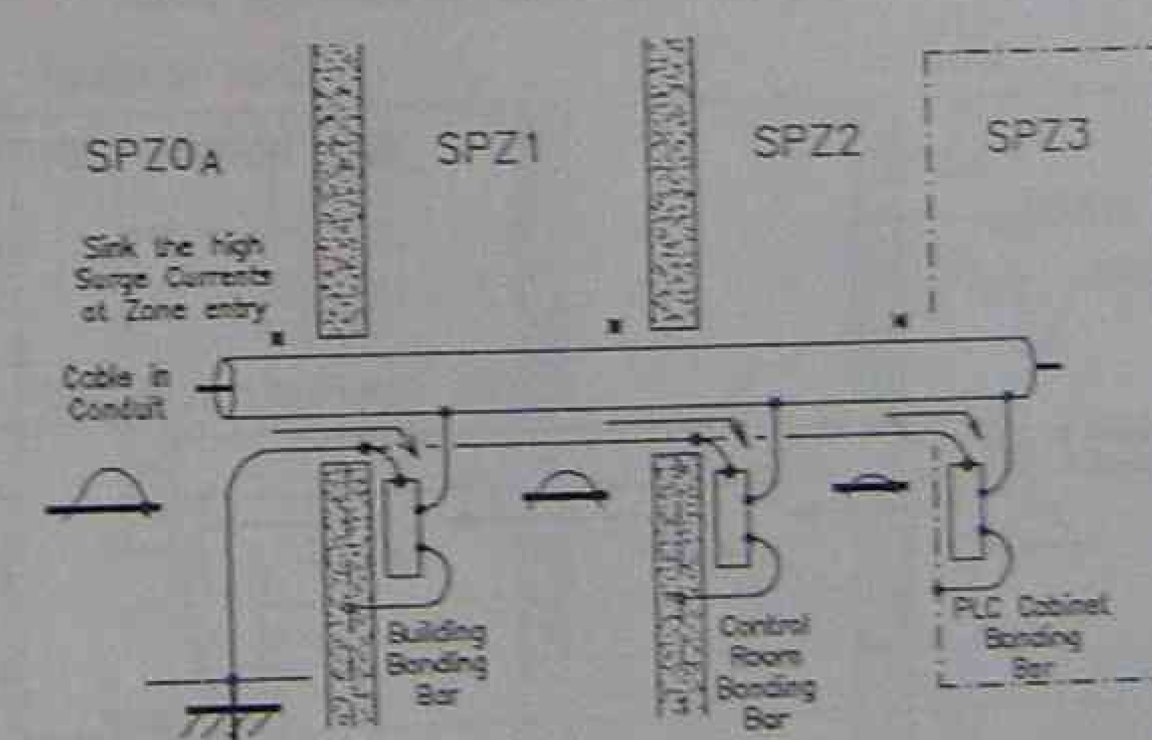


Figure 4.2 : Example of Nested Surge Protection Zones

Figure 4.3 is a diagrammatical representation of the four nested Surge Protection Zones SPZ0A, SPZ1, SPZ2 and SPZ3. For attenuating the noise on the external shield (conduit), provision needs to be made for bonding at each boundary. For the insulated signal lines, Surge Protection Units (SPUs) may also need to be installed at the points of entry to next zone. Figure 4.3 shows the location of an SPU at every zone interface, but in practice it would not be necessary to use this many. The purpose of the SPUs is to limit surge voltages between the signal lines and the earthed screen.

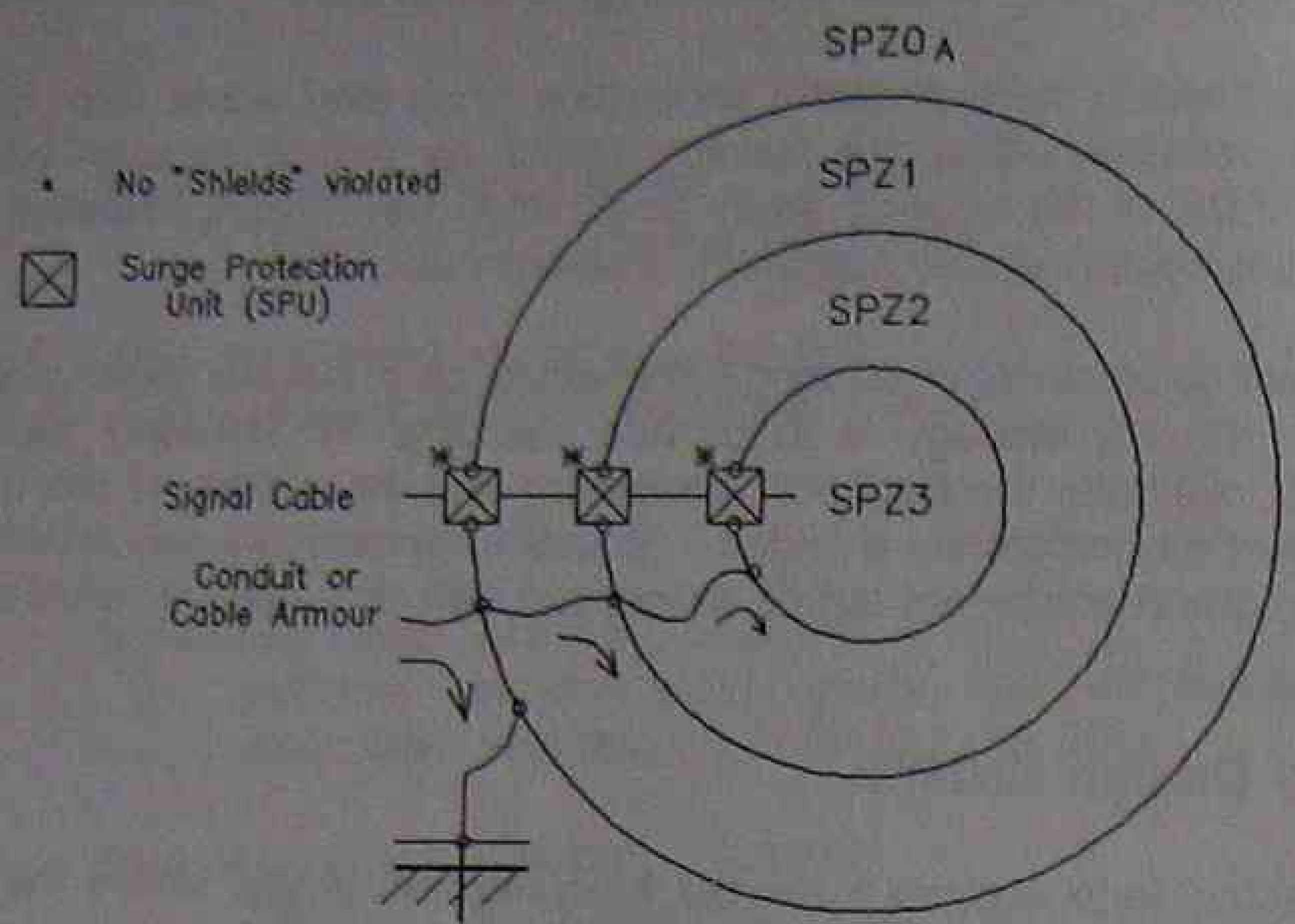


Figure 4.3 : Diagrammatical representation of Nested Shielding Topology

A similar, but different, example is shown in Figures 4.4 and 4.5. In this case, the external shield (e.g. conduit or SWA) is earthed only at the PLC cabinet. With this arrangement, the harsh external electrical environment has been introduced into deeper zones, which violates the shielding criteria for 2 Zones.

This is similar to the situation where the earth bar in a PLC Cabinet is an isolated "clean" earth and runs to a separate 'low impedance' external earthing point.

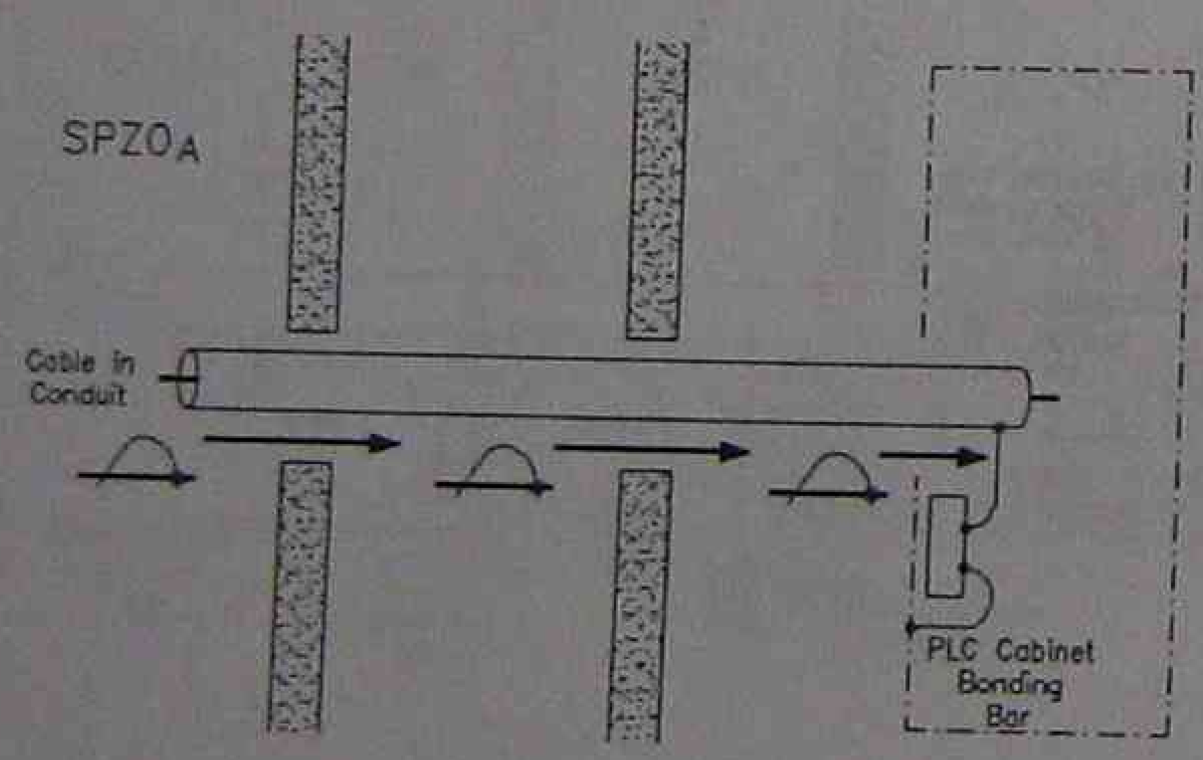


Figure 4.4 : Signal Cable Shield connected at the PLC Cabinet.

Figure 4.5 shows a diagrammatical representation of the nested Surge Protection Zones, which in this case would only be SPZ0A (Outside) and SPZ1 (Inside).

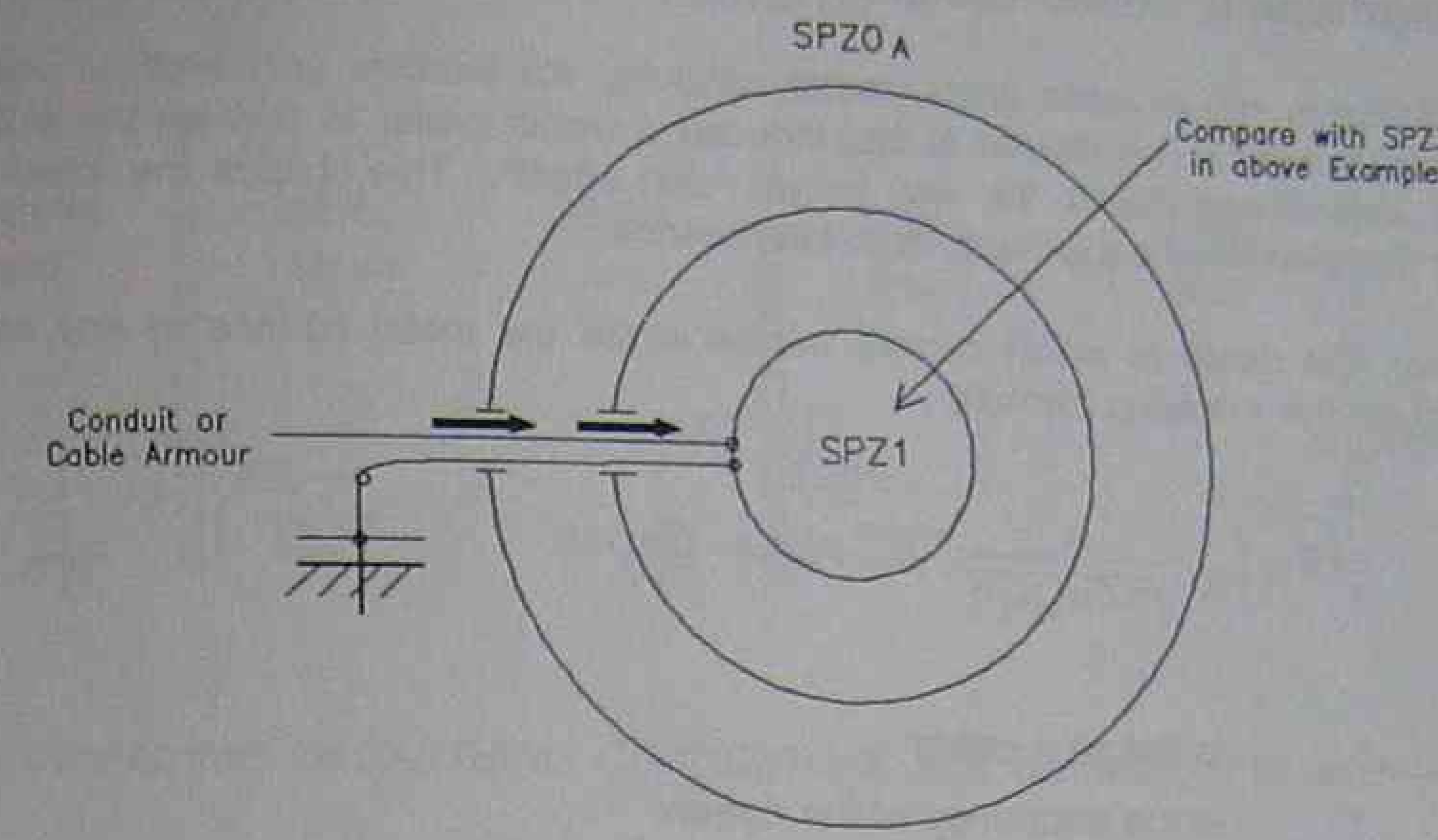


Figure 4.5 : Nested Shielding Topology for the second example

The physical layout of a plant building, showing the exterior zone and two interior surge protection zones, is illustrated in Figure 4.6 below. Two shield interfaces are shown, one at the building perimeter and the second at the equipment room perimeter. Also shown is a shielded cable duct between two parts of the electrical equipment zone (SPZ2).

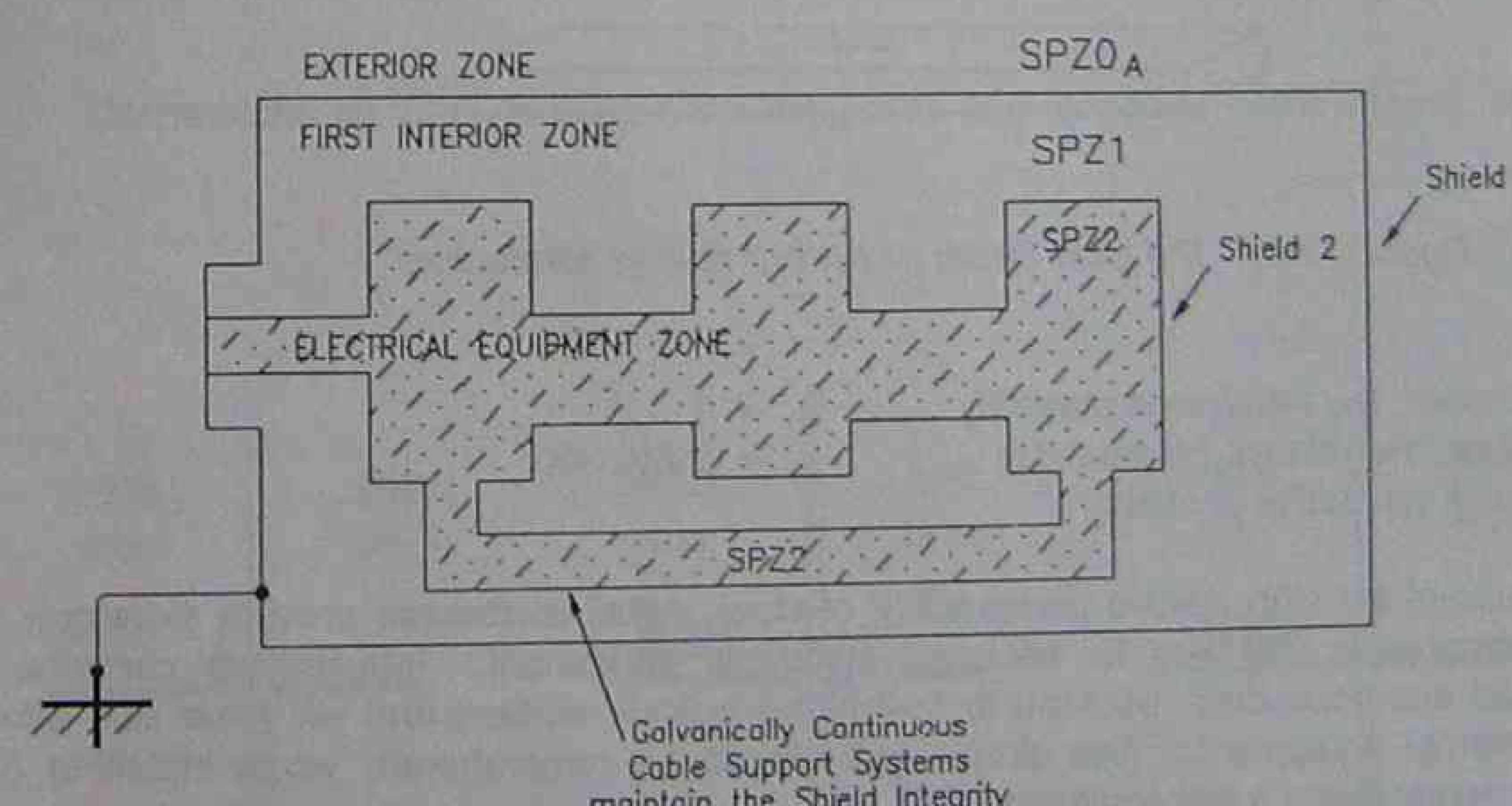


Figure 4.6 : Three Zones of a typical industrial plant layout

4.5 Maintaining Shield Integrity

Metal enclosures, metal cable ducts, metal conduits, etc perform very well as shields for electronic equipment. The reason is that induced currents prefer to flow on the **outside of the metal enclosures** due to the well known "skin effect". This shields the interior zone, containing the electronic equipment, from interference.

Theoretically, the depth to which current will penetrate the metal surface of any conductor is governed by the following formula :

$$\delta = \frac{1}{\sqrt{\pi f \mu_o \mu_r \sigma}} = \textit{skin depth}$$

where :

δ	is the skin depth
f	is the frequency of the current
μ_o	is the permeability of free space
μ_r	is the relative permeability of the conductor
σ	is the conductivity of the conductor

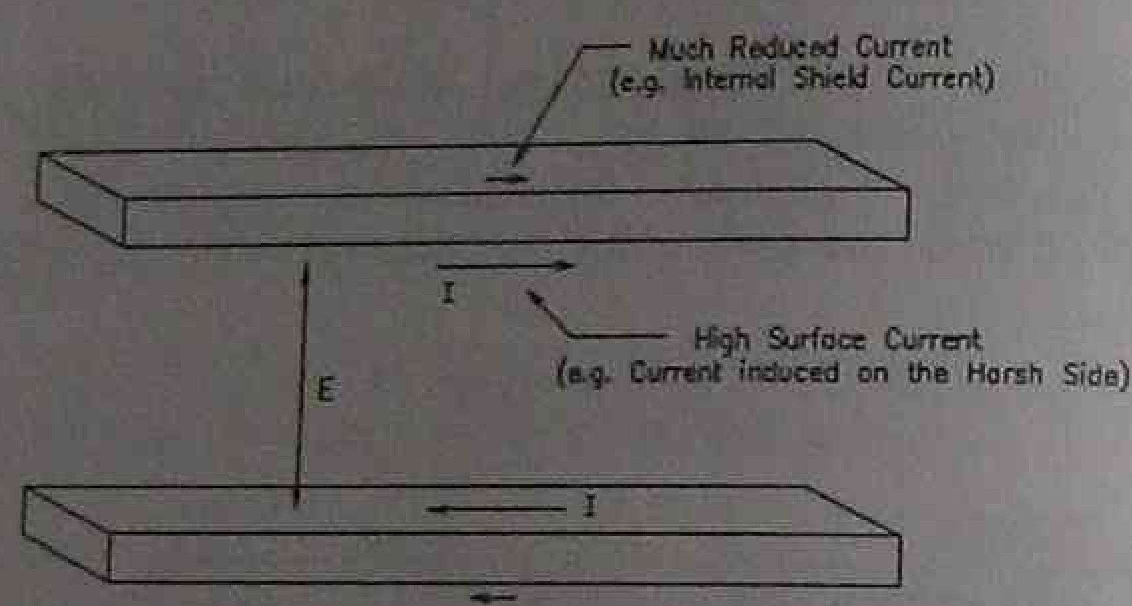


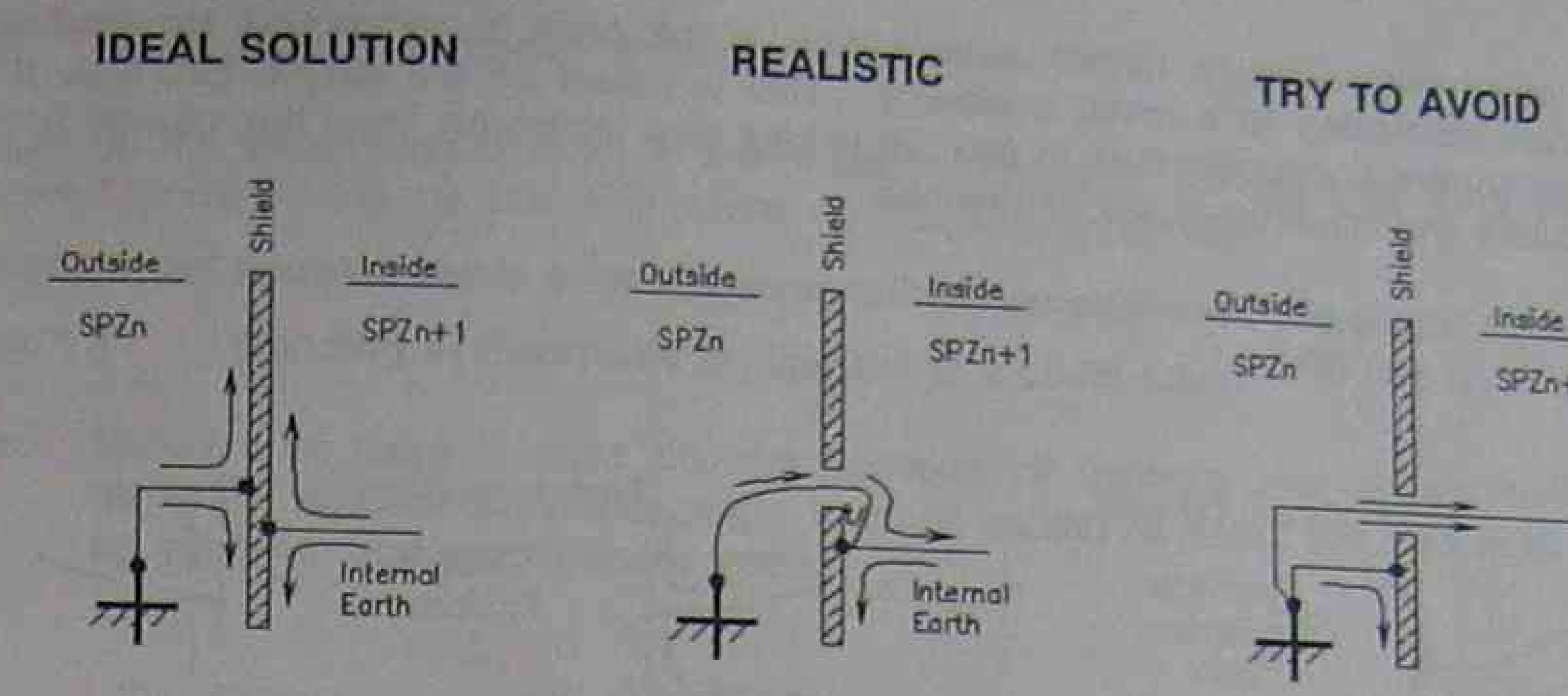
Figure 4.7 : The Skin Depth of current flow in conductors

For Copper, the relative permeability $\mu_r = 1$
For Steel, the relative permeability $\mu_r = 20$ to 300
(depends on quality of steel)

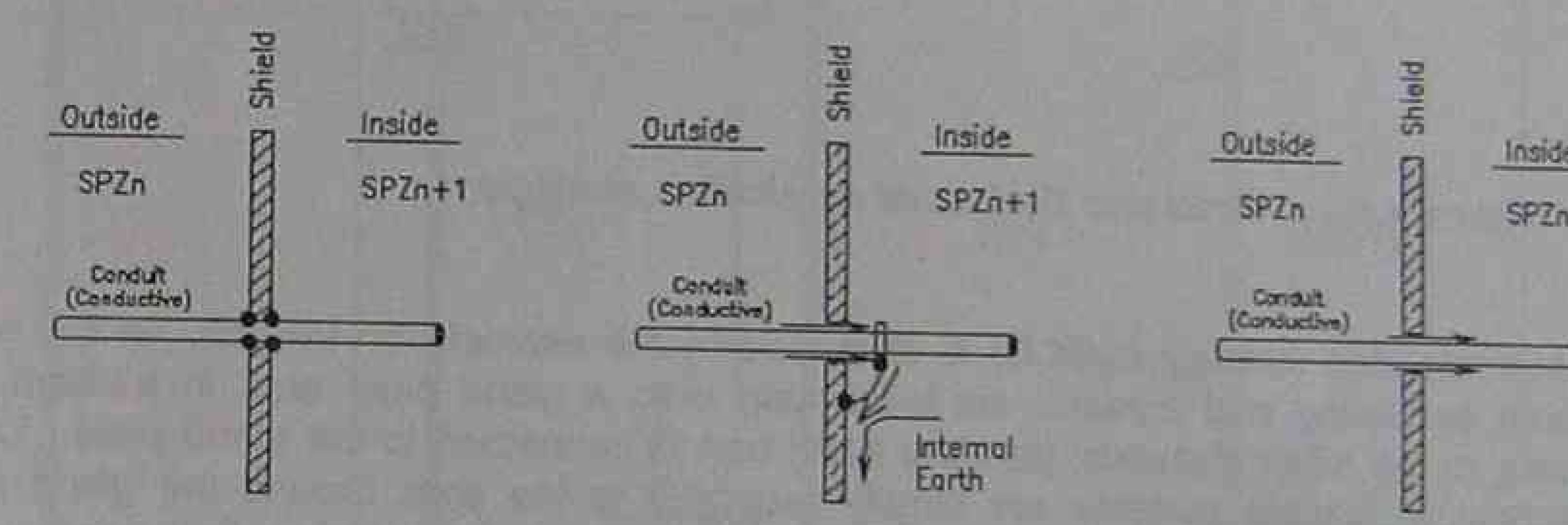
Because of the high relative permeability of steel, metal enclosures provide extremely good electromagnetic shielding for enclosed electronic equipment. Interference currents, both induced and conducted, will tend to flow in the outside surface and will have little effect on the internal equipment. This simple fact should be remembered, when installing SPUs, cable screens and earth conductors.

Figure 4.8 shows a number of alternative techniques for connecting :

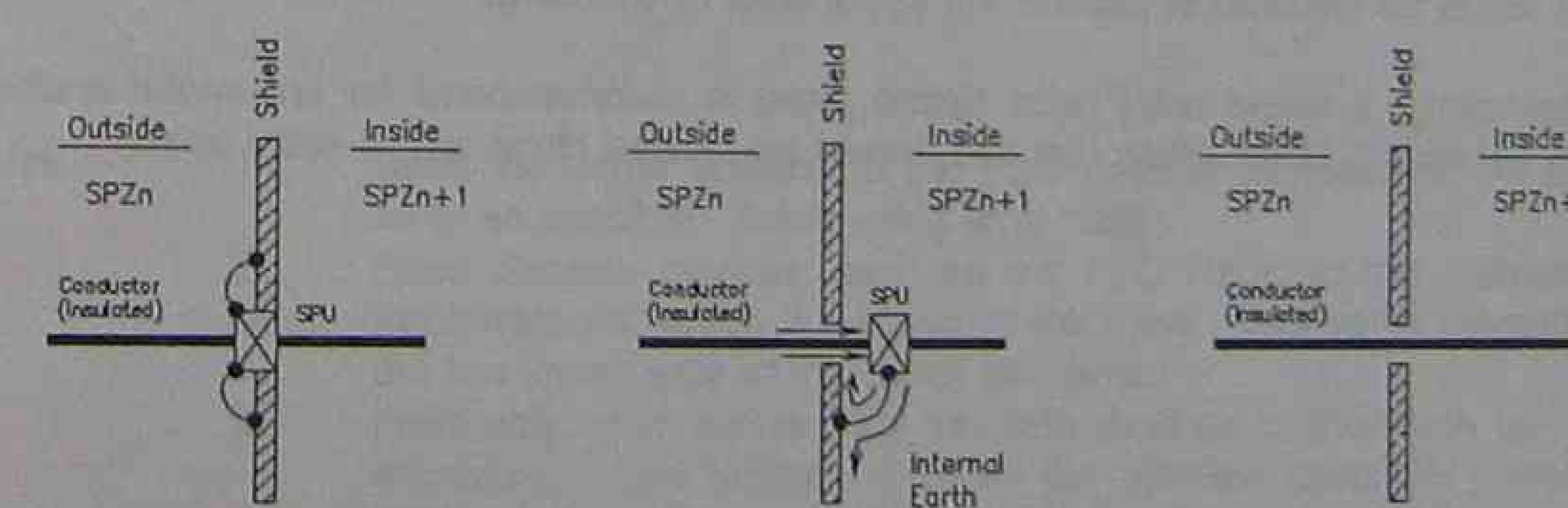
- **Earthing Conductors** (for connecting to an earth bar or earth electrode)
- **Earthable Conductors** (cable support systems .... conduit, SWA, ducts, etc)
- **"Floating" Conductors** (isolated signal cables or power cables)



Connections for EARTHING CONDUCTORS (e.g. connections to earth electrodes)



Connections for EARTHABLE CONDUCTORS (e.g. conduits, cable armour, ducts)



Connections for FLOATING CONDUCTORS (e.g. Signal cable, power cable)

Figure 4.8 : Recommended Connection Techniques

With metal enclosures, a further consideration is the point of connection for conducting materials connected to a metal enclosure. This is based on the simple fact that, if the surface current is not permitted to flow (or is kept to a minimum), then the internal current is reduced and interference will be reduced.

Figure 4.9 shows two alternative connection strategies for a shield between two equipment zones SPZn and SPZn+1 :

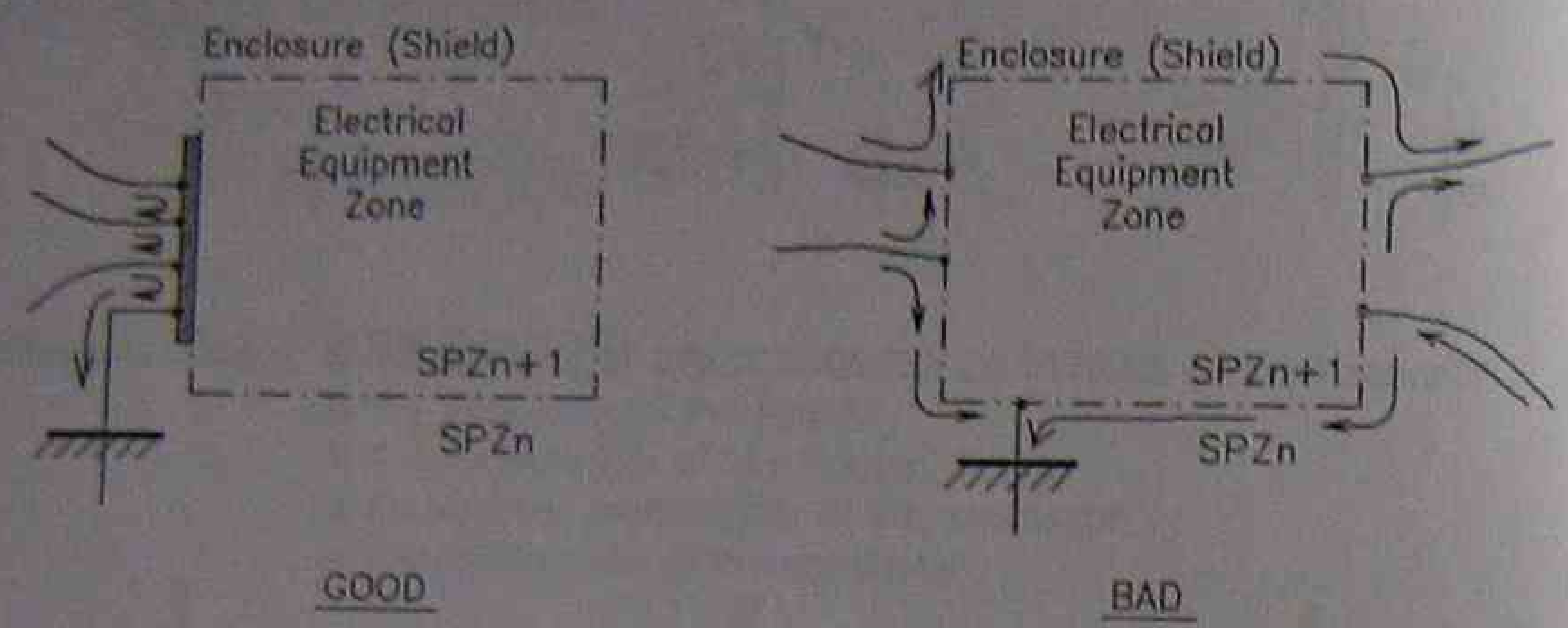


Figure 4.9 : Good and Bad cable termination strategies

The recommended strategy (GOOD) is illustrated by the example on the left. In this case, the cable armouring and screens are terminated onto a gland plate and, in addition, the conductor to the earth electrode (building earth bar) is connected to the gland plate. Using this technique, surface currents are largely restricted to the area around the gland plate and only small currents flow over the rest of the surface. This implies that poor quality shielding materials can be used for the remainder of the shield (enclosure).

The strategy shown in the example on the right is NOT recommended. In this case, cables are terminated at various points on the top and sides of the enclosure. Large interference currents flow over the surface of the enclosure. A better quality shielding material (thicker steel) would be required to provide the same level of shielding.

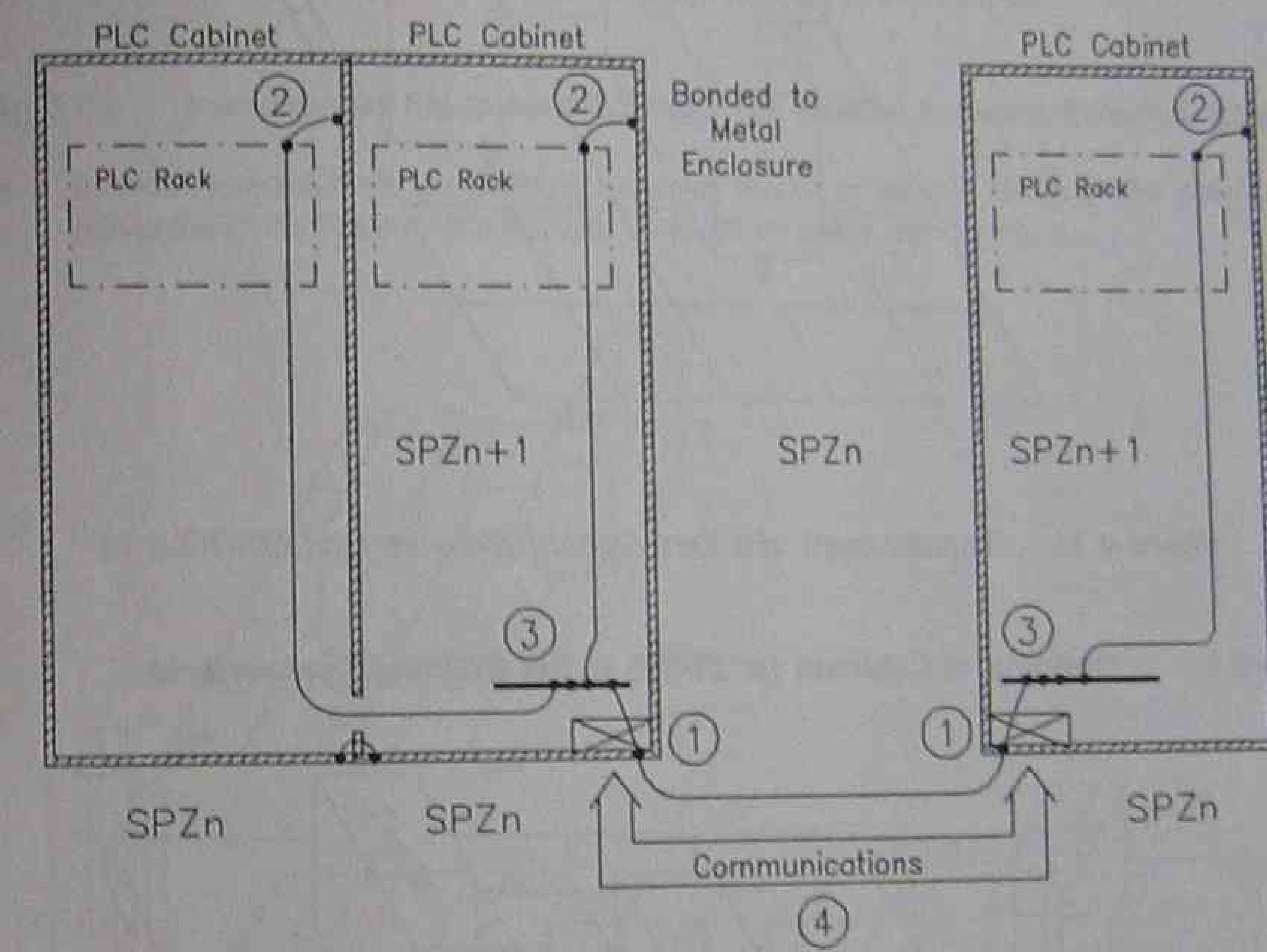
Consequently, a single entry point (gland plate) is recommended for any metal enclosure. Surge Protection Units, when required, would be located close to this entry point.

4.6 Shielding Electronic Systems

Based on the information covered in the preceding chapters, the following steps may be followed for minimising the effects of surges on electronic equipment :

Step 1 : Bonding of Electronic Equipment at a Local Level

- Ensure that there is solid bonding between all cabinets and panels containing electronic equipment within a single room or section of plant. The idea is to create an ***equipotential environment*** locally.



Notes :

1 : Bond the cable screens to the PLC Cabinet as close to the point of entry as possible. Avoid using long "tails".

2 : Bond discrete devices, such as the PLC Rack, to the metalwork of the enclosure, which is earthed at the base. This takes advantage of the low impedance of the metal structure.

3 : Preferably, also connect the discrete devices to the earth bar in the enclosure. Use straight runs by the shortest possible route. DO NOT coil the earth connection as this introduces extra inductance.

4 : The Signal Cable travels through a more harsh zone, so screens should be bonded at the entry to the enclosure.

Figure 4.10 : Typical connections for an Industrial Automation System

- The principle behind the zero signal reference grid (ZSRG) is that a **wide conductor geometry** (several parallel paths) presents a lower inductance than a **narrow conductor geometry**. Similarly the resistance is lower. Therefore the Zero Signal Reference Grid (ZSRG) provides the lowest impedance interconnection of electronic equipment. This is a similar to the strategy in Chapter 3 for interconnecting buildings.

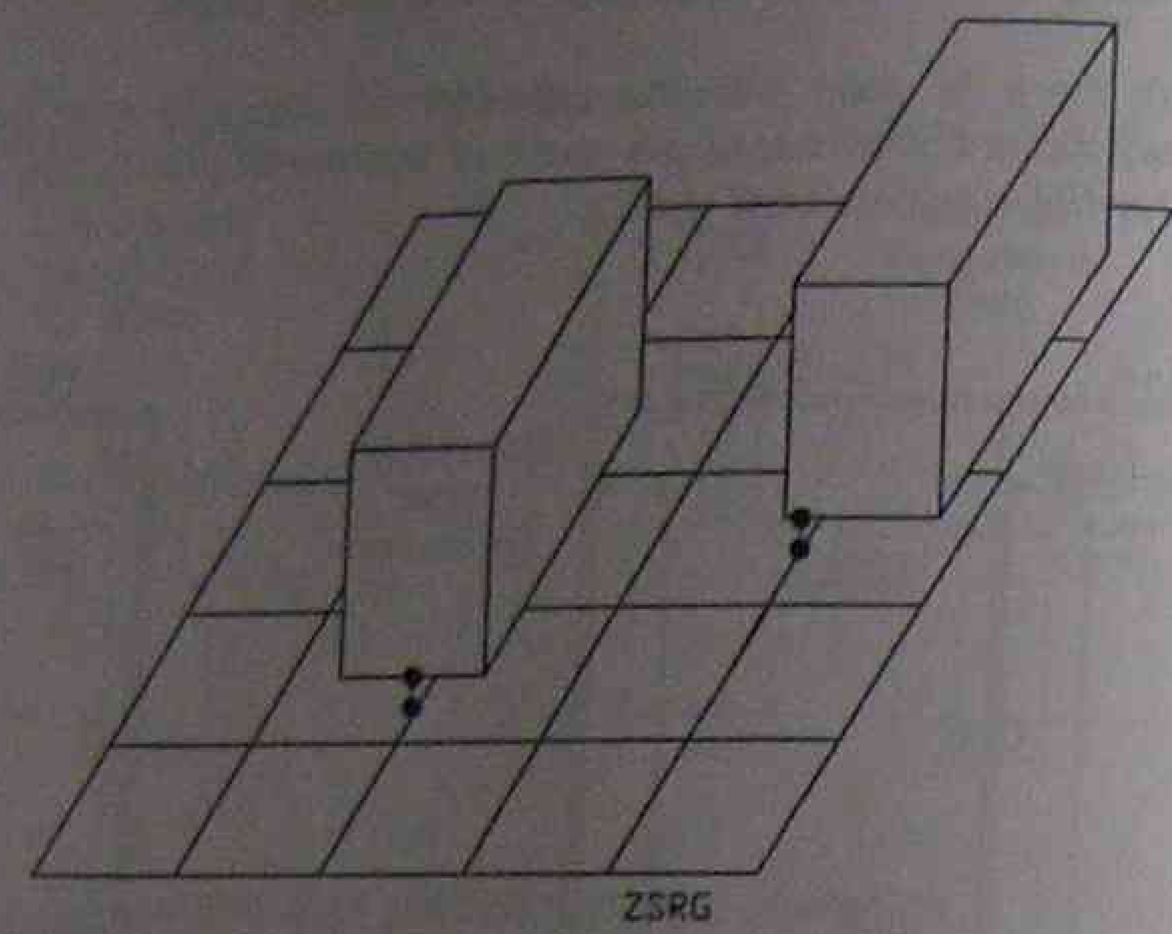


Figure 4.11 : Establishment of a Zero Signal Reference Grid (ZSRG)

Step 2 : Bonding of Cabinets (or ZSRG) to the Building Components

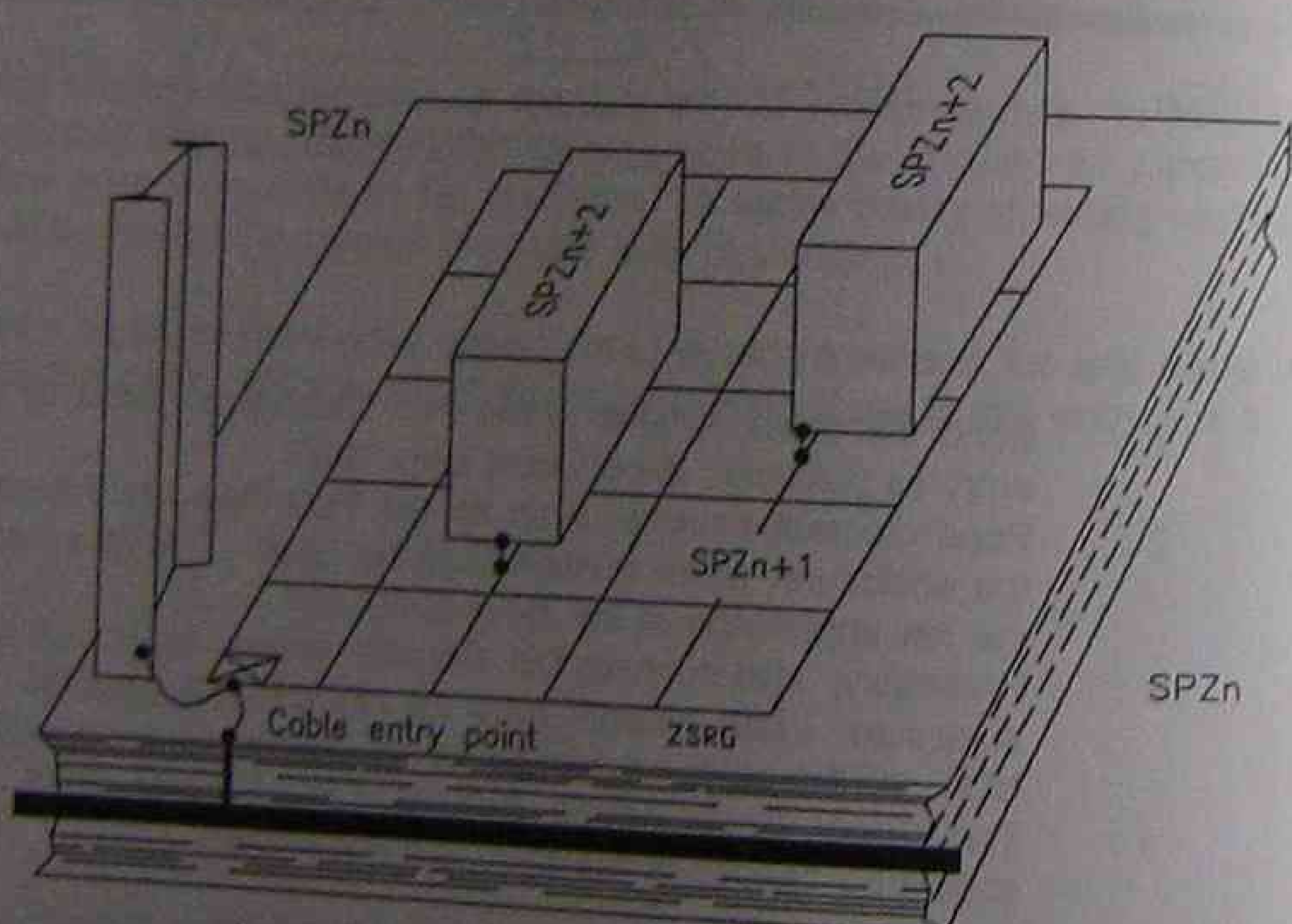


Figure 4.12 : Bonding of the ZSRG to the Structural components of the building

- Bond the metal cabinets wherever possible to the structural metal of the building (rebars and I-beams). This connection is purely for noise considerations and must NOT replace the safety earth. This will assist in establishing a type of low-impedance ZSRG around the metal equipment enclosures.
- In some cases, such as "computer rooms", a dedicated ZSRG is often established for the equipment using a raised conductive floor. This type of ZSRG is effectively insulated from the building except for its safety earth connection. In this case, bond the ZSRG to the structural steel of the building at one point near to the cable entry point for that environment.
- Any unearthed conductor entering this environment is a potential source of conducted noise and should, therefore, be earthed to the ZSRG.

Step 3 : Interconnect Equipment Cabinets (or ZSRGs) between Different Areas

- Interconnect cabinets (or ZSRGs) between rooms or remote areas of the plant using galvanically continuous cable trays, conduits or cable armouring.

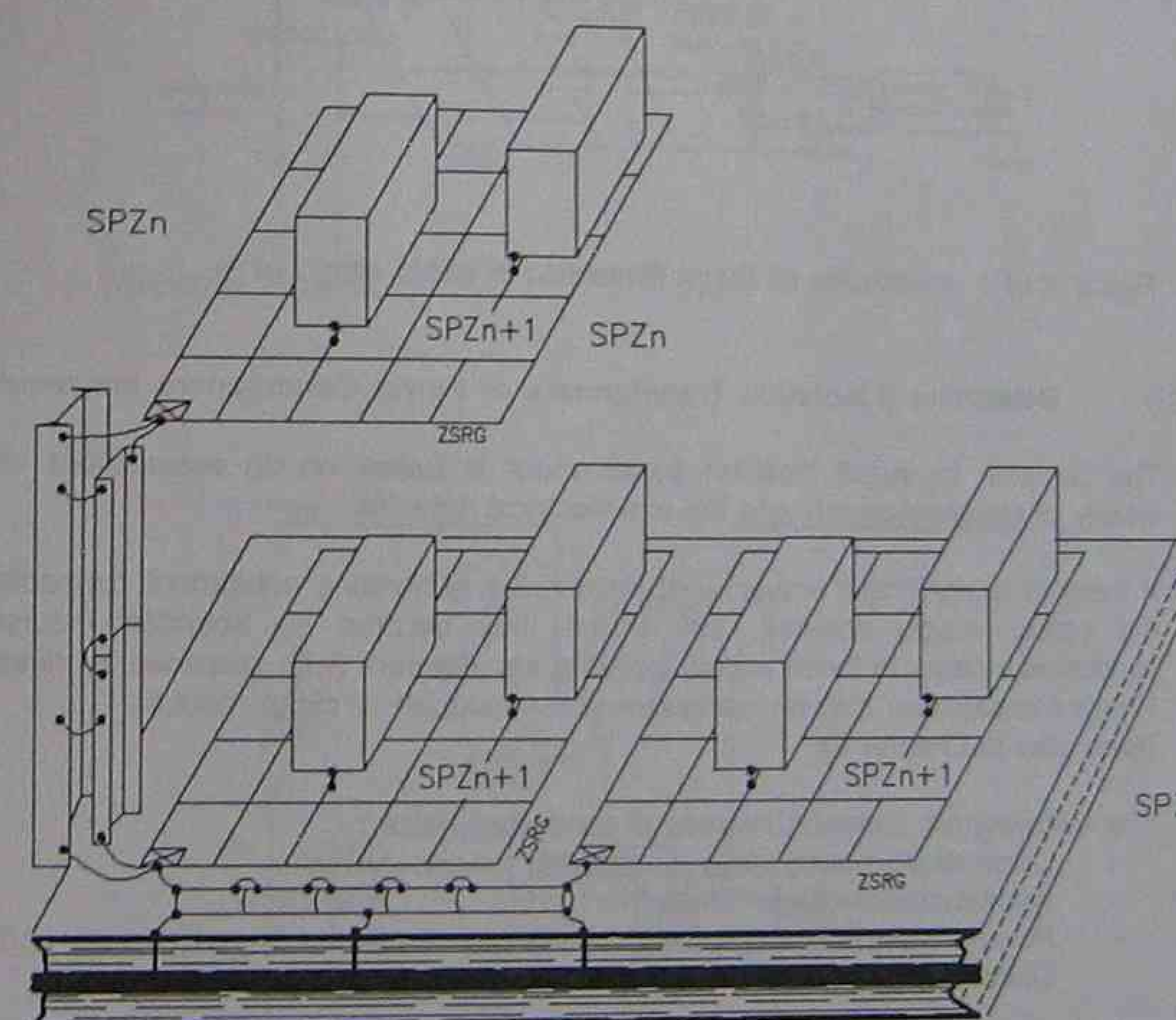


Figure 4.13 : Interconnection between different ZSRGs using galvanically continuous cable trays, conduits or armouring

- Such interconnections should themselves be earthed to structural metalwork wherever possible to ensure a low inductance characteristic. Where equipment is on different floors, rebars are an ideal method for interconnecting ZSRGs.

- Ideally builders should be made familiar with the requirements of using rebars as interconnections and to form a pseudo-faraday cage. This is particularly important where prefabricated reinforced concrete parts are used.

Step 4 : Install Surge Protection Devices at Strategic Points

- Install surge arresters at the cable entry points to the ZSRGs. This must include both power and signal cables. The ZSRG is an effective sink for surge currents.

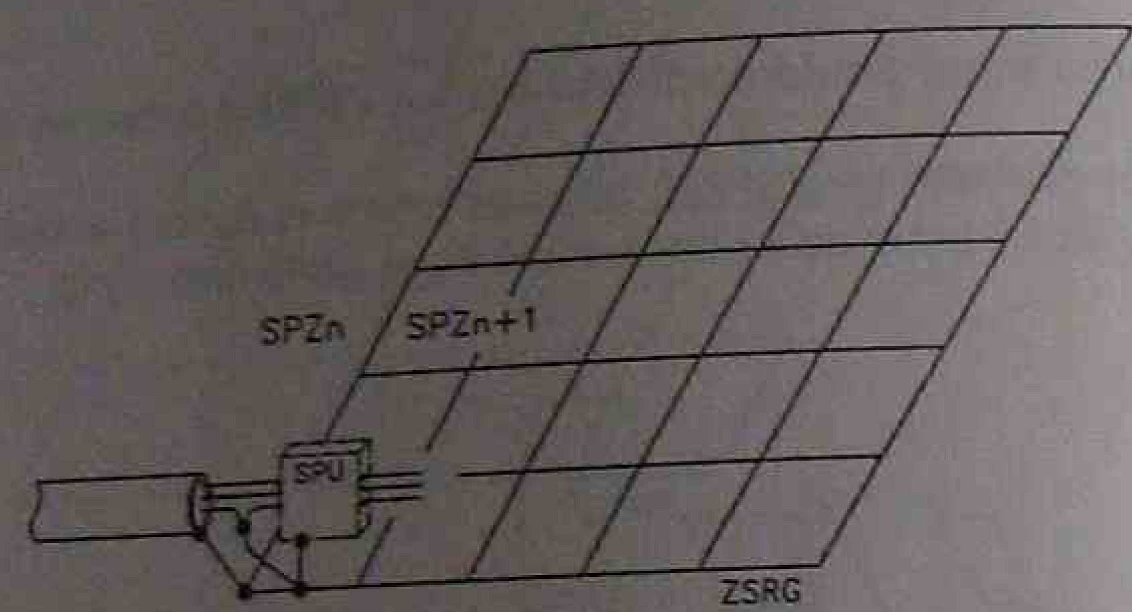


Figure 4.14 : Installation of Surge Protection at cable entry points

Step 5 : Determine if Isolation Transformers or Power Conditioners are required.

- The decision to install isolation transformers is based on an assessment of the quality of electrical supply and the site electrical network.

- If there is a significant presence of large noise generating equipment connected to the power supply network, the neutral may become an abundant source of conducted noise. In these cases, isolating transformers (with screened windings) or Power Conditioners may be necessary to re-establish a "clean" neutral. (refer also to Chapter 5).

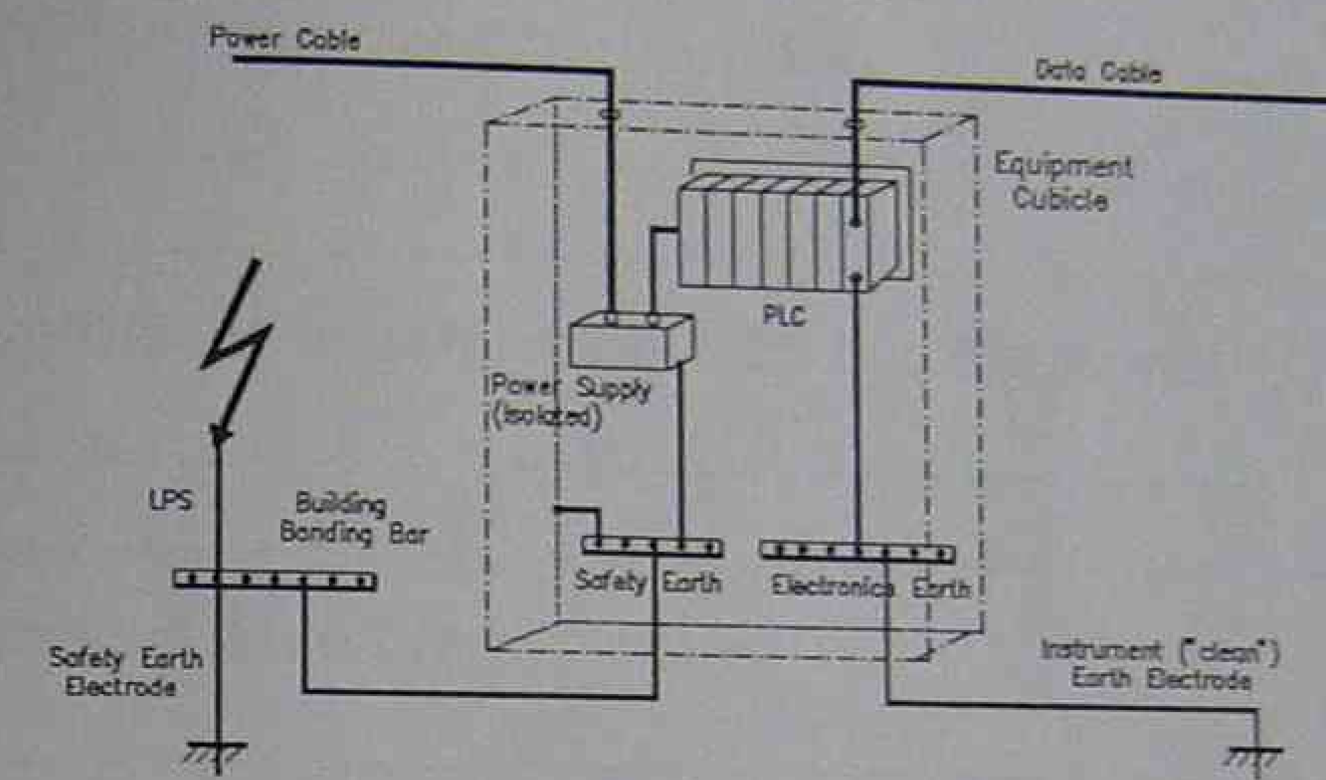
  The following are common sources of conducted noise :
  - Large single phase loads (large 50Hz neutral currents)
  - Arc furnaces (voltage "flicker")
  - Power electronic equipment, such as Variable Speed Drives (VSDs), Uninterruptible Power Supplies (UPSs), induction heaters, etc,

Step 6 : Connections between Buildings

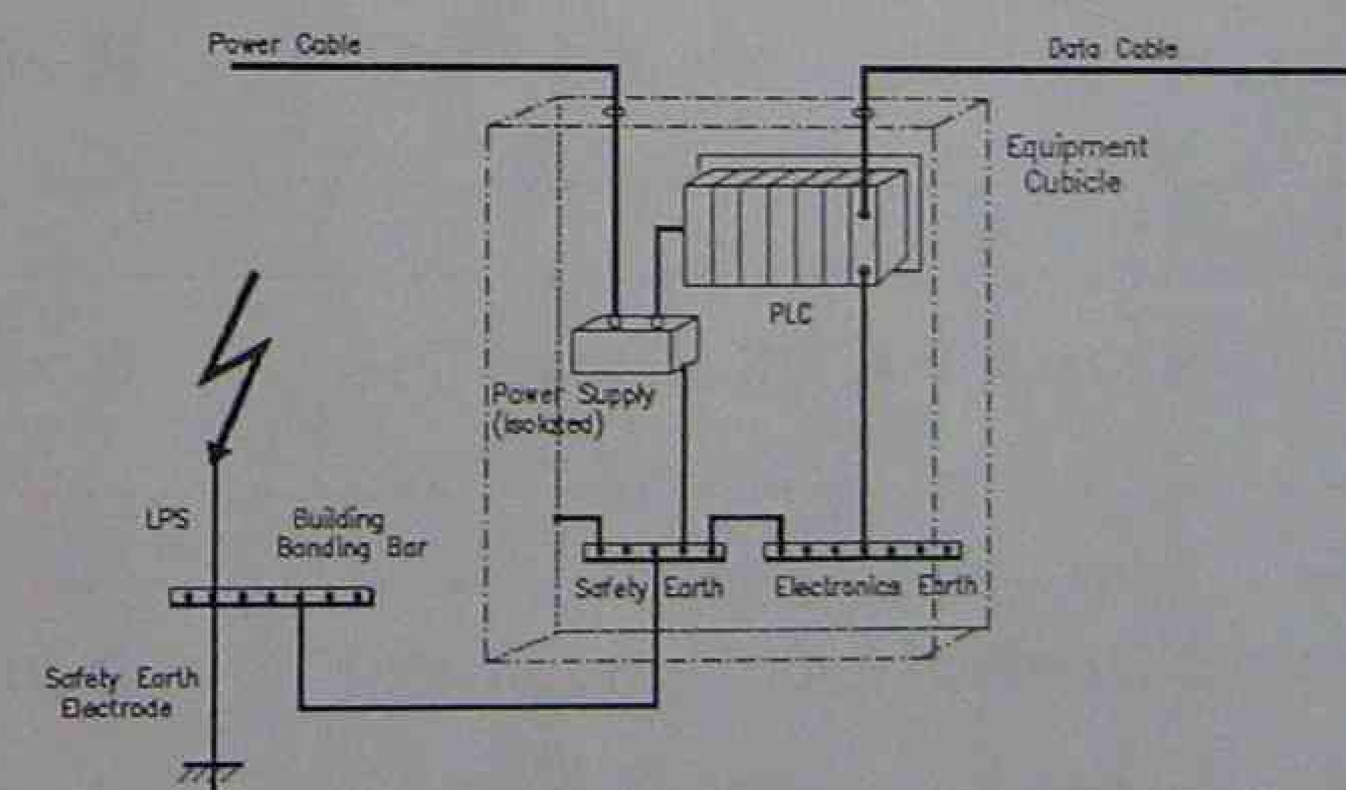
- Where conduit and cable trays run between buildings, these should be bonded to the building earth bar at the point of entry into the buildings. As recommended in Chapter 3, the building earths should first be interconnected to establish an equipotential plane.

4.7 Comment on Segregated Instrument Earthing Systems

In many installations, the power system and the instrumentation system are designed with separate earth bars, the latter usually being referred to as the "clean" or "instrument" earth. In fact, some manufacturers of control equipment recommend this earthing solution. Although this approach may have some merit in excluding noise during normal operating conditions, there are considerable risks of severe equipment damage during abnormal situations, such as those which occur during lightning. To avoid equipment damage, particularly in high lightning areas, these two earths should be bonded together.



(a) Separate Earth Bars



(b) Earth Bars Bonded together with copper conductor > 6mm²

Figure 4.15 : Connecting the Electronics Earth and the Safety Earth

Blank Page

0 Contents

Chapter 5 : SURGE PROTECTION DEVICES AND THEIR APPLICATION

5.1 Introduction

A **Surge Protection Unit** is a combination of electronic, and other electrical components, which is designed to switch on in the presence of high surge voltages and to clamp the voltage as well as divert the associated surge current to earth .... *without damage to itself.*

The use of **Surge Protection** is not necessary for every application where electronic equipment is used, even in industrial applications. Many electronic devices operate reliably for years, even in quite difficult electrical environments. These devices would have been no better off with expensive surge protection units.

Clearly, there are some electronic devices, which are non-critical to the operation of a control system, where surge protection cannot be justified. On the other hand, there are some devices, which are so important to the continued operation of the plant, that surge protection is essential. Many devices have surge protection already built-in, e.g. PLC inputs & outputs.

A question commonly asked by many designers and users is .....

"When do we need to use Surge Protection Devices for our instrumentation and control system components and ... how far do we need to go with this equipment?"

Unfortunately, there is no simple answer to this question and the decision would be based on *JUDGEMENT* rather than on a well proven and well known formula. The closest analogy to Surge Protection is the decision to take out an *Insurance Policy.*

- The amount spent on Surge Protection (Insurance) depends on *Risk Assessment* ...
  - the **likelihood** of a dreaded event ever taking place
  - the **consequences** of a dreaded event actually taking place
- The trade-off of RISK against COST
  - No Insurance (Protection) Purchased ....
    How much will it cost if the dreaded event DOES happen
  - Some Insurance (Protection) Purchased ....
    How much will it cost even if the dreaded event DOES NOT happen

For a modern control system, the following issues should be considered :

- A thorough analysis of the electrical power system .... source of power supply, earthing arrangements, voltage, quality of supply, switching, protection, etc
- Is the environment a high lightning area? What is the probability of a strike?
- Does the designer of the control system understand the *causes and consequences* of Surges and the methods of earthing, shielding and protection.
- What is the likelihood of major power system surges? Consequences?
- What measures have already been taken ... is the earthing adequate?
- What Surge Protection would be necessary and how much would it cost?

After weighing up the above factors, a decision would be made on the level of surge protection required and where it should be applied.

Surges can enter electronic equipment through either the power cables or through the signal cables or both. Inputs and Outputs to/from the electronic equipment, which could provide entry for high voltages during surge conditions, need to be identified and, where necessary, should be isolated, screened or clamped using SPUs (Surge Protection Units).

5.2 Electronic Circuit Protection

5.2.1 Typical Configuration of Electronic Equipment

The configuration of most modern electronic equipment used for instrumentation and industrial control applications is generally very similar. The layout of components, power supply, I/O (inputs & outputs) will invariably be similar to Figure 5.1.

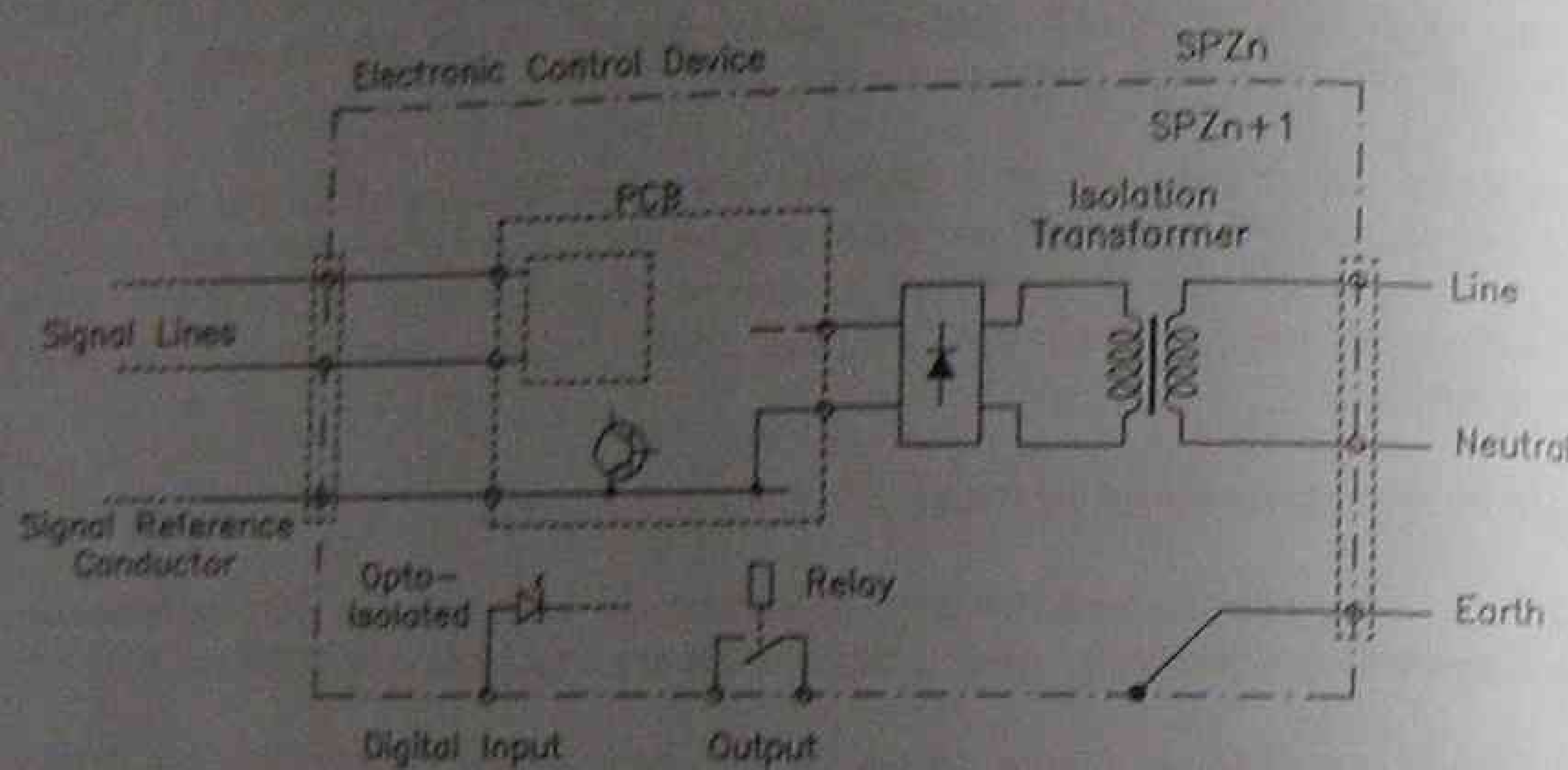


Figure 5.1 : Typical layout and Connections to Electronic Equipment

On the power supply side, the electronic equipment is isolated through a transformer to provide galvanic separation from the power cables and to step the voltage down to a lower level. This removes the possibility of galvanic coupling. In addition, the primary windings are usually screened from the secondary windings to exclude capacitively coupled noise, usually associated with high frequency disturbances. The transformer screen is connected to the chassis of the device and earthed via the safety earth (yellow/green) in the power supply cable. The power supply is then rectified and filtered for supply to the electronic circuits at a suitable DC voltage.

Other I/O (Input/Output) connections are arranged to have galvanic isolation (e.g. Opto-isolated Inputs or Relay Outputs) or are protected in some way, as outlined below.

5.2.2 The Need for Surge Protection of Electronic Components

Electronic components and circuits are characterised by the very small difference between the normal circuit operating voltage and the voltage capable of damaging the components. For example, some semiconductor components, rated at 5Volts, could be damaged by a voltage as low as 10Volts. On the other hand, more robust components, such as the 230Volts isolating transformer, can easily withstand over-voltages of up to 1.5kV.

Where required, the main purpose of Surge Protection Units (SPU) is to clamp the voltage between the signal lines and the signal reference conductor to ensure that the voltage never exceeds a designed value, even in the presence of high voltage surges on the external connection. The concept of an SPU is similar to that of a surge arrestor on a HV power transmission line or transformer.

A number of different components are commercially available to achieve the clamping requirements at the inputs and outputs of electronic circuits. These may be classified into

- Fine Protection e.g. Silicon Suppressors
- Medium Protection e.g. Metal Oxide Varistors
- Coarse Protection e.g. Spark Gap Arrestors

- **MOV : Metal Oxide Varistor**

  A MOV is a robust, but inexpensive, device which exhibits a non-linear relationship between voltage and current .... as the voltage across it increases, the current increases slowly until a "kneepoint" is reached. Thereafter, the current increases rapidly even for a small voltage increase, as shown in Figure 5.2 below.

  The main advantage of MOVs is that they can absorb quite large energies (eg. 200 Joules).

  The main disadvantage of MOVs is that they have a "gentle" knee-point. Also, they are relatively slow to respond to the very fast rise times of lightning and other surges and are not ideal for protecting the delicate P-N junctions of semiconductor devices, such as transistors. They are most commonly used for protecting more robust equipment such as small transformers. They are commonly used to protect the power supply of electronic equipment.

  Another problem with MOVs is that they deteriorate (ageing) with usage. After a number of surges, depending on severity, the MOV can eventually fail through thermal runaway and become a short circuit. Consequently, MOVs need to be protected by fuses, which introduces further problems with fuse coordination. It is also advisable to provide some form of fuse indication otherwise protection will be lost when the fuse blows.

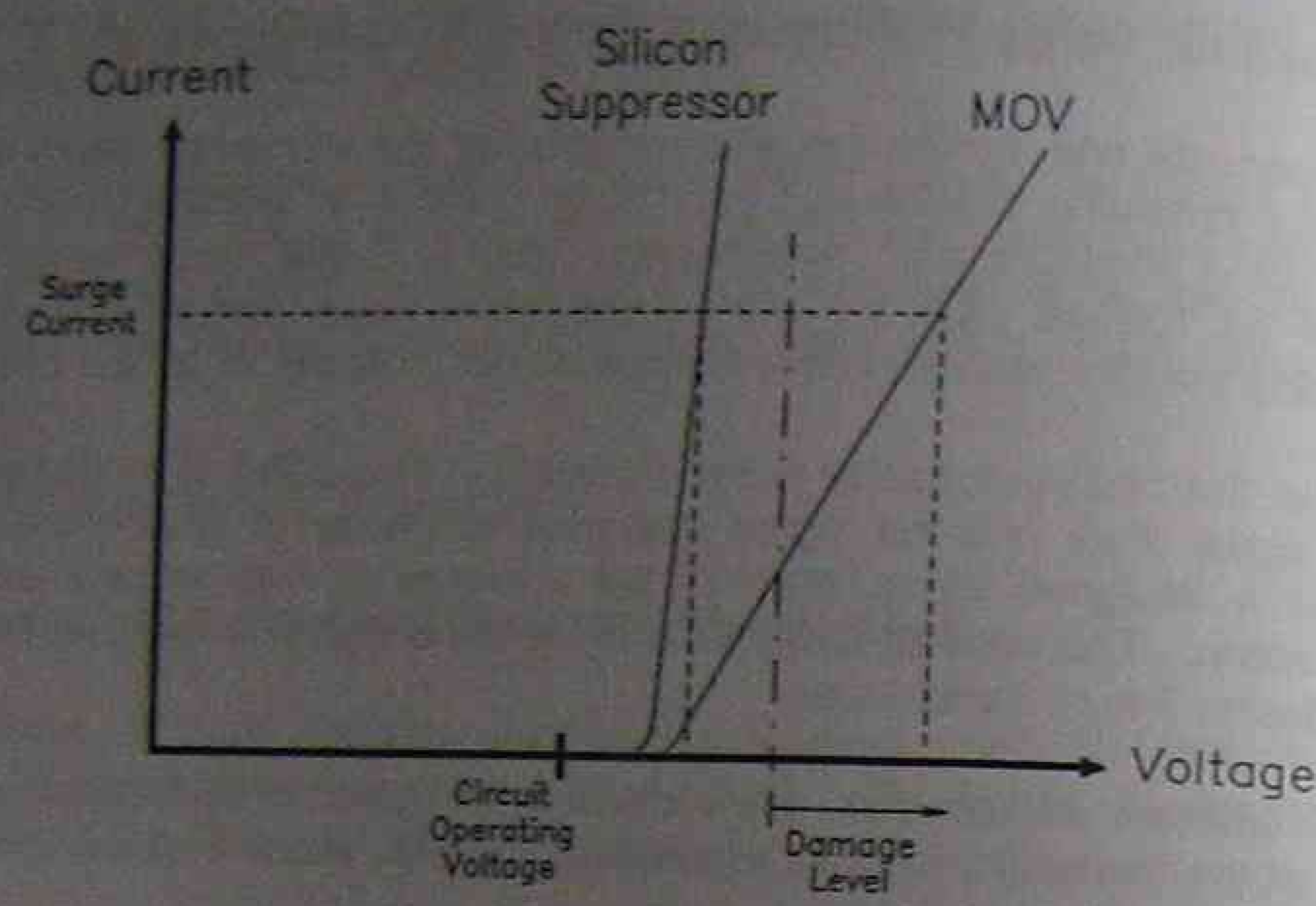


Figure 5.2 : The Voltage-Current characteristics of a MOV compared to a Silicon Suppressor.

- **Silicon Suppressors (eg Transorb – tradename)**

  A Silicon Suppressor is a P-N junction and can be thought of as a high energy Zener Diode. It has a much sharper kneepoint than a MOV, as shown in Figure 5.2, which makes it very suitable for protecting other P-N junction devices.

  The main disadvantage of the Silicon Suppressor is its limited capability to absorb surge energy (eg. 1 Joule). Consequently, additional components, such as spark gaps, must be built into a surge protection unit to protect the Silicon Suppressors. The basic circuit for this type of surge protection unit is shown in Figure 5.4.

- **Spark Gap Arrestor**

  A Spark Gap is a robust protection device that passes no current until the voltage across it increases sufficiently for flashover to occur. A typical minimum spark gap breakdown voltage can be 90Volts, but can be much higher under transient conditions. Ionisation within the device then permits current to pass with relatively small volt drop. Consequently, the spark gap can handle very high energies. Spark gaps are usually used to protect the silicon suppressors. The typical characteristic of the spark gap is shown in Figure 5.3. Unfortunately, flashover only occurs after a period of time (a few hundred nanosecs), which is too long for the protection of electronic P-N junctions.

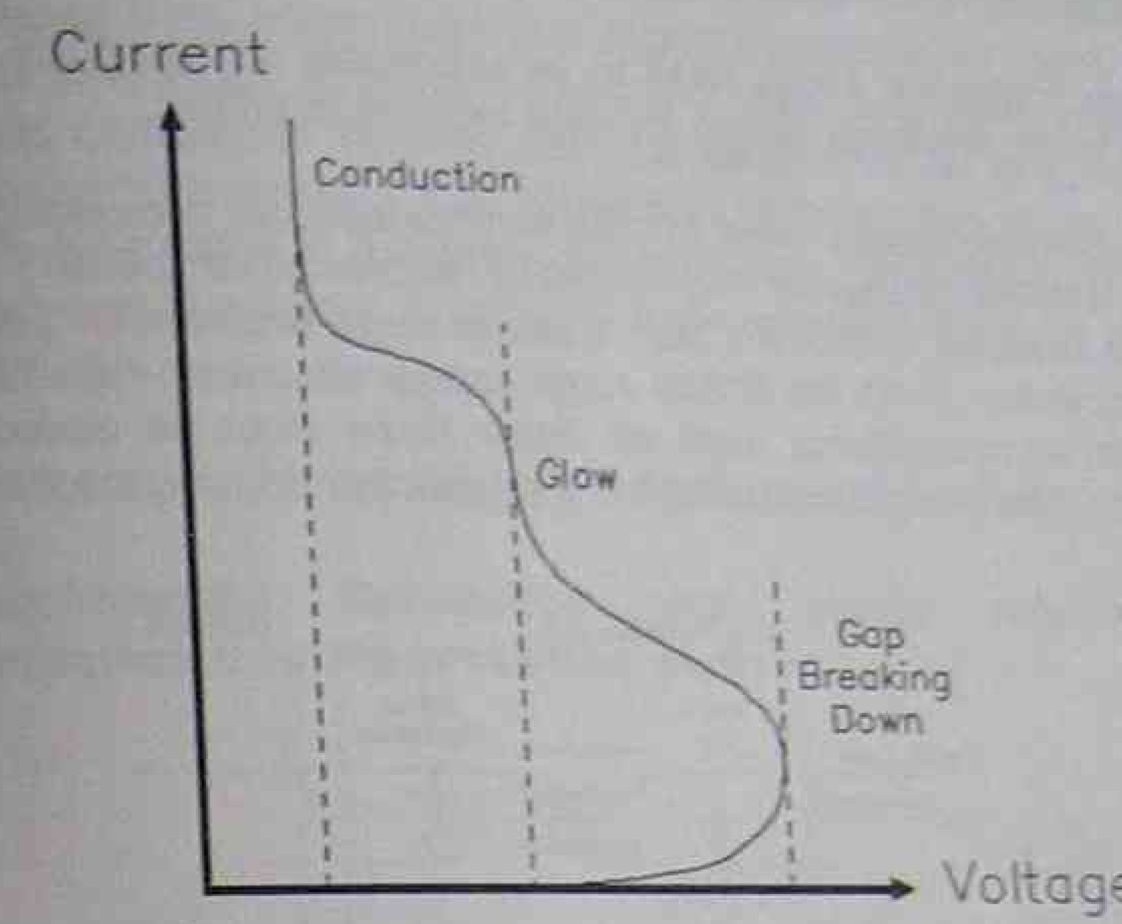


Figure 5.3 : Typical characteristic of the Spark Gap.

5.2.3 The Design of a Surge Protection Circuit

The SPUs (Surge Protection Units) need to be specifically designed for the different I/O and be matched to the electronic device they are required to protect.

For the type of electronic circuits used in data communications, comprising ICs (integrated circuits) such as UARTs (Universal Asynchronous Receiver/Transmitter), line drivers and line receivers, it is essential to use the "fast" types of surge suppression components based on the silicon suppressor. With the limited surge energy absorption capability of the silicon suppressor, additional components such as Spark Gaps must be added to protect the silicon suppressor. The basic circuit used for this type of protection has the following form

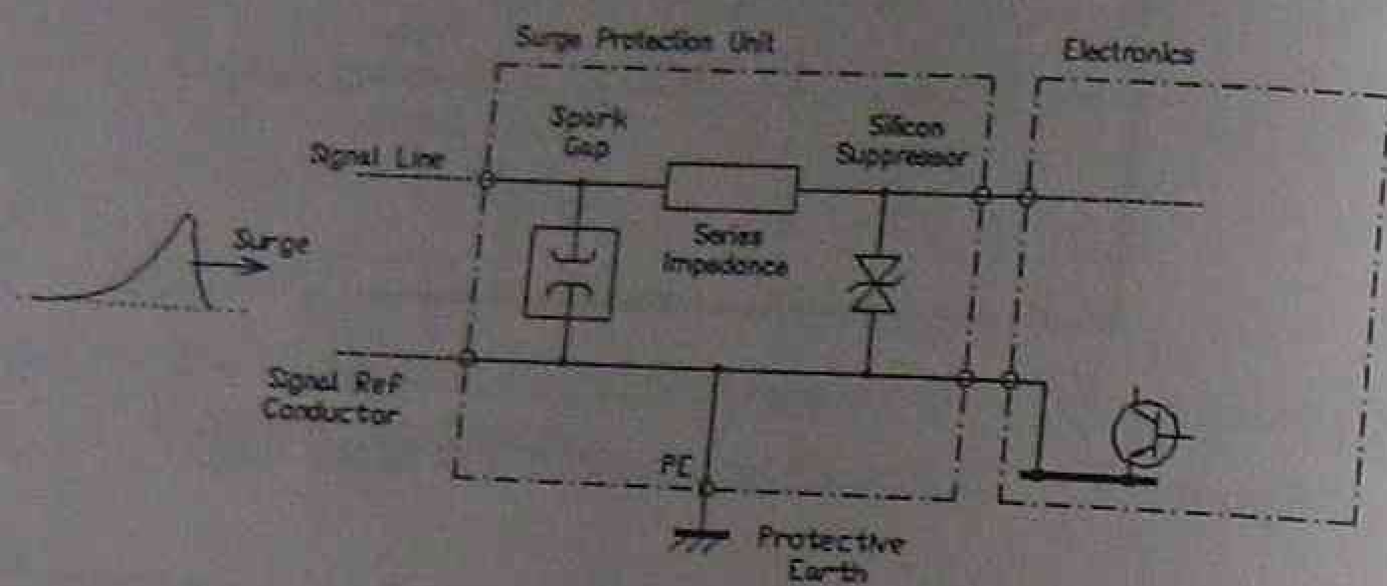


Figure 5.4 : Basic Design of a SPU (Surge Suppression Unit)

The function of the impedance is as follows :

- To limit the current through the silicon suppressor before the spark gap has operated .... the spark gap does not operate instantaneously due to inherent delays in the creation of the arc. This can take several nanosecs.
- To develop a higher voltage across the spark gap than the silicon suppressor to encourage the gap to break down.
- To limit the current through the silicon suppressor after the spark gap has operated. The arc voltage can be as much as 30V.

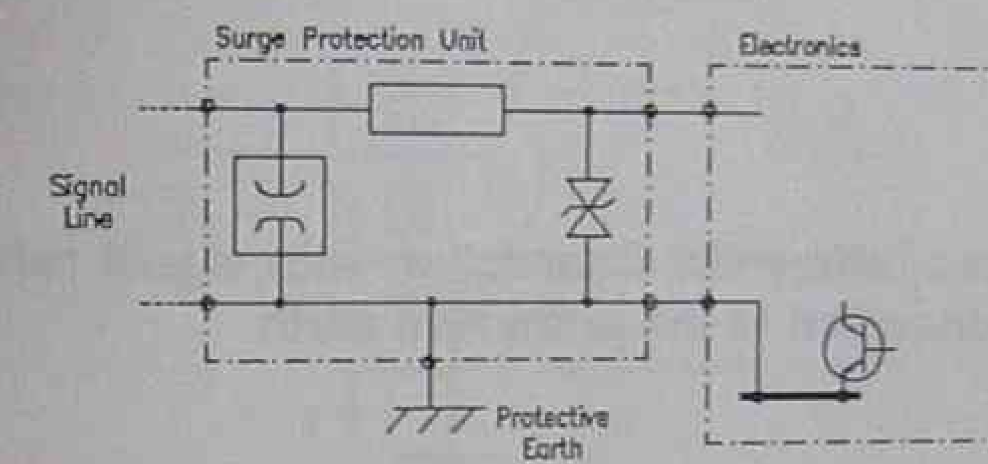
The series impedance between the spark gap and the silicon suppressor can be :

- A *resistor* (typically 5Ω) for signal circuits
- An *air-cored inductance* (typically 5µH) for DC power circuits. The inductance provides a high impedance to the lightning surge (10kHz), but lower impedance to the DC current.
- A *capacitor* for RF (Radio Frequency) circuits. The frequency components of the lightning surge are lower than that of the RF. The capacitor provides a high impedance for the lightning surge but a low impedance to the RF.

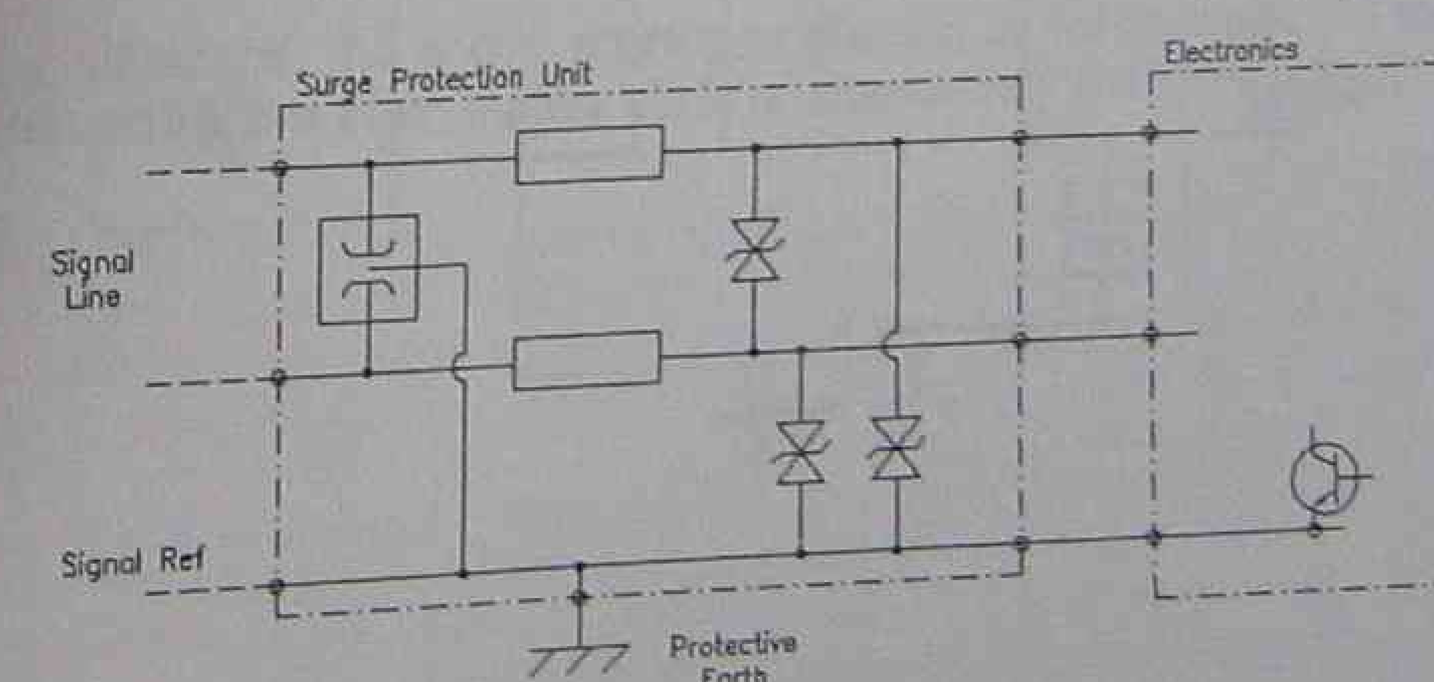
As outlined in a previous chapter, the two main types of communications interface are the *unbalanced type*, which uses one signal conductor for each channel and a signal reference conductor (Common), and the *balanced type*, which uses a two differential signal conductors (twisted pair) for each channel and, usually, a signal reference conductor (Common). The protection of these two types of input against surges needs to be treated in a slightly different way. Knowledge of the topology of the signal reference conductor relative to the protective earth is essential for the correct choice of SPU.

Four common topologies for the **Surge Protection** of signal lines are :–

Type–1 : Unbalanced Connection with signal reference conductor connected to the protective earth

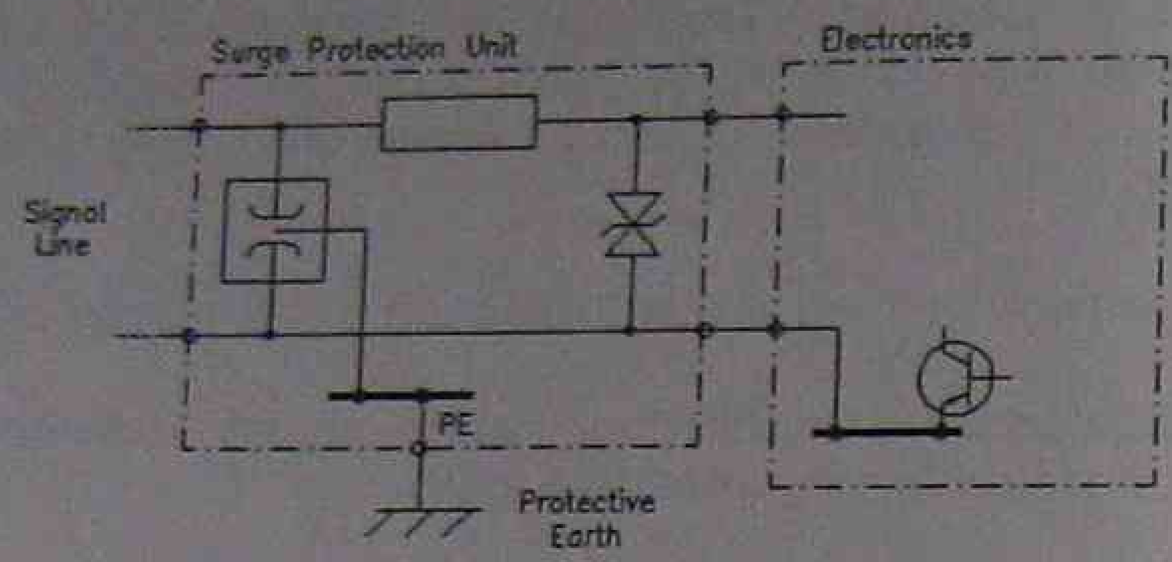


Type–2 : Balanced Differential Connection with signal reference conductor connected to the protective earth

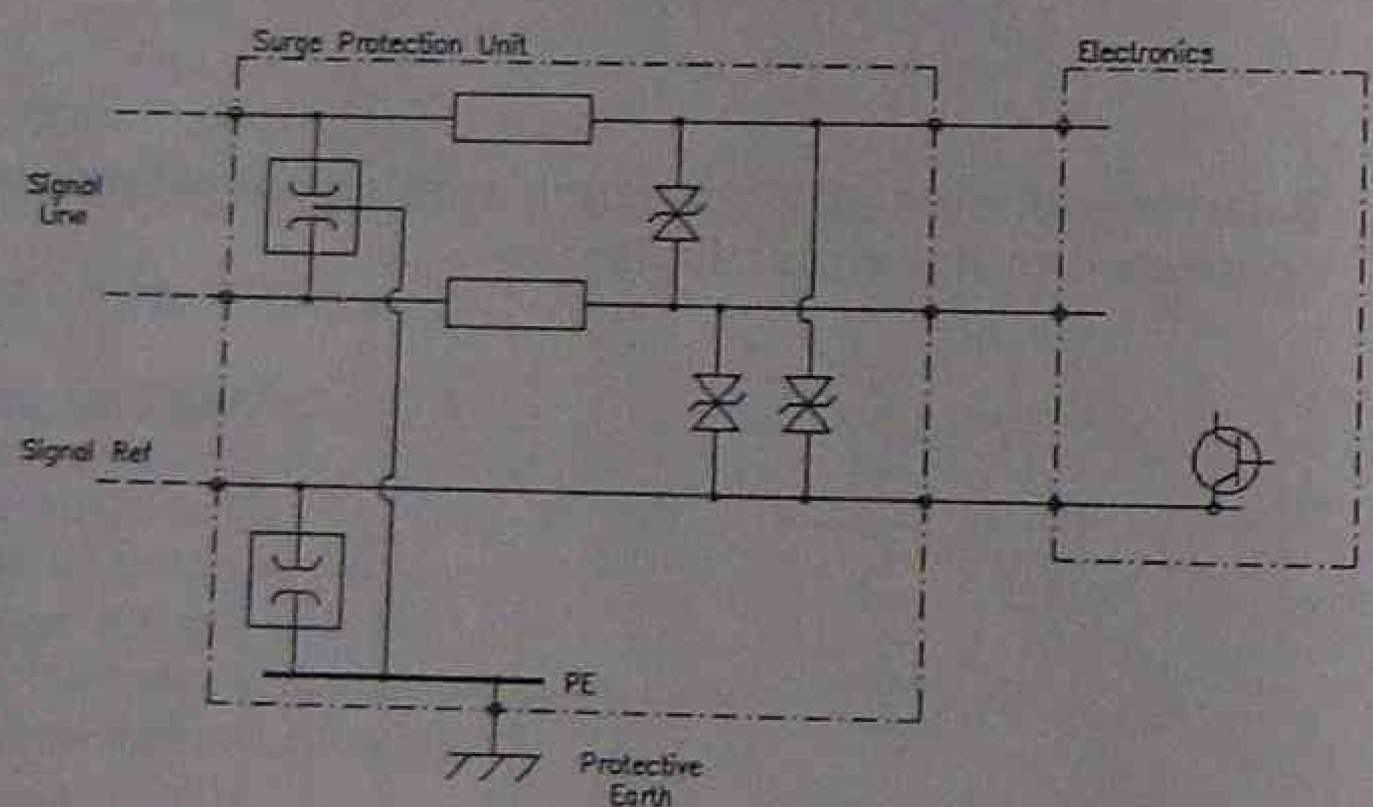


To avoid the generation of high differential mode voltages if only one gap breaks down, three–electrode spark gaps must be used. When the spark gap is ionised, both gaps break down simultaneously.

Type-3 : **Unbalanced Connection with signal reference conductor NOT connected to the protective earth**



Type-4 : **Balanced Differential Connection with signal reference conductor NOT connected to the protective earth**



5.2.4 The Location of Surge Protection Units

An important consideration is where the surge current flows after it has been diverted by the SPU. The spark gap should ideally be placed at a building entrance, where both the cable entry point and the protective earth bar are situated.

The advantages of locating the spark gap close to the cable entry to the building or protected zone are as follows :

- The surge currents do not flow into the signal reference conductor
- SPZ (Surge Protection Zone) Integrity is maintained
- The large magnitude magnetic fields associated with the surge currents are kept away from the sensitive electronic equipment

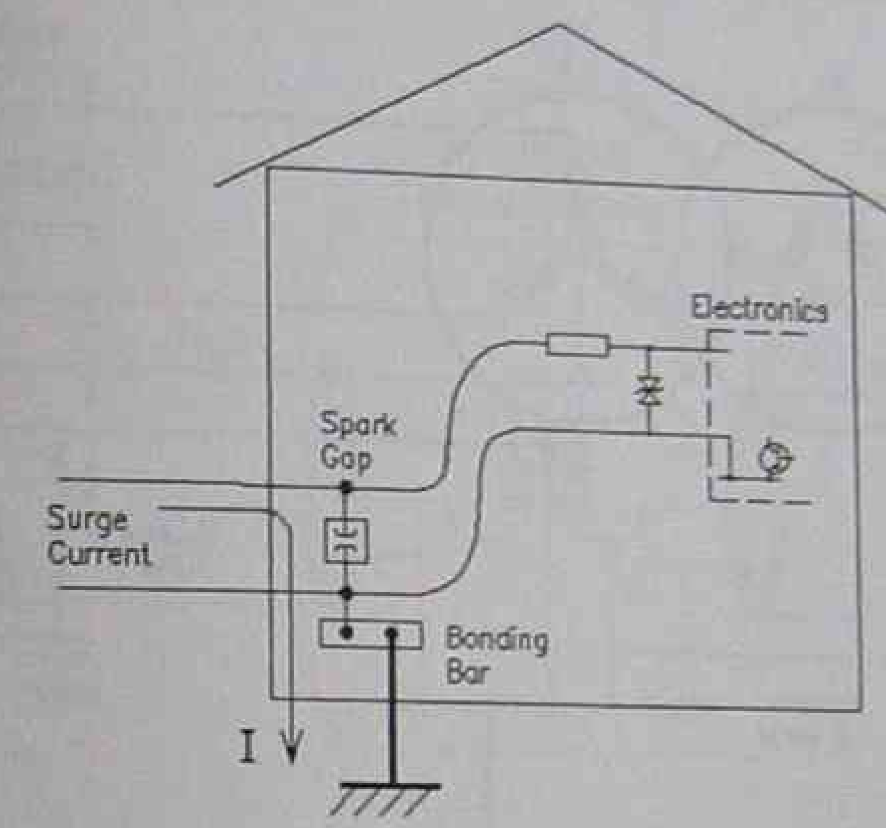


Figure 5.5 : The location of the Spark Gap is important.

For many situations, the above spark gap position is not feasible. In these cases, the closest *protective earth* (safety earth or alternatively the ZSRG) should be used.

5.3 Protecting the Power Supply Side

In the majority of situations the supply authority provides a neutral conductor that has been earthed at least once, usually close to the distribution transformer onto the substation earth. The problem is that perfect earthing is not always achievable and the earth resistance can be 10Ω or even higher. A lightning strike in the vicinity of the power supply system, or an earth fault, will cause current to flow into the earth electrode, which will cause the neutral to rise in voltage relative to earth.

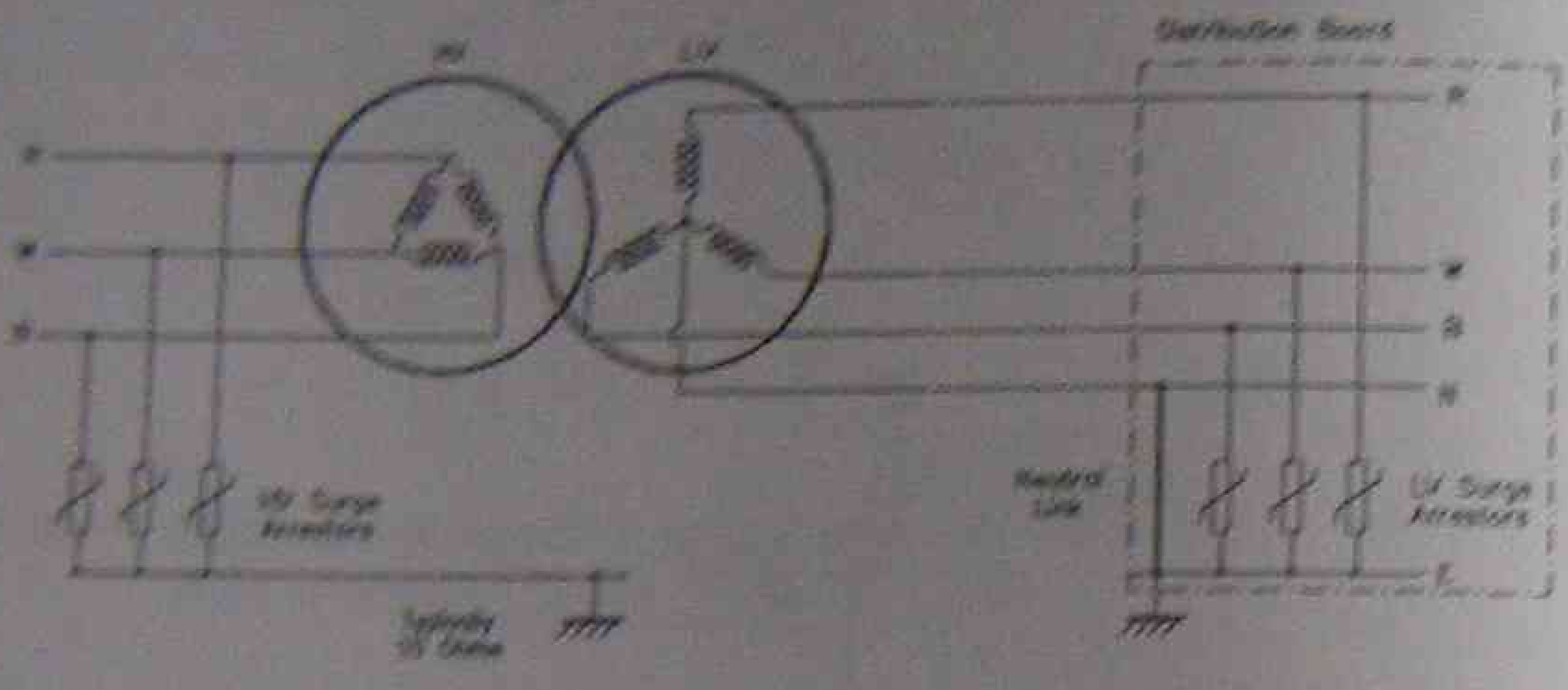


Figure 5.6 : Typical distribution transformer earthing arrangements.

At the point of power supply, a consumer will commonly experience a rise in neutral voltage relative to the local earth electrode. For this reason, surge protection should be installed between the *line and protective earth* as well as between the *neutral and protective earth*.

Another problem with the neutral arises when the neutral acts as an antenna and radiates interference fields as a result of harmonics (mainly 3rd harmonic) and other residual currents. A comment is often made that "there are problems with a noisy earth". It is true to say that there are seldom problems with a noisy earth. What people really mean is that there is a problem with a ***Noisy Neutral***!

When there is a problem with a noisy neutral, an isolation transformer can be used inside the building or substation to regenerate a "clean" neutral. In this case, the neutral is tied to the zero signal reference grid and back to earth. A mains filter can also be installed on the primary side of the isolation transformer to divert the higher order harmonics down to earth.

For the power supply to electronic equipment, such as control and communications equipment, it is recommended that a separate **"clean neutral" power supply** network should be used. This can be achieved by isolating transformers, Power Line Conditioners or UPS (Uninterruptable Power Supply). These devices isolate the secondary from the power system and tend to divert most of the EMI that comes through the power supply system to earth. The main objective is to re-establish a "clean neutral", so care should be taken not to connect the neutral through to the secondary side. (Figure 5.7)

5.3.1 Isolation Transformers

An Isolation Transformer is often provided in the power supply of the electronic equipment to provide complete galvanic separation between the "internal" supply to the electronic components. One leg of the secondary side of the transformer is earthed to establish a new "clean neutral". In addition, the windings of these transformers are often screened to divert capacitively coupled high frequency noise or surges in the power supply conductors.

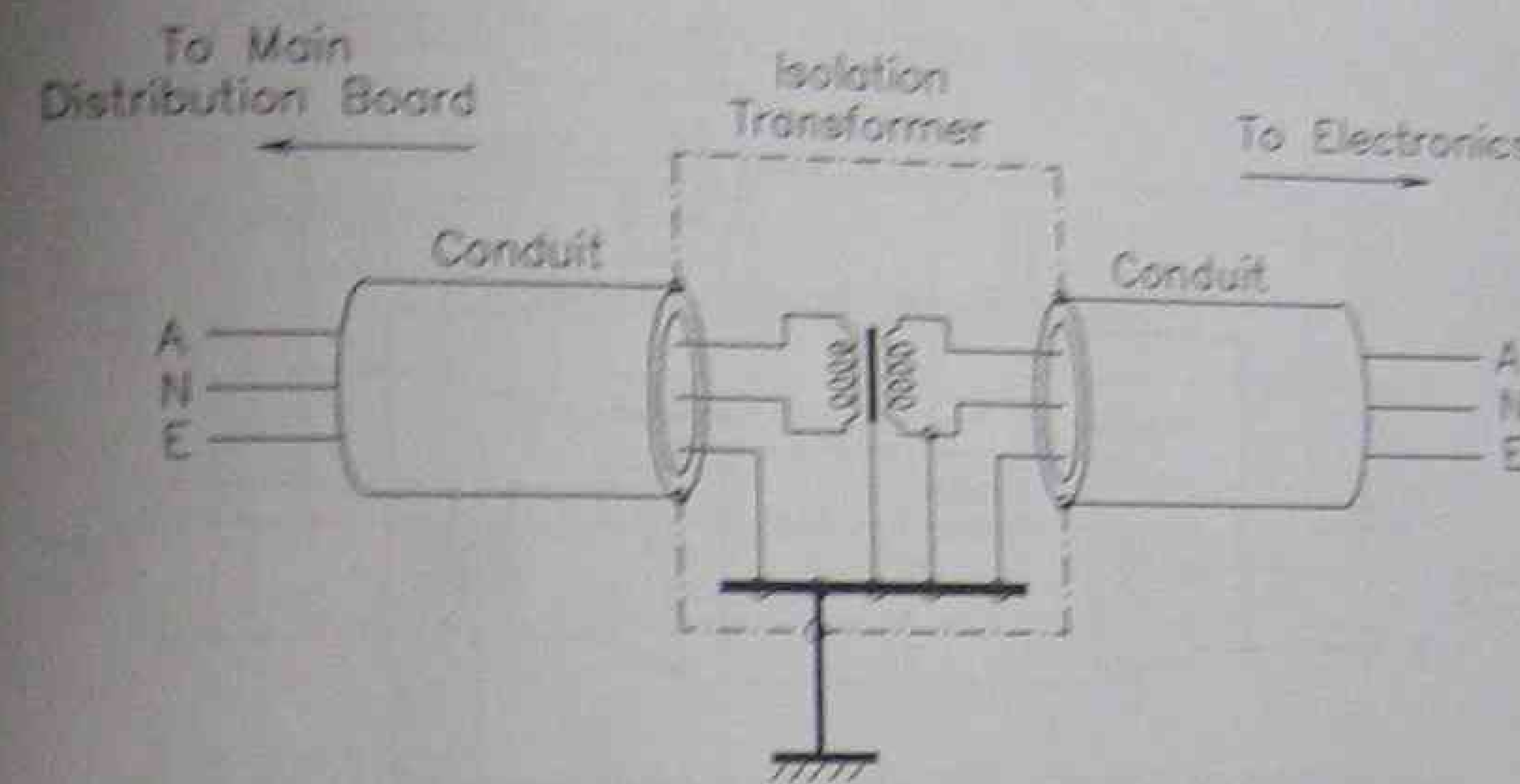


Figure 5.7 : Regeneration of a Clean Neutral

5.3.2 Power Line Conditioners

A Power Line Conditioner is an isolation transformer with some additional feature for regulating the secondary output voltage. The purpose of the voltage regulation is to reduce the effect of voltage surges or dips on the secondary side. These devices are usually used for the power supply to smaller PLC installations.

The voltage regulation can be achieved either electronically, with a regulating circuit on the secondary side of the transformer, or by using a regulating ferroresonant transformer. Ferroresonant transformers are very popular in Australia and are produced by a number of manufacturers.

Power Line Conditioners provide the following features :

- Isolation through a transformer
- Output Voltage Regulation
- Filtering of external noise and harmonics
- Absorb external surge energy
- Often provide short circuit protection

5.3.3 Uninterruptable Power Supplies (UPS)

UPSs (Uninterruptable Power Supplies) provide the following features:

- All the advantages of a Power Conditioner .... (check for neutral isolation)
- No-break (battery backup) standby supply for a certain period to cope with power interruptions and allow a controlled shutdown of the control system.

The common UPS connection is shown in Figure 5.8 below.

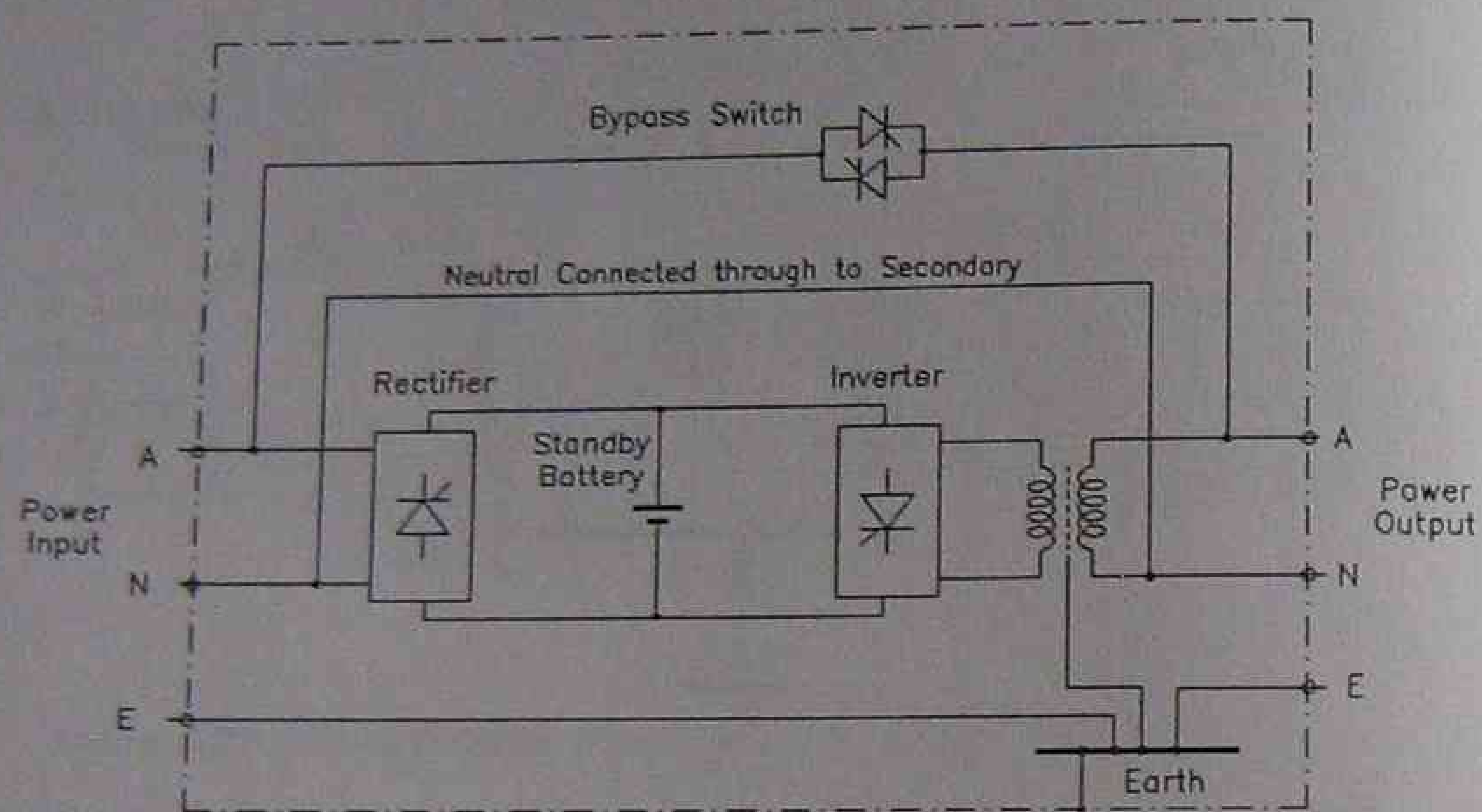


Figure 5.8 : Connections through a UPS with Neutral not isolated

The disadvantage of the above configuration is that any noise on the neutral conductor is conducted through into the "clean" control electronics environment. This is an important factor, which is often ignored with UPSs. One of the main objectives of isolating the power supply is to re-establish a "clean neutral". The cheaper UPSs usually do not have neutral isolation. They are usually cheaper because they have saved the cost of the additional neutral isolating transformer, as shown in Figures 5.8 and 5.9.

A preferred arrangement is where the incoming neutral is limited to the input terminals of the UPS and thus prevented from entering the ZSRG environment. The neutral of the UPS output is then connected to the ZSRG as shown in Figure 5.9.

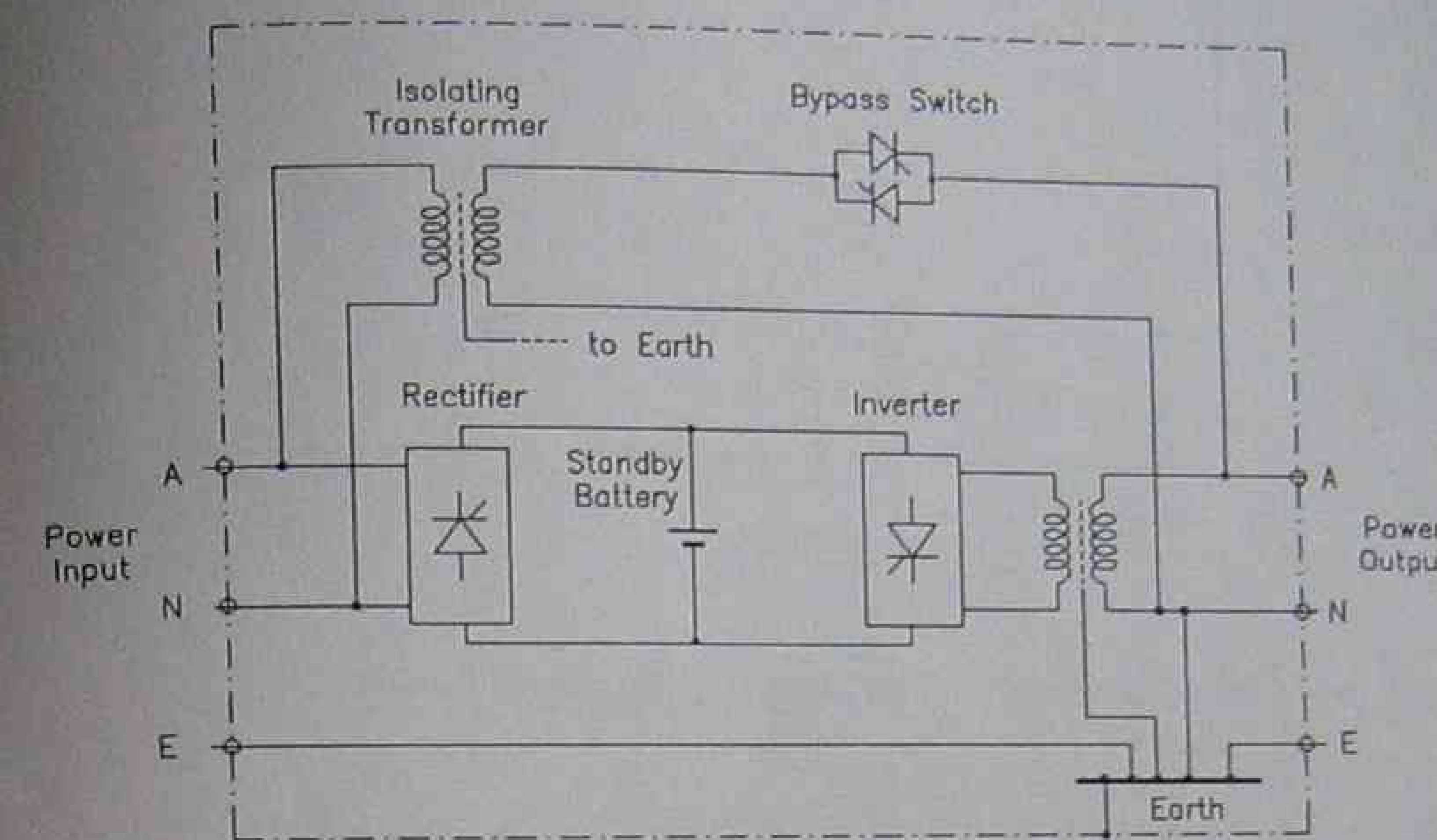


Figure 5.9 : Preferred (more expensive) UPS Connections for Neutral

5.4 Testing Surge Protection Devices

There is ***no alternative to actual laboratory testing*** of SPUs (Surge Protection Units). The influence of stray effects can never be predicted. Testing is performed by applying "standard" voltage and currents surges to the device.

A typical current waveform is 10kA (8/20μs)

- Peak current I_{peak} = 10kA
- Rise time to crest t_{cr} = 8μs
- Time to half value of t_d = 20μs

A typical voltage waveform is 10kV (1,2/50μs)

- Peak voltage V_{peak} = 10kV
- Rise time to crest of t_{cr} = 1.2μs
- Time to half value of t_d = 50μs

The shape of these test waveforms is shown in Figure 5.10. This waveform is generated by the test circuit shown in Figure 5.11.

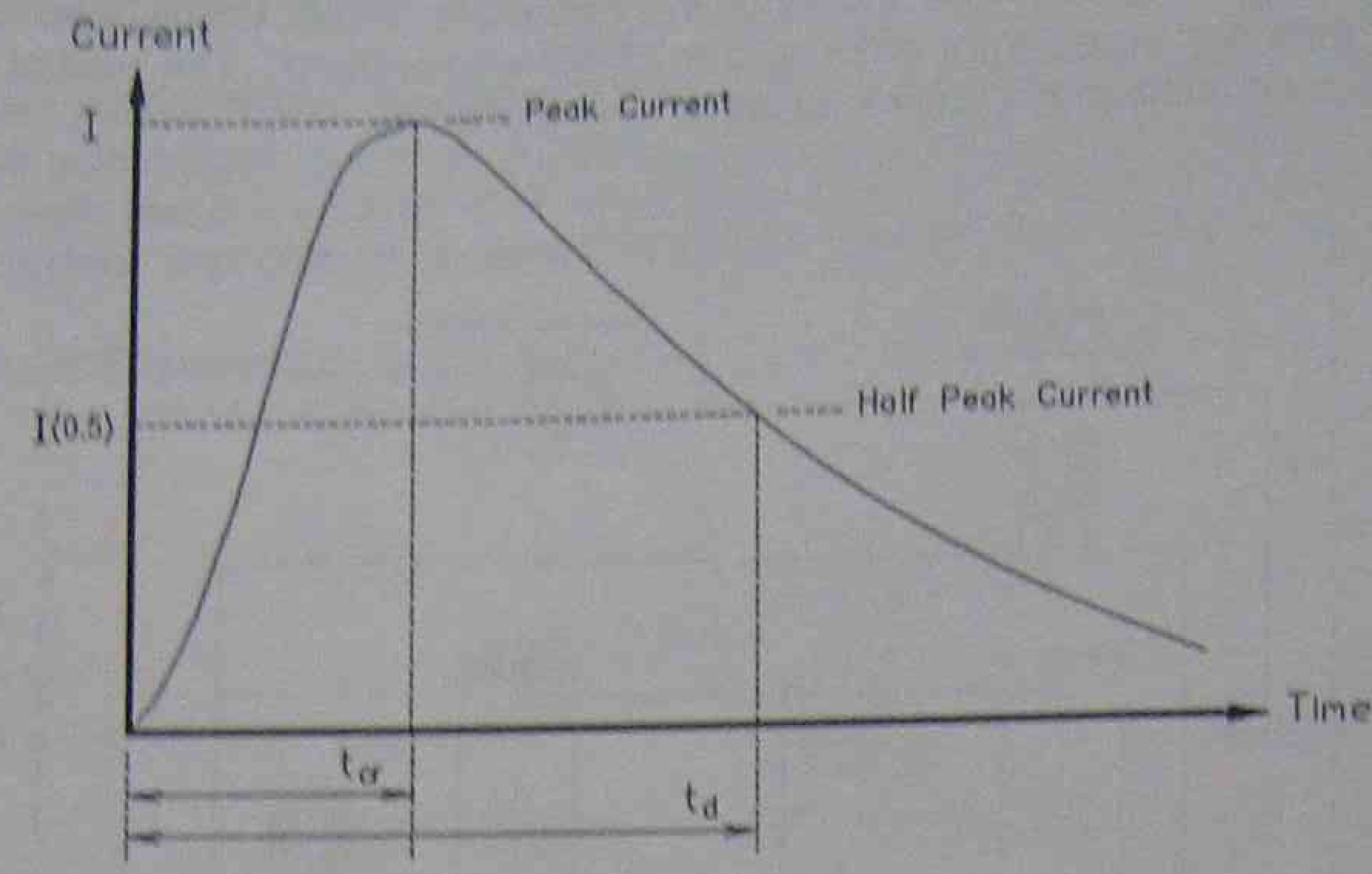


Figure 5.10 : Definitions of Rise Time and Time to Half Value

The circuit of the type of test equipment required to generate these waveforms is relatively simple and has the following form. A capacitor is charged through a charging circuit. At the appropriate time, it is discharged via a spark gap into a waveshaping circuit and on to the device under test. For testing a Mains Protection Unit, the testing circuit can be modified to include a power frequency follow-through current.

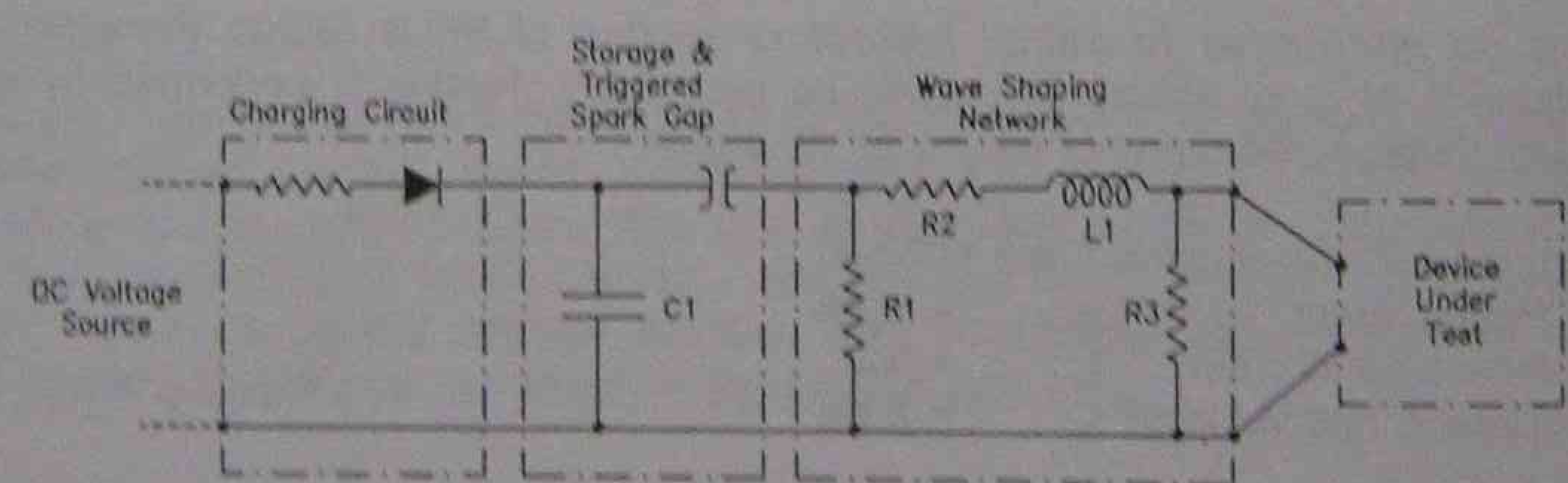


Figure 5.11 : Typical Test Circuit for Surge Protection Devices

4

Appendix A : LIGHTNING AND LIGHTNING PROTECTION

A.1 Introduction

The danger of *Lightning* can be evaluated if there is a clear understanding of :

- the basic physics of lightning
- the concept of the attractive radius of a structure on the ground
- the lightning current waveform parameters
- current and voltage surges due to direct lightning strikes
- induced voltage surges due to lightning strikes to adjacent structures
- how structures should be protected against damage by direct lightning strikes

A.2 The Physics of Lightning

Lightning is an ionised channel that propagates from one charge region to another oppositely charged region and permits an *electric current* to flow between the two charged regions. For *cloud-to-cloud* lightning the initiating and terminating charge regions are both in a thundercloud, while for *cloud-to-ground* lightning the initiating charge region is in a thundercloud and the terminating charge region is on the ground. The ionised channel can, in some cases, be as long as 10km.

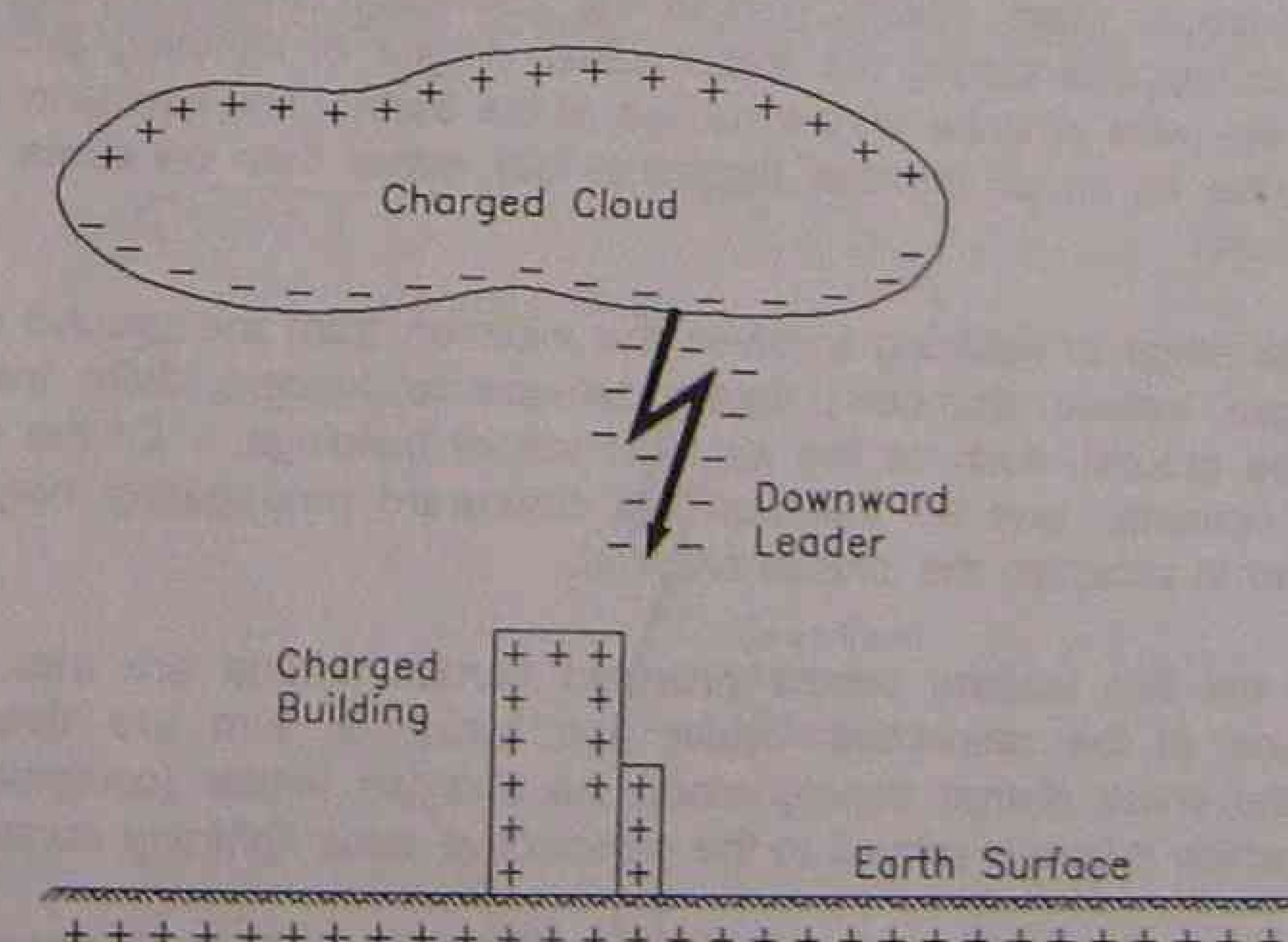


Figure A.1 : The Initial Stages of Lightning
(1) The build up of charge in the cloud and on the ground.
(2) The establishment of the ionised Downward Leader

Cloud-to-ground lightning occurs when a large charge gathers in the cloud above, which attracts an equal and opposite charge in the ground below. The charge movement in the ground on a thundercloud day reveals itself as a current flow in buried metal pipes. Lightning does not necessarily occur with all rain-clouds.

Lightning is mainly associated with convectional rainfall, whose two main ingredients are moist air and high (sun-heated) temperatures on the surface of the earth. For example, the Amazon basin in Brazil has an extremely high incidence of lightning due to high levels of moisture in the air and high surface temperatures. By contrast, Canada, which also has very damp air but experiences very little lightning because of low surface temperatures.

Lightning depends initially on the existence of a high electrical charge in the cloud and, subsequently, on the establishment of a conductive channel to transfer the charge to the ground. While it is well understood how clouds form, the mechanism of charge separation is not. The general consensus is that ice particles become positively charged and are carried up to the top of the cloud, while the water droplets, which carry negative charge, congregate at the bottom of the cloud. The voltage difference between the bottom of the cloud and ground can be millions of volts.

The very high electric field between the cloud and the ground can initiate the ionisation of the air, usually at the cloud end. This is known as the *downward leader*, or *stepped leader*.

Once initiated, propagation of the ionised channel is ensured by the high electric field generated ahead of the relatively thin, highly ionised channel. The ionised channel assumes the polarity of the initiating charge region. The ionised channel advances in a series of steps (20m to 50m long) towards the ground. The majority of lightning strokes to ground, terminating on "low" structures (less than 60m high), are of the *negative downward* type ... a channel of negative charge propagates from a negative charge region in the cloud towards the positively charged ground.

Of crucial importance when designing lightning protection systems for structures and buildings is what happens during the *intermediate stages* of lightning propagation, since this determines the point of strike on the surface of the earth. The aim is to ensure that the lightning terminates on an *air terminal* (lightning rod) rather than on some more sensitive part of the structure.

The intermediate stage of lightning involves the initiation from the ground of a number of positively charged ionised channels, known as *upward leaders*, from trees or parts of structures on the ground, such as the *air terminals* of buildings. Of the upward leaders that propagate upwards, one will intercept the downward propagating negatively charged *downward leader* to establish the ionised channel.

Interception of the two leaders occurs provided certain criteria are met concerning the relative velocities of the respective leader tips, which in turn are determined by the magnitude of the *linear charge density* along the stepped leader (coulombs per metre of leader length) which in turn is related to the prospective *peak lightning current*.

Thus upward leaders initiated from a structure are able to intercept downward leaders in the vicinity of the structure and hence result in the termination of the stroke on the structure, thereby increasing the incidence of lightning strikes to the structure.

This ability to attract adjacent downward leaders is described in terms of the *attractive radius or attractive area* of the structure.

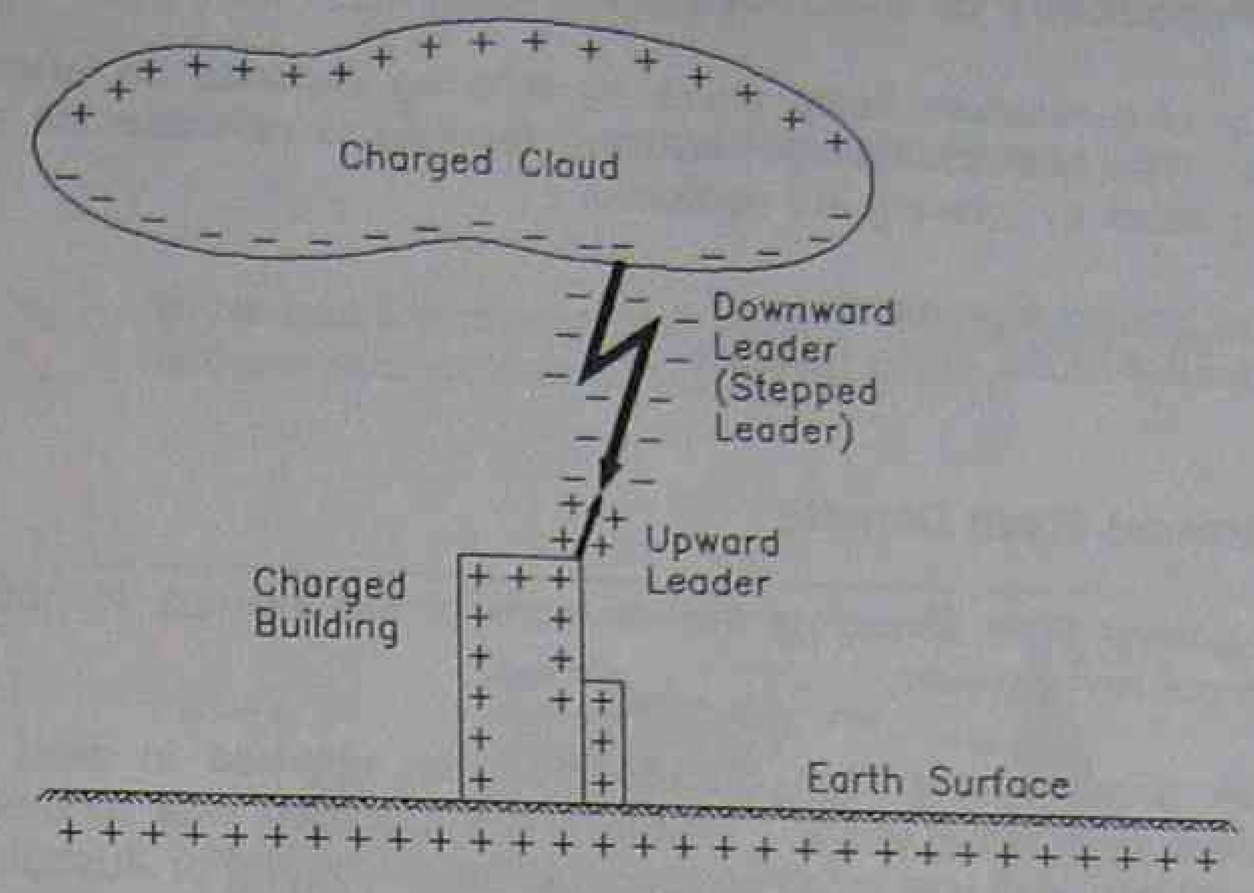


Figure A.2 : The Intermediate Stages of lightning
(3) The establishment of the ionised Upward Leader
(4) The interception of the downward leader by the upward leader

After the interception of the downward leader by the upward leader, an ionised channel of high conductivity is established between the cloud and the ground through which charge equalisation between the cloud charge region and the ground occurs. Virtually all the energy associated with the lightning is converted into light, heat, sound (thunder) and radio waves. The peak temperature in the ionised channel is approximately 25,000°C, but this lasts for only a few microseconds. This charge equalisation involves the flow of current down the ionised lightning channel, through any intervening structure and into the ground.

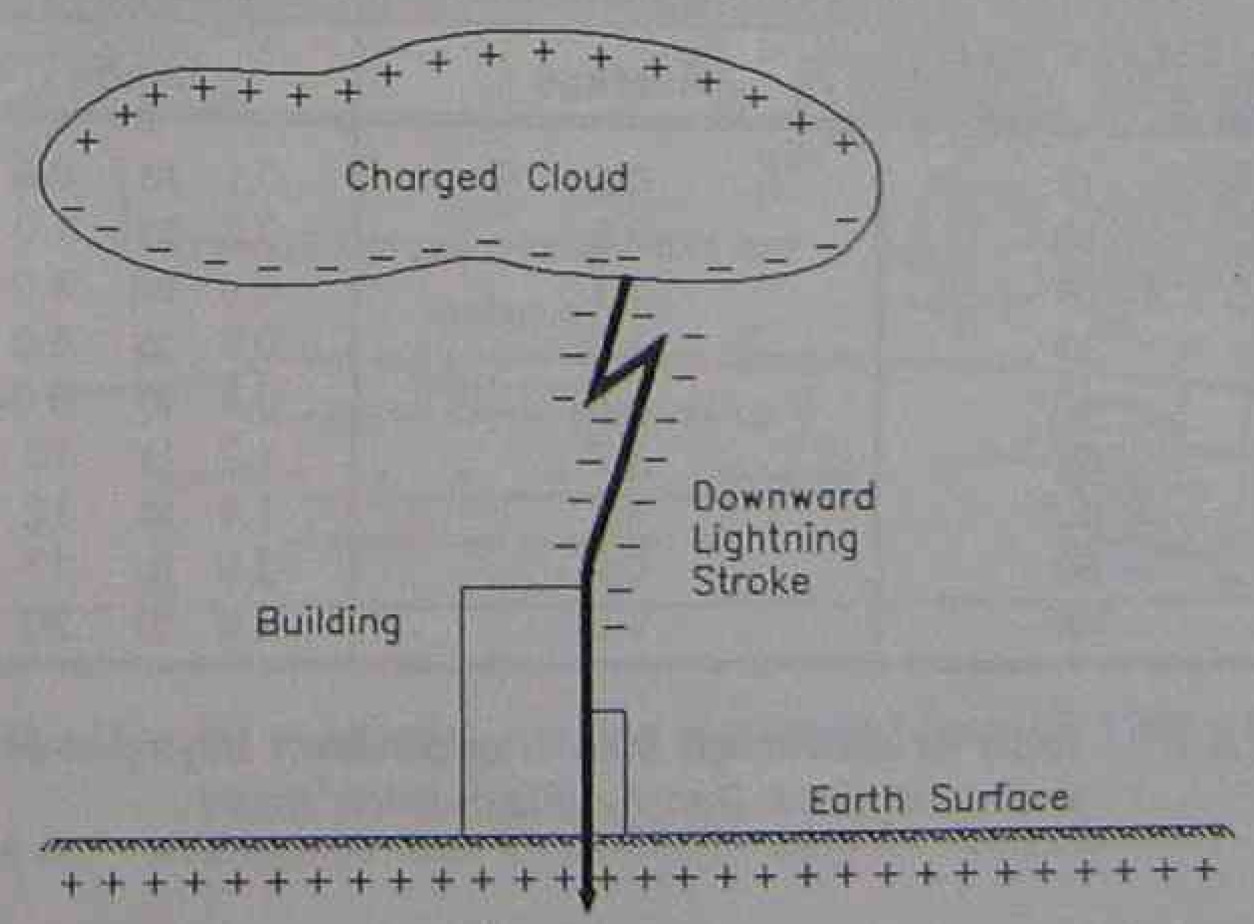


Figure A.3 : The Final Stage of Lightning
(5) The establishment of a conducting path for the transfer of charge from the cloud to the ground

A.3 The Probability of a Structure being Struck by Lightning

The probability of a structure being struck by lightning depends on where it is located geographically. The two parameters which are required to calculate the probability of a structure being struck by lightning are as follows :

- the local *ground flash density*
- the *attractive radius* of the structure

A.3.1 The Ground Flash Density

The *lightning ground flash density* is the measure of the average number of *cloud-to-ground* flashes per km^2 per year.

The information about *ground flash density* has been obtained in most countries from extensive surveys over many years. Initially, this information was recorded as *Average Annual Thunderstorm Days* and recorded on isoceraunic maps. For Australia, a map of the average annual thunder-days is available from the Bureau of Meteorology. A copy (reduced in size) is shown in Figure A.4. For some areas, this may be the only information available about thunderstorm activity. However, modern lightning flash counters have been installed at many sites around Australia. These systems can detect the number of ground flashes in the area around the detector as well as record data about the peak current of the discharge. The objective of maintaining a network of lightning flash counters is to obtain estimates of regional values of *ground flash density (Ng)*. These results are summarised in an annual data sheet produced by the Bureau of Meteorology.

The information from this map, given as the average annual number of thunderstorm days, may be converted to the more commonly used *lightning ground flash density* by using the following table extracted from a paper by Anderson RB & Eriksson AJ.

Thunderstorm days per year	Ground Flash Density (Flashes/km^2/year)	
	Average	Limits
5	0.2	0.1 to 0.5
10	0.5	0.2 to 1.0
20	1.1	0.3 to 3.0
30	1.9	0.6 to 5.0
40	2.8	0.8 to 8.0
50	3.7	1.2 to 10
60	4.7	1.8 to 12
80	6.9	3.0 to 17
100	9.2	4.0 to 20

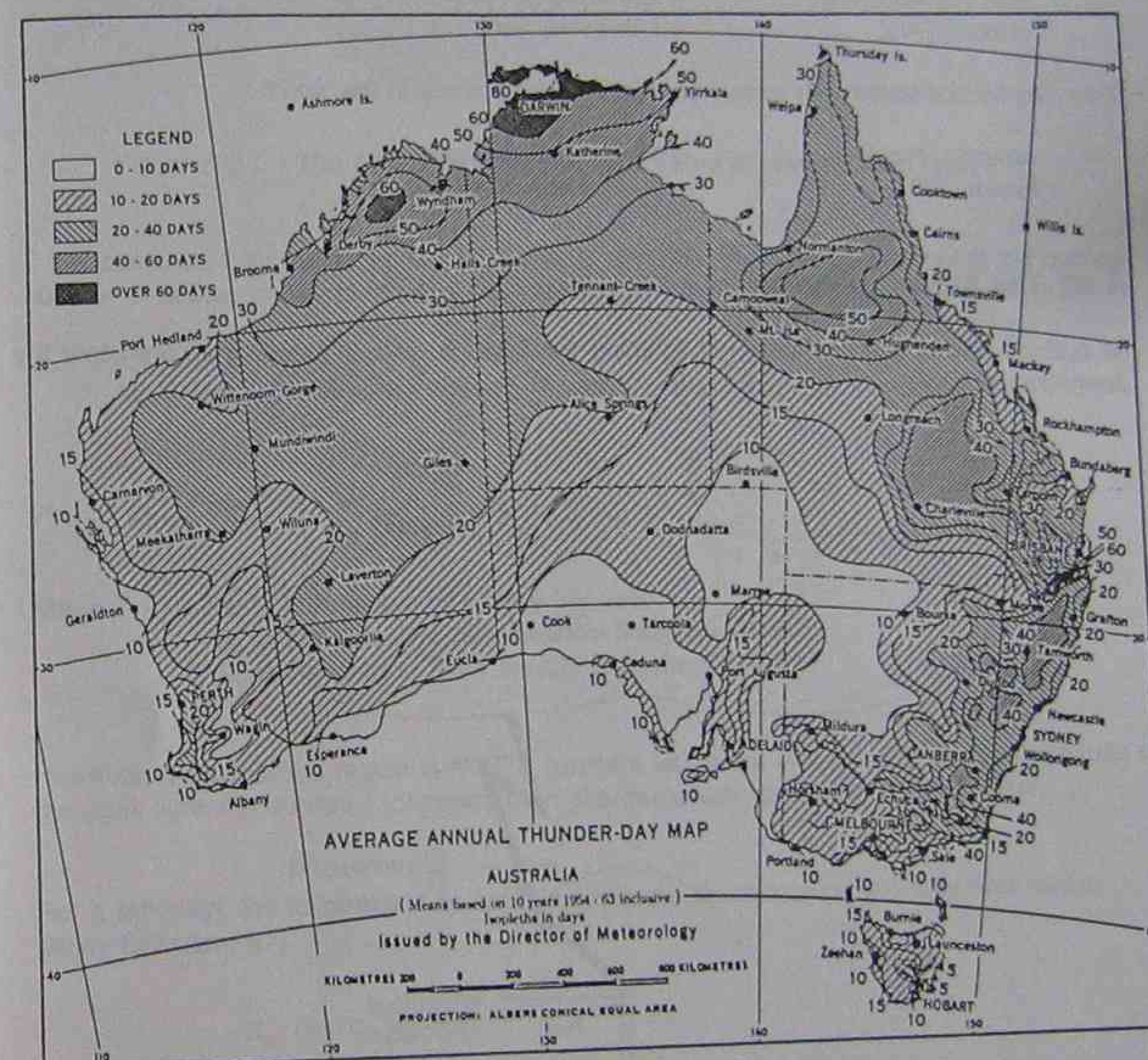
Figure A.4 : Table for conversion from Thunderstorm Days per year to Ground Flash Density (Flashes/km^2/year)

Another method is to apply the formula from IEC 1024.1.1-1993 page 17, which is based on figures gathered from sources worldwide. Like the table above, the relationship varies considerably with changes in climatic conditions, so wide tolerances should be used.

The conversion formula from IEC 1024 is as follows :

$$N_g = 0.04 \times T_d^{1.25} \quad \text{ground flashes/km}^2\text{/year}$$

where : N_g is the lightning ground flash density in strikes/km2/year
T_d is the annual number of thunderstorm days



Map issued by the Director of Meteorology and reproduced from AS 1768-1991 Page 11.

Figure A.5 : Average Annual Thunder Day Map for Australia

Typical values for some of the test stations in Australia, taken from a recent Bureau of Meteorology report are as follows :

Kununurra, WA	≈ 3.0 flash/km^2/year
Darwin Airport, NT	≈ 2.9 flashes/km^2/year
Grafton Airport, NSW	≈ 2.1 flashes/km^2/year
Bowraville, NSW	≈ 1.5 flashes/km^2/year
Mnt Isa, QLD	≈ 1.2 flashes/km^2/year
Port Augusta, SA	≈ 0.8 flash/km^2/year
Melbourne Airport, VIC	≈ 0.7 flash/km^2/year
Perth Airport, WA	≈ 0.4 flash/km^2/year
Port Hedland, WA	≈ 0.4 flash/km^2/year
Hobart, TAS	< 1 flash/km^2/year

This may be compared with some very high lightning areas in the world :

Amazon, Brazil	≈ 15 flashes/km^2/year
Florida, USA	≈ 13 flashes/km^2/year

A.3.2 The Attractive Radius of a Structure

As outlined above, the final stage of lightning involves an *upward leader* that intercepts the *downward leader.*

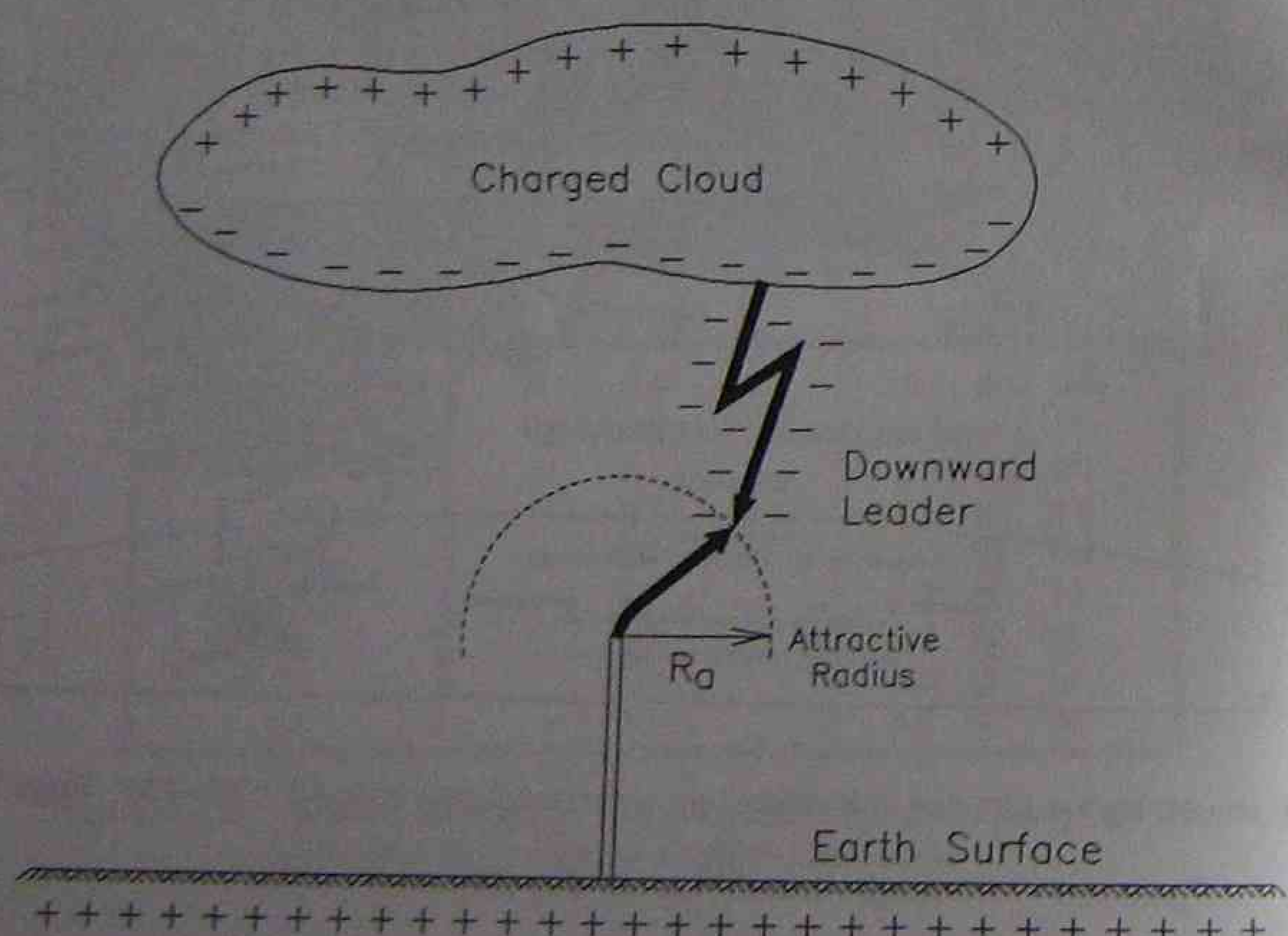


Figure A.6 : The Attractive Radius of a Structure

The upward leader is able to intercept a downward leader provided the downward leader approaches within a distance known as the *attractive radius* R_a of the structure from which the upward leader is initiated. In the case of a tall mast, all leaders propagating downward within a radius R_a from the mast will terminate on the mast. The area within radius Ra of the mast is known as the *attractive area* of the mast.

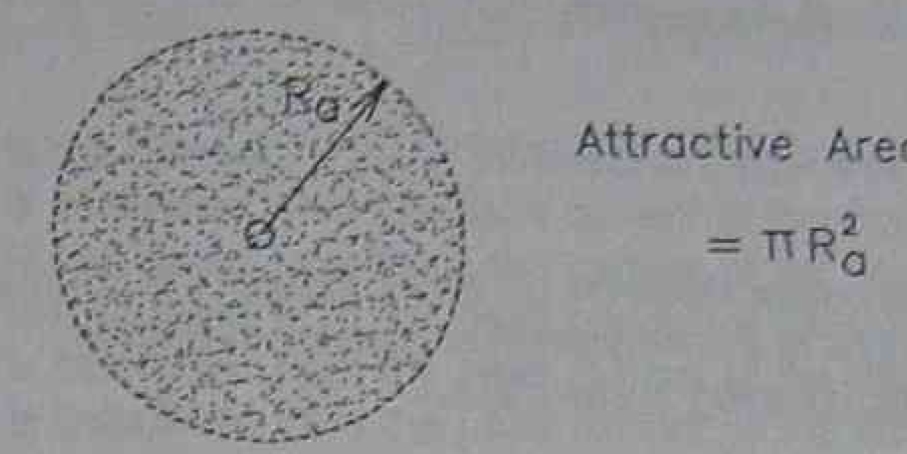


Figure A.7 : The Attractive Area of an Air Terminal, viewed from above

If the attractive area were a constant value (it is NOT), then the calculation of the average number of strikes to the mast per year could simply be calculated from :

N_s = *attractive area* (as fraction of km^2) x *ground flash density* (in flashes/km^2/year)

or

$$N_s = \pi \left[\frac{R_a}{1000} \right]^2 N_g$$

where : N_s is the number of strikes per year
R_a is the attractive radius of the mast in metres
N_g is the ground flash density in flashes/km^2/year

However, the attractive radius is NOT a constant value but is a function of the magnitude of the peak lightning current I (dependent on charge) which varies from flash to flash.

For a *tall mast*, the following is an empirical formula for estimating the attractive radius (Andy Eriksson, 87)

$$R_a \approx 0.84 \times h^{0.6} \times I^{0.74}$$

where : R_a is the attractive radius of the mast in metres
h is the height of the mast in metres
I is the peak lightning current in kA

For example, for a lightning flash to a 15m high mast with a typical peak current of 34kA

$$R_a \approx 0.84 \times 15^{0.6} \times 34^{0.74} = 58m$$

Thus all negative leaders with a prospective peak current of 34kA propagating downward within 58m of the above mast would terminate on the mast.

Another common structure is that of a conductor that extends horizontally along the ground above the surface, such as a transmission line. For a *horizontal conductor* above the ground, the following is an empirical relationship for estimating the attractive distance on either side of the conductor (Eriksson, 87)

$$R_a = 0.67 \times h^{0.6} \times I^{0.74}$$

where : R_a is the attractive distance on either side of the conductor in metres
h is the height of the horizontal conductor in metres
I is the peak lightning current in kA

A.3.3 Prediction of the Number of Strikes to a Structure per Year

Clearly, to calculate the number of flashes that will terminate on the structure, the peak current of each prospective lightning flash needs to be known in advance. This is obviously not possible. The way round this problem is to use computer based mathematical techniques to predict the number of strikes to a structure per year and the magnitude.

The scatter of the peak current of lightning flashes can be simulated using a random number generator, known as Monte Carlo analysis, which is easily implemented on a modern computer. The computer produces a sequence of peak currents such that the spread of values matches that of actual lightning (e.g. 98% of the simulated strokes have a peak current > 4kA, 50% > 4kA and 5% > 90kA). For each of these simulated strokes the attractive radius of the mast is calculated from the height of the mast and the simulated peak current.

For example, if the first simulated stroke has a peak current of 20kA and the object has a height of 15m, then the **Attractive Radius** is :

$$R_{a_1} = 0.84 \times 15^{0.6} \times 20^{0.74} = 39m$$

Consequently the **Attractive Area (km²)** of the mast associated with this first simulated peak current is given by

$$\pi\left[\frac{R_{a_1}}{1000}\right]^2$$

Assuming that the simulated downward leader can propagate downward at any point within a square kilometre of area, the probability of the first downward leader terminating on the mast is related to the ratio of this Attractive Area to one km² of area.

If the object is situated in an area where there is an average of five ground flashes per km² per year, then five flashes should be simulated to give the average number of times the mast is struck per year.

$$N_s = \pi\left[\frac{R_{a_1}}{1000}\right]^2 + \pi\left[\frac{R_{a_2}}{1000}\right]^2 + \pi\left[\frac{R_{a_3}}{1000}\right]^2 + \pi\left[\frac{R_{a_4}}{1000}\right]^2 + \pi\left[\frac{R_{a_5}}{1000}\right]^2$$

where : N_s is the number of times the mast is struck per year
R_{a1} is calculated from the peak current of the first simulated flash
R_{a2} is calculated from the peak current of the second simulated flash
R_{a3} is calculated from the peak current of the third simulated flash
R_{a4} is calculated from the peak current of the fourth simulated flash
R_{a5} is calculated from the peak current of the fifth simulated flash

To obtain a more accurate average value of the number of times the mast is struck per year, many more flashes may be simulated .... perhaps 500 flashes to simulate 100 years. The average is then calculated from the following :

$$N_s = \frac{1}{100}\left[\pi\left[\frac{R_{a_1}}{1000}\right]^2 + \pi\left[\frac{R_{a_2}}{1000}\right]^2 + \ldots\ldots + \pi\left[\frac{R_{a_{500}}}{1000}\right]^2\right]$$

For the case where a lightning mast is performing a lightning protective function then, if the probability of protection failure is p (usually increases with increasing stroke current I), then the probability of the mast being struck and there being protection failure can be calculated by replacing

$$\pi\left[\frac{R_{a_1}}{1000}\right]^2 \quad with \quad \pi\left[\frac{R_{a_1}}{1000}\right]^2 p_1$$

where : p_1 is the probability of protection failure for the first simulated flash

For the full simulation of 500 flashes the number of times the mast is struck and protection failure occurs per year is given by

$$N_s = \frac{1}{100}\left[\pi\left[\frac{R_{a_1}}{1000}\right]^2 p_1 + \pi\left[\frac{R_{a_2}}{1000}\right]^2 p_2 + \ldots\ldots + \pi\left[\frac{R_{a_{500}}}{1000}\right]^2 p_{500}\right]$$

Extensive research has been conducted into the assignment of values to p, especially for strikes to transmission lines. However, this is beyond the scope of this course.

A.4 Shielding of Structures against Lightning

The figure below shows an air terminal on a mast (lightning rod) which has been installed to shield a small building from direct lightning strikes. Unless the building to be protected is small and close to the lightning rod, it is possible that the attractive radius of the building will extend beyond that of the lightning rod. In this case, the building may intercept the *downward leader* instead of the lightning rod.

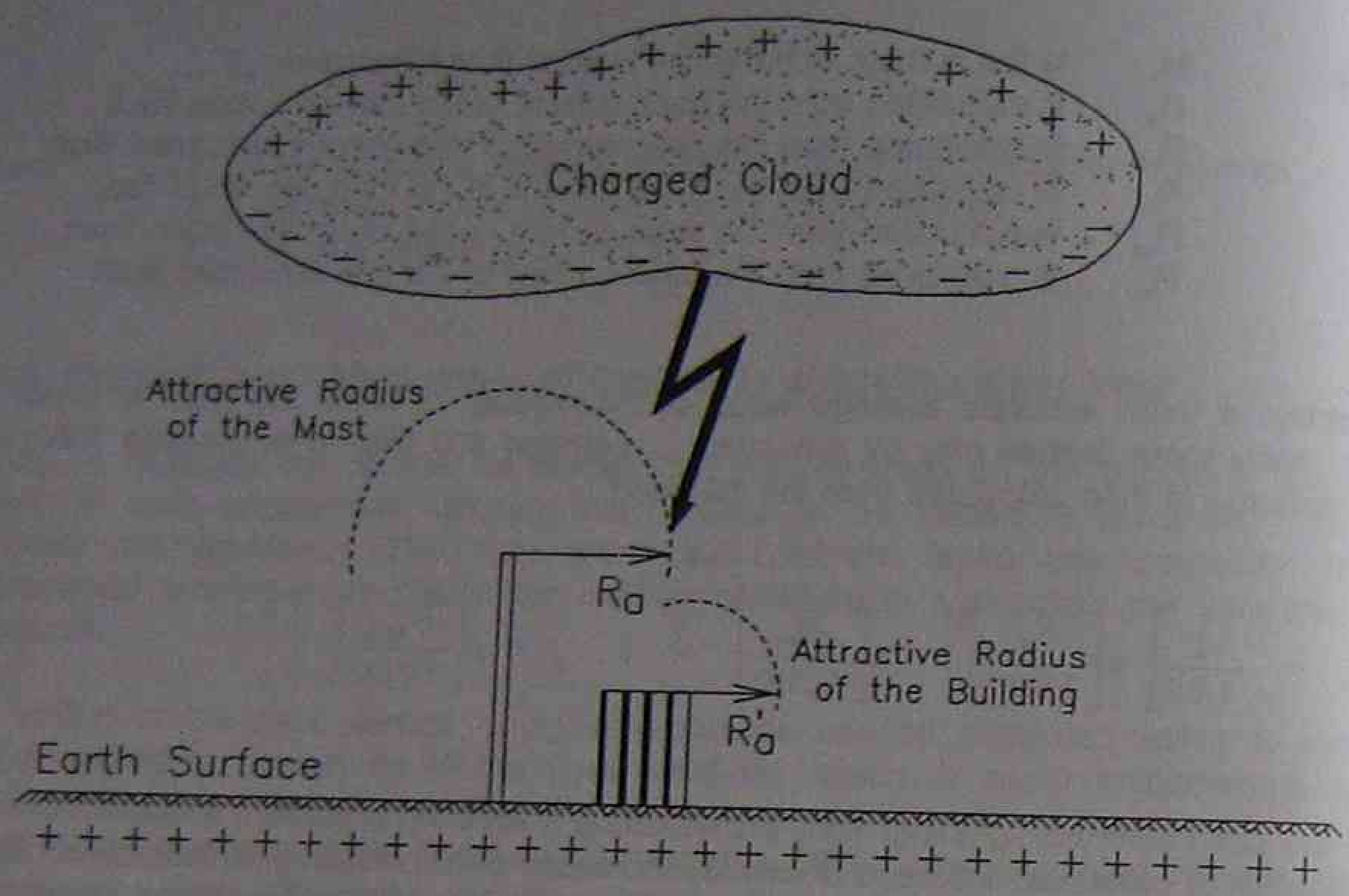


Figure A.8 : The Attractive Radius of a Structure

The basis for deciding when a building is considered to be relatively small and close enough is defined by two alternative methods defined in the Standards :

- Protective Angle Method (IEC 1024)
- Rolling Sphere Method (IEC 1024 and AS 1768)

Four Protection Levels are defined in IEC 1024-1990 as follows :

I: **Structure dangerous to social and physical environments**
Structures which may cause biological, chemical and radioactive emissions as a consequence of being struck by lightning ... eg. nuclear power station

II: **Structure dangerous to its surroundings**
Structures which can be dangerous to their immediate surroundings if struck by lightning ... eg. munition store, petroleum refinery

III: **Structure with confined danger**
Structures whose construction materials, contents or occupants make the whole volume of the structure vulnerable to the consequential effects of lightning ... eg. power station

IV: **Common structure**
Structures used for ordinary purposes ... eg. building, factory or house

A more conservative approach to lightning protection should be used for structures containing very dangerous materials. Consequently, smaller protective angles or sphere radii, which results in more certainty of protection.

A.4.1 The Protective Angle Method

The Protective Angle method states that if the building or object to be protected lies within an imaginary cone with apex at the tip of the lightning rod it will be protected. This applies to installations where the air terminal is a mast or rod.

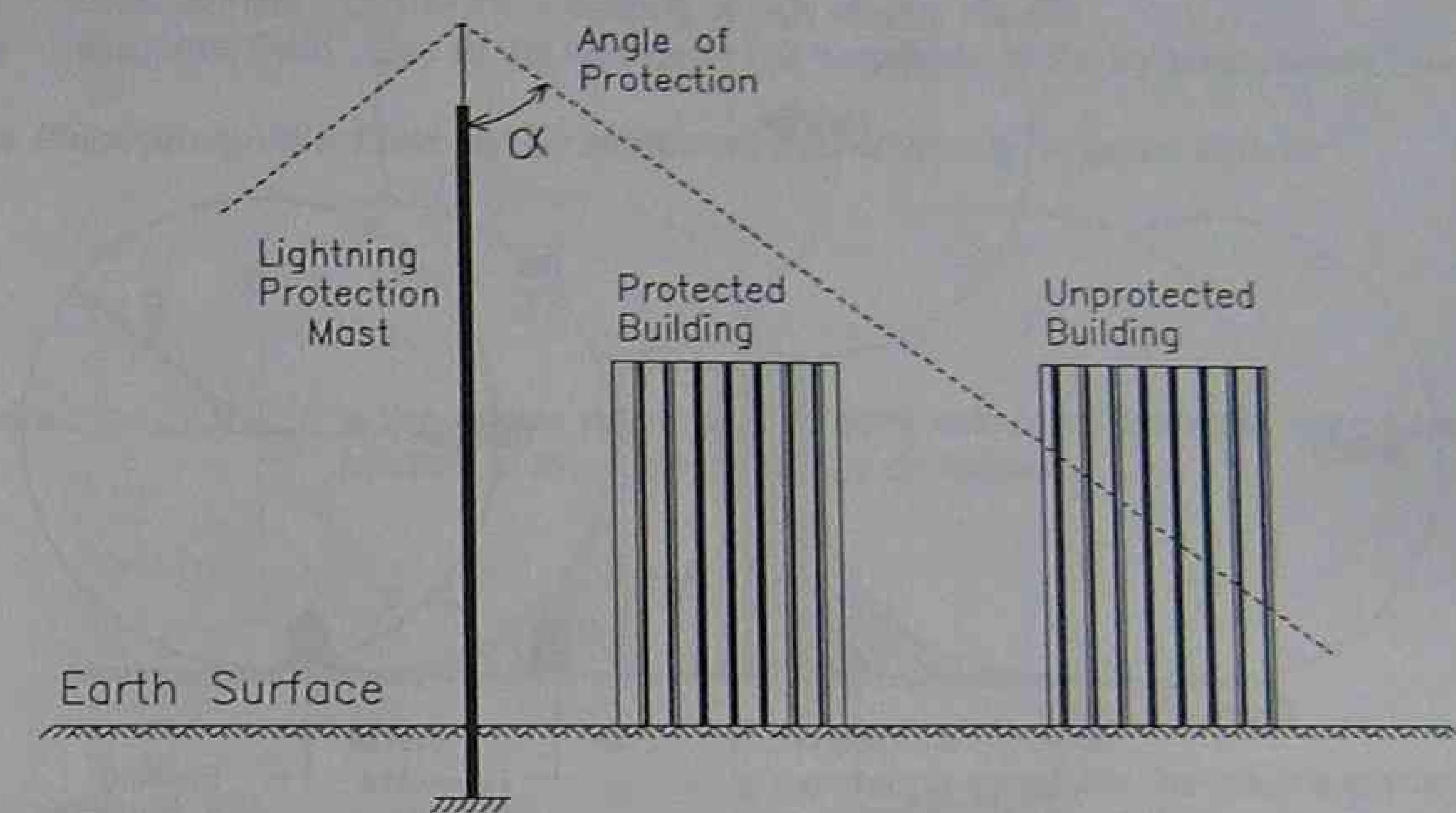


Figure A.9 : The Protective Angle Method

Clearly, the choice of the angle at the apex of the cone is important in determining the protected area. The angle chosen depends on the protection level required, which is dependent on the type of building to be protected (defined in IEC 1024-1990).

Protection Level	Height of Structure			
	20m	30m	45m	60m
I	25°	n/a	n/a	n/a
II	35°	25°	n/a	n/a
III	45°	35°	25°	n/a
IV	55°	45°	35°	25°

n/a = Cone of protection approach is not applicable for these cases

Figure A.10 : Recommended Values of Cone Angle α from IEC 1024-1 1990

A.4.2 The Rolling Sphere Method

With the Rolling Sphere approach, an imaginary sphere, with radius given in the table below, is rolled over the structure. Where the sphere touches, there is a possibility of direct lightning strikes. Sections which cannot be touched by the sphere are considered to be protected by the lightning rod.

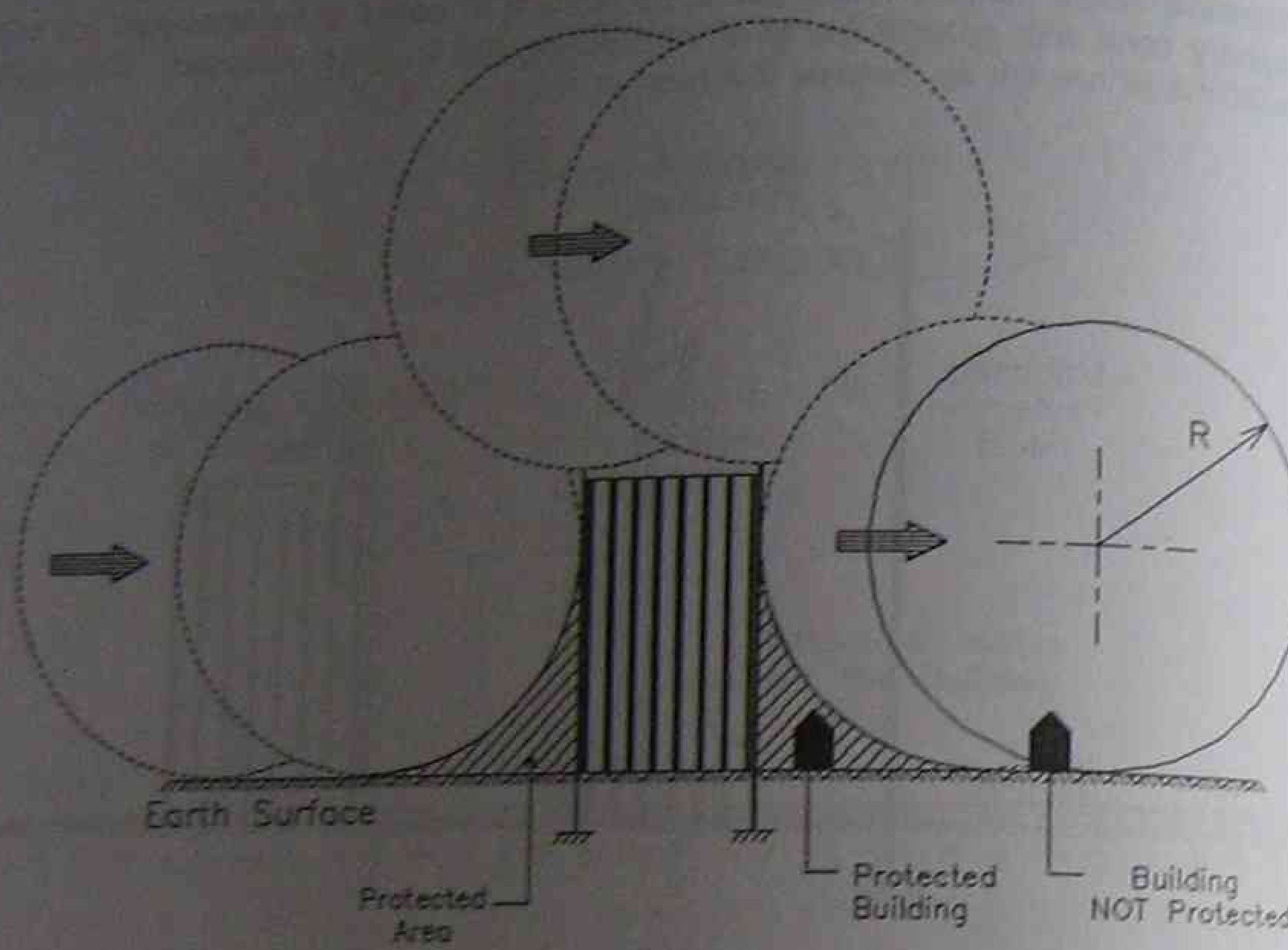


Figure A.11 : *The Rolling Sphere Approach*

Protection Level	Radius of Ball
I	20m
II	30m
III	45m
IV	60m

Figure A.12 : *Recommended Values of Radius of the Ball from IEC 1024-1 1990*

A.5 Induced Surges due to Adjacent Lightning Strikes

Experience of power system engineers in regions where there are high levels of lightning has shown that the insulation levels of up to 300kV is required on 11kV/22kV lines for adequate lightning performance. The purpose of this high BIL (Basic Insulation Level) is to improve the performance of the distribution line insulation. The peak induced voltage can be fairly high even for adjacent lightning strikes.

Mathematically the electro-magnetic field has two components :

- Electric Field : Due to the presence of high charge density
- Magnetic Field : Due to the change in the magnitude of the lightning current flow

The ***Electromagnetic Field*** can be expressed mathematically in vector form as :

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}$$

where : V is the scalar potential at a point calculated from the magnitude and position of the lightning charge as follows :

$$V = \frac{1}{4\pi\epsilon}\iiint \frac{\rho}{r}\,dv$$

where : ϵ is the permittivity of air
ρ is the charge density in the volume element dv
r is the distance of the volume element from the point of measurement

$\vec{A}$ is the vector potential at a point calculated from the magnitude and direction of lightning current flow

$$\vec{A} = \frac{\mu}{4\pi}\iiint \frac{\vec{J}}{r}\,dv$$

where : μ is the permeability of air
$\vec{J}$ is the current density in the volume element dv
r is the distance of the volume element from the point of measurement

The above mathematics is relatively simple to understand and implement. The difficulty is to decide on a value of ρ (the charge density). Research indicates that there is a wide scatter of appropriate values for ρ.

Therefore, to simplify the problem for most practical purposes, an empirical formula ha been developed which yields the peak induced voltage, which is of course directl proportional to the peak lightning current. The empirical formula has the form :

$$V_{peak} = KI\frac{h}{d}$$

where : V_{peak} is the peak induced voltage
K is a constant
I is the peak lightning current
h is the height of the conductor above the ground
d is the distance of the conductor from the point of lightning strike

From the above formula, there are a number of ways to limit the amplitude of the induce voltage surges in overhead transmission lines. These are as follows :

- Reduce the height of conductors above the ground (not always possible due t other technical requirements)
- Reduce the field local to the conductor by installing an overhead earth conducto (shield wire), which should be earthed at every pole
- Bury the cables below the ground
- Surround the conductor with an equipotential surface, such as a co-axial scree metal conduit or metal cabinet, which behaves like a Faraday cage.

The above four techniques all help to reduce the induced effect, but do not eliminate it.

For example, it is not a good idea in high lightning areas to run signal cables suspende from poles (h is large, so V_{peak} is large). It is preferable to bury the cables underground t reduce the inductive coupling associated with lightning. But this does not mean that th cables are protected from the electric field, which extends several tens of metres below th surface .... due to the "skin effect". The earth is NOT a perfect conductor and, since th main frequency components of lightning are high (about 10kHz), the electric and magneti fields penetrate well below the surface. So ideally, the cables should be screened as we For example, they can be run in metal conduit or can be steel wire armoured.

A.6 Useful Tables from IEC 1024-1 (1990)

The following tables (IEC 1024-1 (1990)) offer guidance in the design of external lightning protection systems (LPSs) for buildings.

Material	Use		
	In Open Air	In Soil	In Concrete
Copper	Solid, Stranded or as a Coating	Solid, Stranded or as a Coating	Do NOT Use
Hot Galvanised Steel	Solid or Stranded	Solid	Solid
Stainless Steel	Solid or Stranded	Solid	Do NOT Use
Aluminium	Solid or Stranded	Do NOT Use	Do NOT Use
Lead	Solid or as a Coating	Solid or as a Coating	Do NOT Use

Figure A.13 : Recommended Usage of Materials from IEC 1024-1 1990

Material	Corrosion		
	Resistance	Increased by	Electrolytic with
Copper	Against many materials	Concentrated Chlorides, Sulphur compounds and organic materials	–
Hot Galvanised Steel	Good even in Acid Soils	–	Copper
Stainless Steel	Against many materials	Water with dissolved Chlorides	–
Aluminium	–	Basic Agents	Copper
Lead	High concentration of sulphates	Acid Soils	Copper

Figure A.14 : The Corrosion properties of different materials

Protection Level	Materials	Air Termination	Down Conductor	Earth Electrode
I to IV	Copper	35mm^2	16mm^2	50mm^2
	Aluminium	70mm^2	25mm^2	–
	Steel	50mm^2	50mm^2	80mm^2

Figure A.15 : Minimum Dimensions of Lightning Protection System Materials

Protection Level	Materials	Cross-section
I to IV	Copper	16mm^2
	Aluminium	25mm^2
	Steel	50mm^2

Figure A.16 : Minimum Dimensions for Bonding Conductors carrying a substantial part of the Lightning Current from IEC 1024 (SPZ 0-1)

Protection Level	Materials	Cross-section
I to IV	Copper	6mm^2
	Aluminium	10mm^2
	Steel	16mm^2

Figure A.17: Minimum Dimensions for Bonding Conductors carrying no significant part of the Lightning Current from IEC 1024 (SPZ 1-2, 2-3, etc)

Appendix B : SOIL RESISTIVITY AND EARTH ELECTRODES

B.1 Introduction

One of the main objectives of Earthing electrical systems is to establish a common reference potential for the power supply system, building structure, plant steelwork, electrical conduits, cable ladders & trays and the instrumentation system. To achieve this objective, a suitable low resistance connection to Earth is desirable. However, this is often difficult to achieve and depends on a number of factors :

- Soil Resistivity
- Size and type of Electrode used
- Depth to which the Electrode is buried
- Moisture and chemical content of the soil

B.2 Soil Resistivity

Resistance is that property of a conductor which opposes electric current flow when a voltage is applied across the two ends. Its unit of measure is the Ohm (Ω) and the commonly used symbol is **R**. Resistance is the ratio of the applied voltage (E) to the resulting current flow (I) as defined by the well known linear equation from Ohm's Law :

$$E = I \times R$$

where :
- E — Potential Difference across the conductor (Volts)
- I — Current flowing through the conductor in (Amperes)
- R — Resistance of the conductor in (Ohms)

"Good conductors" are those with a low resistance. "Bad conductors" are those with a high resistance. "Very bad conductors" are usually called Insulators.

The Resistance of a conductor depends on the atomic structure of the material or its *Resistivity* (measured in Ohm-m or Ω-m), which is that property of a material that measures its ability to conduct electricity. A material with a low resistivity will behave as a "good conductor" and one with a high resistivity will behave as a "bad conductor". The commonly used symbol for resistivity is ϱ (Greek symbol rho).

The resistance (R) of a conductor, can be derived from the resistivity as :

$$R = \frac{\varrho \times L}{A}$$

where :
- ϱ — Resistivity (Ω-m) of the conductor material
- L — Length of the conductor (m)
- A — Cross sectional Area (m^2)

Resistivity is also sometimes referred to as 'Specific Resistance' because, from the above formula, Resistivity (Ω-m) is the resistance between the opposite faces of a cube of material with a side dimension of 1 metre.

Consequently, *Soil Resistivity* is the measure of the resistance between the opposite sides of a cube of soil with a side dimension of 1 metre.

Soil Resistivity at a specific location is dependent on several factors including :

- Chemical composition of the soil (presence of conductive salts)
- Mechanical condition of the soil (level of compaction)
- Moisture content of the soil
- Temperature of the soil

The variation of Soil Resistivity with the above factors is illustrated in Tables on pages 67 and 68 of **AS 1768-1991 - Lightning Protection**.

In general, a high percentage of conductive salts and a high moisture content in the soil will reduce soil resistivity and improve its qualities as a conductor of electricity.

Chemical additives, such as chlorides, nitrates or sulphates, are often used to artificially reduce soil resistivity at earthing points. Although this may provide a short term solution to high soil resistivity problems, there are a number of potential dangers :

- The corrosion of the earth electrode may be increased
- The chemical additives will tend to leach away from the vicinity of the electrode over a period of time
- Some of these chemical additives are not desirable from an environmental viewpoint

As recommended in AS 1768-1991, for high resistivity soils, a backfill of material such as sodium or calcium bentonite clay, or montmorillonite mixed with finely ground gypsum, will reduce soil resistivity in the vicinity of an earth electrode for a considerable period of time. This backfill will provide a non-corrosive environment and maintain some moisture in the vicinity of the earth electrodes.

B.3 Measurement of Soil Resistivity

Before designing an earth electrode system, it is necessary to know the resistivity of the soil at the proposed location of the earth electrode. This can readily be measured on site using a technique known as the 4-point or Wenner method. This method uses 4 spike electrodes which make contact with the soil at 4 locations. The 4 spikes should be driven to the same depth (L) and be evenly spaced along a straight line so that the spike diameters and their depth (L) are small when compared to the separation distance (S) between the spikes. It is recommended that the depth (L) should be less than 1 metre and less than 5% of the separation distance (S).

When a measured current (I) is passed between the two outer conductors, the voltage (V) difference between two inner electrodes yields a resistance value of :

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

Assuming that the soil is homogeneous, the average soil resistivity (ρ) at the depth of L metres is then :

$$\rho = 2\,\pi\,S\,R \qquad ohm\text{-}m$$

where : S Separation distance between inner spikes (m)
R Measured Resistance between inner spikes (Ω)

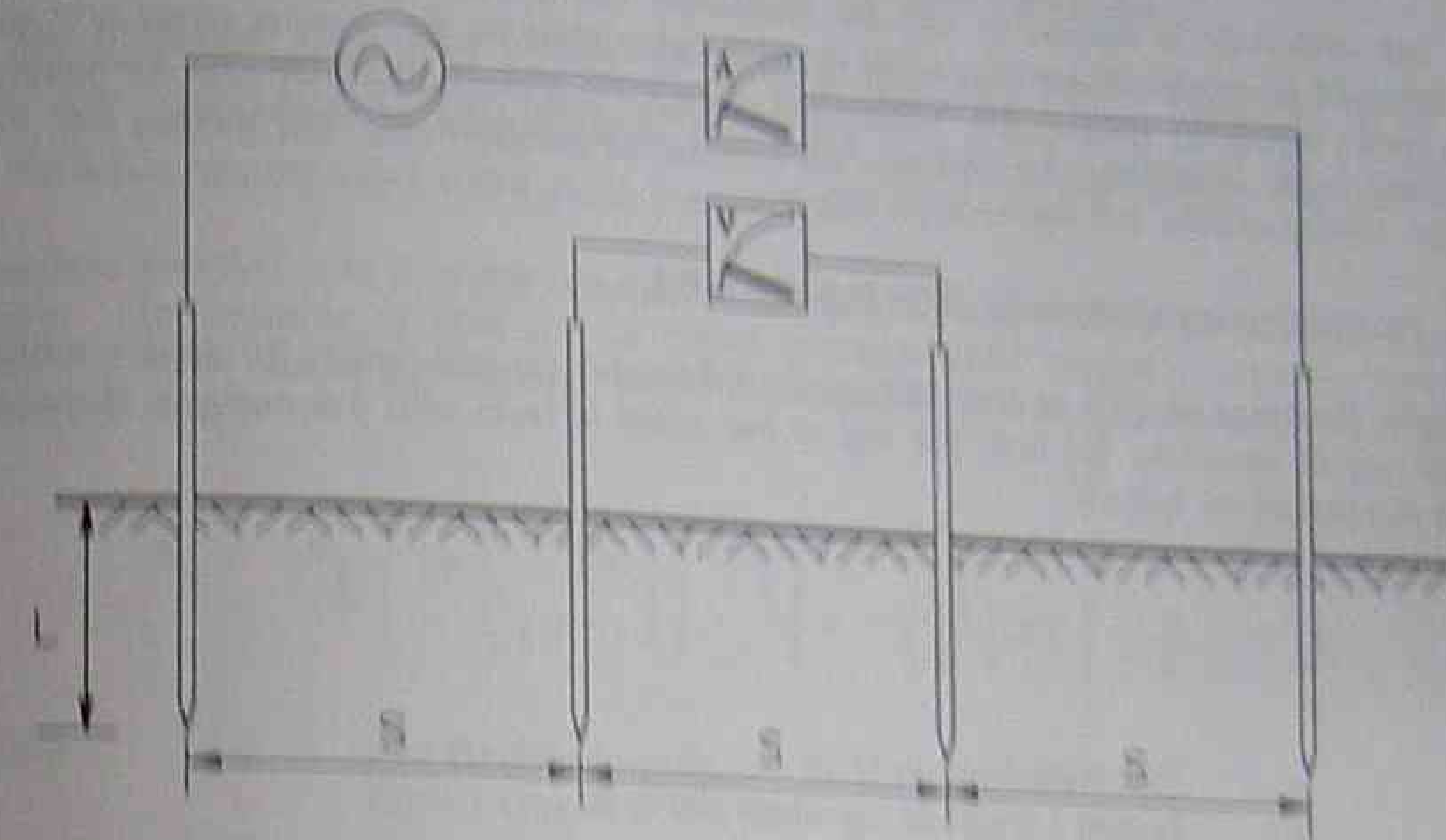


Figure B.1 : The 4-point or Wenner Method of Soil Resistivity Measurement

Some practical observations are :

- In practice, the soil is seldom homogeneous, so several resistivity measurements need to be taken in the area designated for an earth electrode. Adjusting the spike separation (S) can give an indication of the nature of the underlying soil.
- The depth to which the spikes are driven will also affect the soil resistivity measurement since different strata below the surface can have higher or lower resistivity. Adjusting the spike depth (L) can give additional information about the nature of the underlying soil strata.
- The seasonal variation of rainfall and temperature will affect the moisture content and temperature of the soil and consequently the soil resistivity.

B.4 Types of Earth Electrodes

Earth electrodes must ideally penetrate into the moisture level below the ground level. They must also consist of a metal (or combination of metals) which do not corrode excessively for the period of time they are expected to serve. Because of its high conductivity and resistance to corrosion, copper is the most commonly used material for earth electrodes. Other popular materials are hot-galvanised steel, copper covered steel, stainless steel, aluminium and lead.

Earth electrodes may be rods, plates, strips, solid section wire or mats.

B.5 Earth Resistance of an Electrode – Calculation

Since soil exhibits a resistance to the flow of an electrical current and is not an "ideal" conductor, there will always be some resistance (can never be zero) between the earth electrode and "true Earth". The resistance between the earth electrode and "true Earth" is known as the *Earth Resistance of an electrode* and it will depend on the soil resistivity, the type and size of the electrode and the depth to which it is buried.

If the soil resistivity is known or can be measured using the 4-point method, the Earth Resistance of an electrode configuration may be **calculated** for the various types and sizes of the earth electrode used. **AS 1768-1991** pages 68 and 69 provides the formulae for calculating earth resistance for various types and configurations of electrodes. The most common configurations will be covered below.

B.5.1 Rods Driven Vertically into the Ground

The **Earth Resistance** (R_g) of a single spike, of diameter (d) and length (L) driven vertically into the soil of resistivity (ϱ) until the top of the spike is level with the surface of the soil, can be calculated as follows :

$$R_g = \frac{\varrho}{2 \pi L} \left[\ln \left(\frac{8L}{d} \right) - 1 \right]$$

where :

ϱ	Soil Resistivity in Ω–m
L	Buried Length of the electrode in m
d	diameter of the electrode in m

Example B.1

(a) 20mm rod of 3m length and Soil resistivity 50 Ω–m ...... R = 16.1Ω

(b) 25mm rod of 2m length and Soil resistivity 30 Ω–m ...... R = 13.0Ω

B.5.2 Rod Electrodes in Parallel

If the desired earth resistance cannot be achieved with one earth electrode, the overall resistance can be reduced by connecting a number of electrodes in parallel. These are also sometimes called "arrays of rod electrodes".

The combined resistance of parallel electrodes is a complex function of several factors, such as the number and configuration of electrodes, the separation between them, their dimensions and soil resistivity.

If the separation of the electrodes is much larger than their lengths and only a few electrodes are in parallel, then the resultant earth resistance can be calculated using the ordinary equation for resistances in parallel. In practice, the effective earth resistance will usually be higher than this. Typically, a 4 spike array may provide an improvement of about 2.5 to 3 times. An 8 spike array will typically give an improvement of maybe 5 to 6 times.

B.5.3 Trench Electrodes – Horizontal Electrodes buried under the Surface

Trench Electrodes, conductors buried horizontally under the surface of the ground, also make very good connections to earth. They are particularly effective when a down-conductor is connected to a point between the ends of the trench electrode. With this configuration, the surge inductance is halved, because there will be two parallel transmission paths. Trench electrodes are very effective when used in combination with spike electrodes, located close to the junction of the down–conductor.

These horizontal electrodes should not have a very long length because, for a typical lightning current rise time of 0.5μs and a propagation speed of 0.75 times the speed of light, the current will have reached its peak at the connection point before the leading edge of the wave has travelled 100m along the conductor.

Standard practice is to bury the conductor underground at a depth of >0.5m and a length of >30m. For example, a 50m run of 10mm diameter solid copper conductor buried at a depth of 0.5m below the surface yields a theoretical 4Ω earth resistance in a soil with resistivity of 90Ω–m.

$$R_g = \frac{\varrho}{\pi L} \left[\ln \left(\frac{4L}{(d\,h)^{\frac{1}{2}}} \right) - 1 \right]$$

where :

ϱ	Soil Resistivity in Ω–m
L	Buried Length of the electrode in m
d	diameter of the electrode in m
h	buried depth of the electrode in m

Practical earth connections can also be made from various "star" arrangements radiating from a central point. This is sometimes called a "crow's foot" earth electrode. This has an improved surge impedance performance, with several parallel paths. But the multiple trench electrode will have a higher low frequency (50Hz) resistance because of the interaction of the fields of each of the radial conductors. The formula for calculating the earth resistance of radial wires is given on Page 69 of AS 1768–1991.

B.5.4 Ground–grid Mesh Electrodes

Another example of the use of conductors, buried under the surface of the earth, is the ground–grid mesh. Grid meshes are often used to complement rods or can be used separately when deep driven rods are impractical due to soil and terrain considerations. Grid meshes are often used for the earthing in substations to create an equipotential platform and also to handle the high fault currents returning to the transformer neutrals. Earthing resistance of buried grid meshes can be considerably lower than those implemented using vertical earth spikes. Increasing the area of the grid coverage can also significantly reduce the earth resistance.

B.6 Earth Resistance of an Electrode - Measurement

When an earth electrode system has been designed and installed, it is usually necessary to measure and confirm the earth resistance between the electrode and "true Earth". The most commonly used method of measuring the earth resistance of an earth electrode is the 3-point measuring technique shown in Figure B.2. This method is derived from the 4-point method, which is used for soil resistivity measurements.

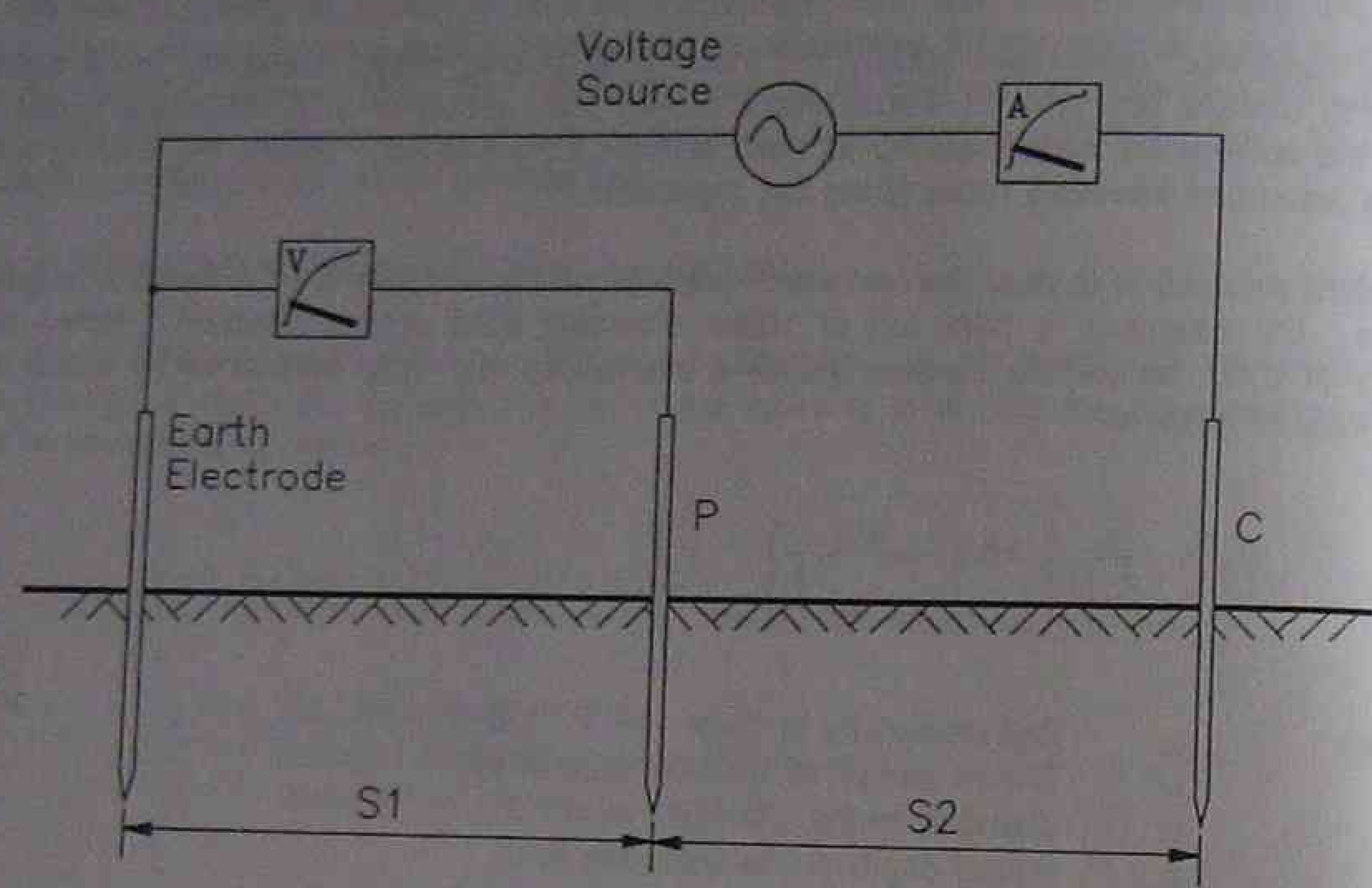


Figure B.2 : The 3-point Method of Earth Resistance Measurement

The 3-point method, called the "fall of potential" method, comprises the Earth Electrode to be measured and two other electrically independent test electrodes, usually labelled P (Potential) and C (Current). These test electrodes can be of lesser "quality" (higher earth resistance) but must be electrically independent of the electrode to be measured. An alternating current (I) is passed through the outer electrode C and the voltage is measured, by means of an inner electrode P, at some intermediary point between them. The Earth Resistance is simply calculated using Ohm's Law .... $R_g = V/A$.

An *alternating* power source is necessary for this test to avoid the problem of DC polarisation on the test spikes, which would give a superimposed error on the voltage measurement. Current and voltage can be measured by using individual ammeters and voltmeters. In practice, a commercial Earth Resistance Test Set is normally used for measuring Earth Resistance. Various configurations of instrument are available.

The placement of the test spikes is important to avoid measurement errors. In general, the test spike C should be located at a distance of at least 10 times the depth of the earth electrode. It is recommended that spike C should be located as far as reasonably possible from the earth electrode to avoid errors due to inhomogeneity of the soil. Test spike P, for measuring voltage, should be located about half the distance between them (ie. S1 ≈ S2).

However, a high voltage may appear during testing between the two electrodes due to power faults or lightning strikes. Insulating gloves are recommended for the operator.

B.7 Resistance seen by the Earth Electrode

To complete the electrical connection to "true" earth, the down conductor must be connected to the *earth electrode*. When the lightning current flows from the earth electrode into the soil, the earth electrode rises in voltage as a result of some impedance in this part of the circuit. This behaviour at the earth electrode is represented by a *resistance* connected to the base of the down conductor and known as the *resistance of the earth electrode*.

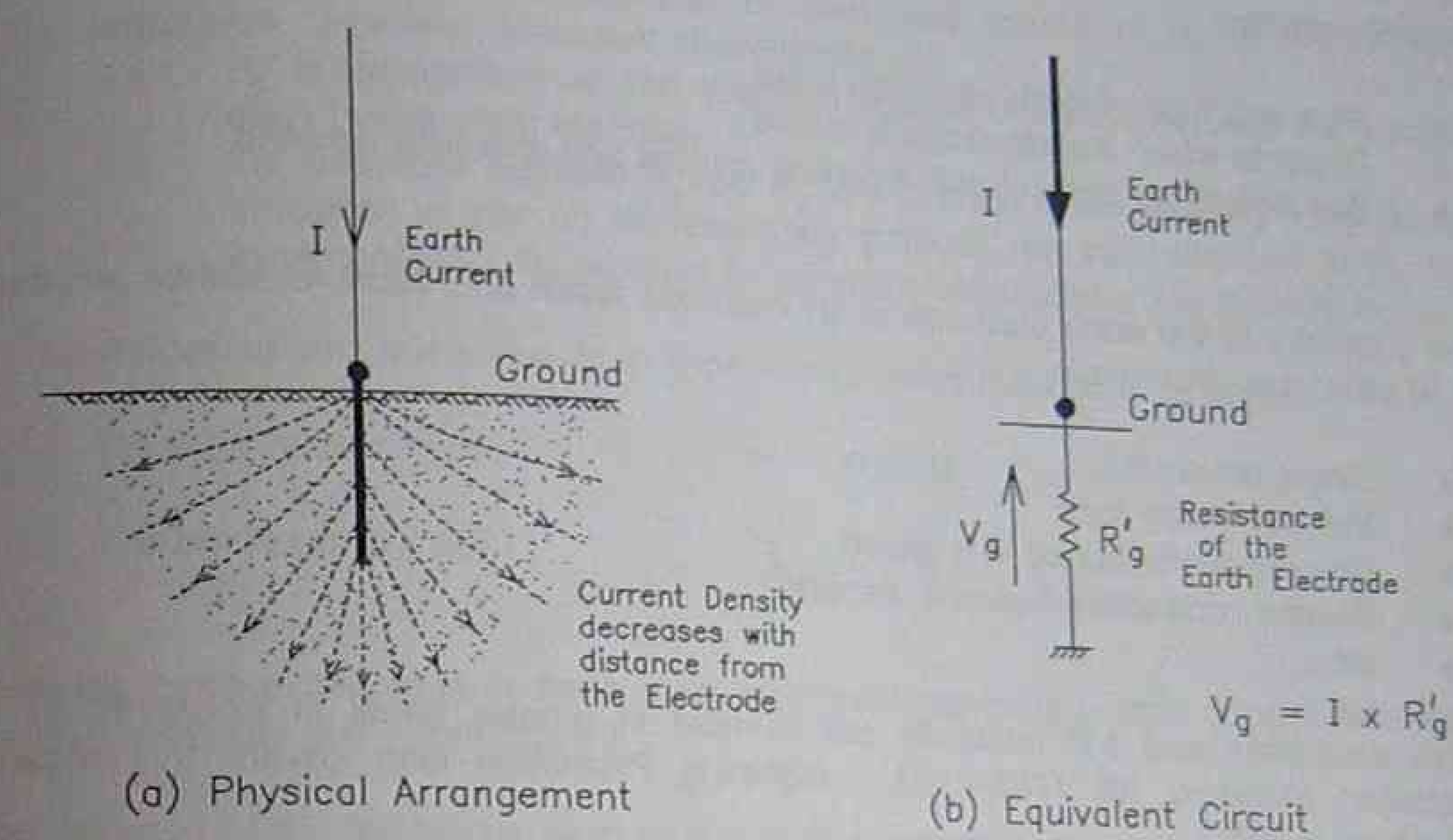


Figure B.3 : The Resistance of the Earth Electrode

This representation of the earth electrode as a *resistance* can be more easily understood from its derivation outlined as follows :

- When the lightning current passes from the earth electrode into the soil, it imposes a current density J in the soil. As the current spreads out, the current density decreases with distance from the electrode. From the fundamental version of Ohm's law, if the soil resistivity is ρ, this produces an electric field E in the soil as follows :

$$E = J\rho$$

- From the electric field E in the soil, the voltage V at the earth electrode can be derived by integrating over distance from the earth electrode.

$$V = \int E \, dx$$

- Finally, the earth resistance R_g is obtained by dividing the above voltage by the total lightning current.

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

This value of *earth resistance* R_g can be calculated or measured and is a function of several variables :

- Size and type of earth electrode used
- Depth to which the electrode is buried
- Soil Resistivity (type of soil, moisture content and chemical content)

The geometry of the earth electrode is an important factor and earth resistance will depend on whether the electrode is :

- Single driven rod
- Multiple driven rods
- One conductor buried in a trench
- Several conductors buried in trenches
- etc ....

Earth electrodes and soil resistivity are covered in greater detail in Appendix B. The Australian Standard AS 1768-1991 : Lightning Protection also covers this subject in considerable detail.

Several points about earth electrodes are worth noting :

- At large distances from the earth electrode (> 10m), the lightning current is flowing through such a large cross-sectional area that the current density J becomes negligible. Therefore, the electric field in the soil at this distance is also negligible and does not contribute significantly to the voltage V or to the earth resistance R_g. Consequently, R_g is determined by the soil in the *immediate vicinity* of the earth electrode. The soil at larger distances can be considered to be a perfect conductor.

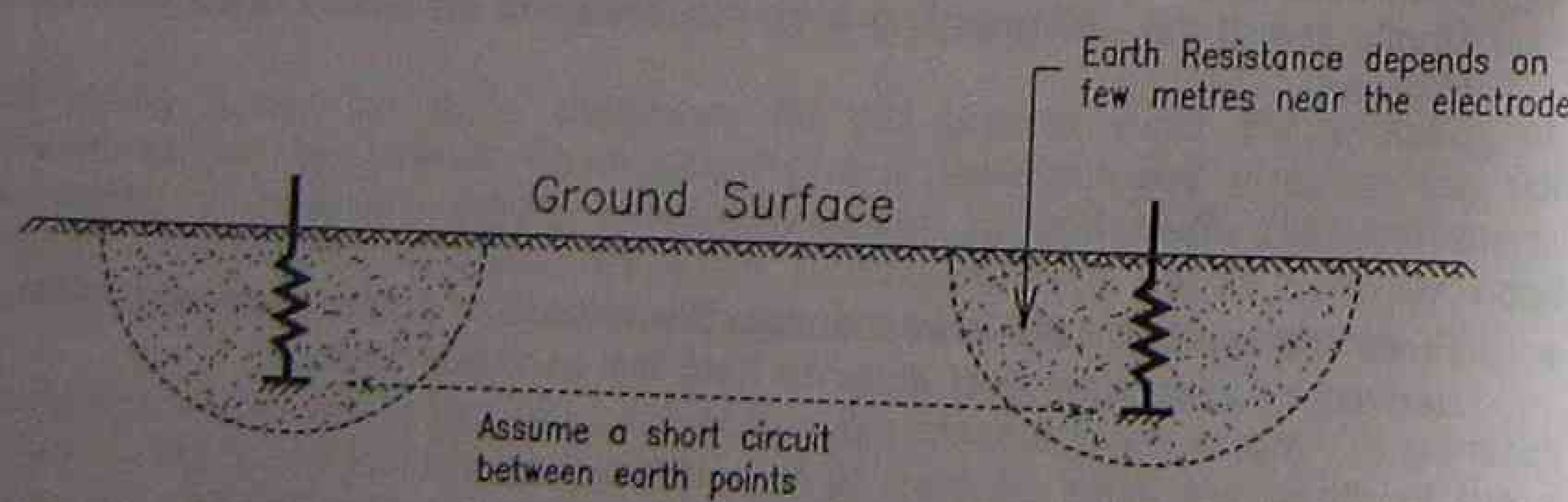


Figure B.4 : The Resistance of the Earth between Electrodes

- just as there is a maximum electric field that can be sustained between two electrodes in air before breakdown, there is a maximum electric field that can be sustained in soil before soil ionisation. Soil ionisation reduces the effective soil resistivity during the passage of high currents (high electric fields).

  This point suggests that there is a difference between the low-current earth resistance R_g, which is the value usually measured by testing or from calculation, and the high-current earth resistance seen by the lightning current, R_g'.

  Calculation of R_g' from measured or calculated values of R_g is difficult, if not impossible. However, important observations are
  - R_g' is considerably smaller than R_g because ionisation reduces the resistance seen by the earth electrode
  - the difference between R_g and R_g' is a function of the peak lightning current I
  - ionisation is not an instantaneous process, so the reduction in R_g is not instantaneous. R_g' reaches its minimum value after a few microseconds.

For most applications, it is sufficient to approximate these reductions as follows :

For high resistivity soil : $R_g' = 0.25\ R_g$

For low resistivity soil : $R_g' = 0.5\ R_g$

Thus the *relative decrease in earth resistance* under lightning current conditions is greater for high resistivity soil – fortunately!!

The variation of the resistance seen by the earth electrode as a function of the peak lightning current can be plotted graphically and has the following form

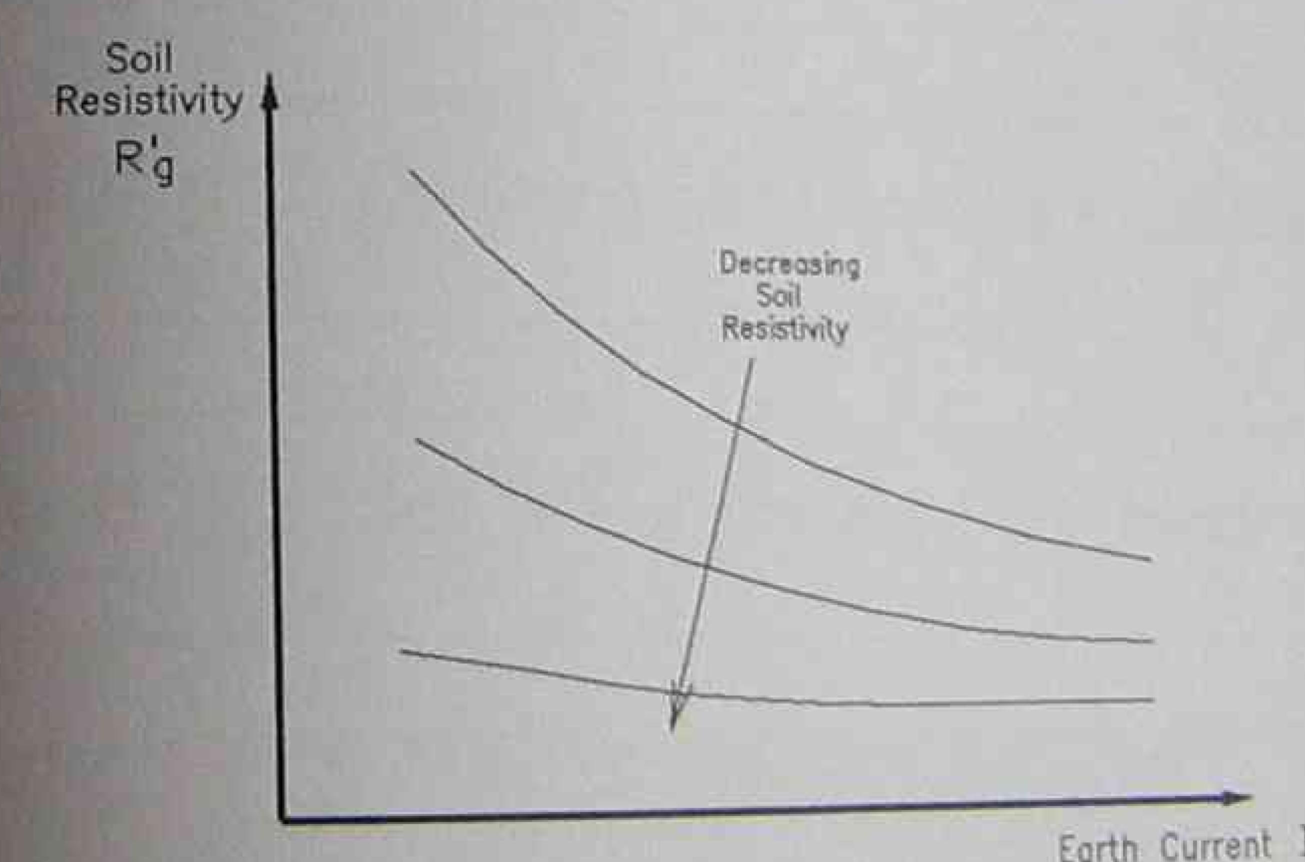


Figure B.5 : The Decrease in Soil Resistivity with Current

Blank Page

0 Contents

Appendix C : INTERNATIONAL & NATIONAL STANDARDS

C.1 Introduction

International trade, and the acceptability of imported and exported products, is dependent on the existence of internationally acceptable Standards and Norms. This Appendix summarises the various International and National Standards, which are applicable to electrical engineering.

C.2 International Standards

Standardisation is coordinated internationally by the **ISO - International Standards Organisation**, which draws its members from all countries of the world. ISO concentrates on coordinating standards internationally. ISO has published almost 9000 Standards, covering a broad range of subjects. To facilitate international trade, there is a general movement in most countries towards bringing their own standards into harmony with the International Standards. Standardisation is achieved through the participation of interested parties, usually from national standards organisations, interested academics, scientists and manufacturers. Reaching consensus on Standards internationally is a tedious process and it is coordinated through :

- TC : Technical Committees
- SC : Technical Sub-Committees
- WG : Working Groups

Standardisation of electrotechnical matters is coordinated internationally by the **International Electrotechnical Commission** (IEC). In a similar way to ISO, standardisation is achieved through the participation and consensus of interested parties, usually from national standards organisations, interested academics, scientists and manufacturers. As in ISO, standardisation is coordinated through :

- TC : Technical Committees
- SC : Technical Sub-Committees
- WG : Working Groups

C.3 European Standards

To a greater or lesser degree, all European countries have developed their own national standards. Since 1945, the major countries of Europe have been actively working towards a common market and, during this period, there has been a great expansion of inter-European trade. Initially this common market was called the European Economic Community (EEC), then the European Community (EC) and most recently the European Union (EU). To overcome the technical differences between the products manufactured in European countries, several committees have been established to harmonise standards. In some cases, new standards known as European Norms (EN) have been introduced.

The following committees have been established to coordinate European standardisation :

CEN	:	*Comite European de Normalisation* (Committee for European Standardisation)
CENELEC	:	*Comite European de Normalisation - Electrotechnique* (Committee for European Electrotechnical Standardisation)
CCITT	:	*Comite Consultatief International Telegraphique et Telephonique* (Consultative Committee for International Telegraph and Telephone)
ECISS	:	European Committee for Iron and Steel Standards

Because of the economic power of Europe, these "Norms" will inevitably have relevance to non-European countries, which seek to trade with Europe. Many of these ENs will become de facto international standards or be embodied in ISO or IEC standards.

C.4 United States of America Standards

Economically and militarily, the USA has been the most powerful and influential country in the world for at least the past 50 years. The sheer size of its economy and the large number of high calibre technical experts working there has provided the USA with an unusually high capacity for technical innovation. Many well known standards, which have become de facto international standards, have been developed in the USA. Most electrical engineers are familiar with the USA standards, developed by organisations such as ANSI, FCC, IEEE, NEMA, MIL, EIA/TIA and UL. Many of these have been formally embodied in ISO and IEC standards. Also, because of the large defence industry in USA, a wide range of military (MIL) standards have been developed for difficult environments. These are usually significantly tighter than their civilian counterparts.

In spite of this economic and technical power, standardisation in the USA is largely out of step with the rest of the world. This is mainly a result of the different units of measure used in the USA compared to the rest of the world. Almost all countries outside the USA, such as Western Europe, Eastern Europe, Japan, Australia & New Zealand, Africa, South America, China, Taiwan and the fast growing SE Asian countries have based their industries on the METRIC SYSTEM of measurement and have actively tried to harmonise their standards along the lines of ISO and IEC. On the other hand, the USA is only partially metricised and has largely kept the old English system of measurement, which is based on feet, inches, pounds, gallons, etc. In general, the USA has largely been reluctant to move in the direction of harmonising their standards with ISO and IEC. This continues to create difficulties with international free trade.

C.5 National Standards

All industrialised countries have their own national standards bodies, who establish and co-ordinate national standards. These standards organisations are usually members of ISO and IEC. To facilitate international trade, National Standards are increasingly "harmonised" with the relevant ISO and IEC Standards. Any differences that still remain between the national and international standards are usually associated with some special local conditions and established local practice.

Country	Initials	Name of Standards Organisation
Australia	AS	Standards Australia
Belgium	IBN	Institut Belge de Normalisation
Canada	CSA	Canadian Standards Association
CIS (ex USSR)	GOST	Gosudarstvenne Komitet Standartov
Denmark	DS DEMKO	Dansk Standardisieringsraad Danmarks Elektrise Material Kontrol
European	CEN CENELEC CCITT	Comite European de Normalisation Comite European de Normalisation - Electrotechnique Comite Consultatief International Telegraphique et Telephonique
Finland	SFS	Suomen Finland Standardisoimisliitto
France	AFNOR UTE	Association Française de Normalisation Union Technique de l'Electricité
Germany	DIN VDE	Deutches Institut für Normierung Verband Deutscher Elektrotechniker
International	IEC ISO ITU	International Electrotechnical Commission International Organisation for Standards International Telecommunications Union
Italy	CEI	Comitato Electrotechnico Italiano
Japan	JIS	Japanese Industrial Standard
Netherlands	NNI	Nederlands Normalisatie Instituut
New Zealand	NZS	Standards Association of New Zealand
Norway	NSF DNV	Norges Standardisieringsforbund Det Norsk Veritas
Poland	PRS	
Saudi Arabia	SASO	Saudi Arabian Standards Association
South Africa	SABS	South African Bureau of Standards
Spain	UNE	Una Norma Española
Sweden	SIS	Standardisieringskommissionen I Sverige
Switzerland	SEV	Schweizerischer Electrotechnischer Verein
United Kingdom	BSI	British Standards Institution
United States of America	ANSI FCC IEEE NEMA UL	American National Standards Institute Federal Communications Commission Institute of Electrical and Electronic Engineers National Electrical Manufacturers Association Underwriters Laboratories

Figure A.1 : The Names and Initials of the major Standards Organisations

C.6 Australian Standards

In order to harmonise with the rest of the world, Standards Australia has resolved to adopt international standards wherever possible, provided that they are appropriate. This has changed the emphasis away from writing our own standards to looking critically at those from other organisations, such as ISO, IEC and CENELEC and participating in the continual review and updating of those standards.

The Standards which are applicable to the technical issues covered in this book are listed under the "Standards" section of the *Bibliography & Recommended Additional Reading*.

Appendix D : **GLOSSARY OF COMMON TERMS USED WITH LIGHTNING, EARTHING AND SURGE PROTECTION**

AC	**Alternating Current**, an electrical transmission system where the voltage and the associated current alternatively adopt a positive and negative polarity, typically at 50 cycles per sec.
A/D Converter	Device used to convert Analog signals into the Digital format.
Air Terminal	Part of the lightning protection system, usually attached to the top of a structure, intended to intercept the potential lightning strikes
Algorithm	A procedure or set of steps which are used, usually in a computer program or processor, to solve a problem.
Analog	A continuously varying waveform or signal that may represent a Voltage, Current or any other continuously changing value.
ANSI	**American National Standards Institute**, which is the main standards organisation in the USA.
Armouring	Protective metal covering, usually steel wire, commonly installed around insulated electric cables. Armouring is used both as a physical protection for the cable and as a shield to attenuate magnetic fields. The armouring is usually earthed at both ends of the cable.
AS	**Australian Standards** of the Standards Association of Australia (SAA), the main standards organisation in Australia.
Attenuation	A decrease in the magnitude of a signal, sound or voltage down a transmission path, usually expressed in dB (deciBels).
AWG	American Wire Gauge for cross-sectional area of conductors
Bandwidth	Range of frequencies in Hz, being the difference between the lowest and highest frequency, which can be transferred along a transmission medium without significant attenuation.
BS	**British Standards** of the British Standards Institution (BSI), the main standards organisation in the United Kingdom.
Bonding	The connection together of the metal parts of an electrical system so that they are at a common voltage, usually earth potential.
CAD	**Computer Aided Design**, computer based design program.
CAE	**Computer Aided Engineering**, computer based engineering program.
CAM	**Computer Aided Manufacturing**, computer based manufacturing program.
Capacitance	The property of an AC electrical circuit to store electrical energy when a voltage is applied. Capacitance is normally associated with two plates, where the capacitance is proportional to the area of the plates and inversely proportional to the distance between them. When an alternating voltage is applied, the resulting current will be such that the current peak will lead the voltage peak by 90°. Unit of capacitance : Farad.
Capacitive Coupling	The mechanism of transfer of electrical noise signals from a source circuit to another circuit, usually a signal circuit, as a result of the **changing electric field (due to dv/dt)** associated with the source circuit.
CENELEC	**Comite European de Normalisation - Electrotechnique**, whose standards are applied by European countries.
CNC	**Computer Numerical Control**, a computer controlled machine.
Co-axial Cable	A type of cable consisting of two concentric conductors separated by insulating material, usually used to transmit high frequency signals.

Common Mode Volts	The Voltage between a signal conductor and the common reference point or signal common conductor, usually connected to earth.
Conduit	A pipe for the mechanical protection of electrical cables installed inside them. When the conduit is made of galvanised steel, it provides protection for the enclosed circuits from inductive coupling, due to magnetic fields.
CPU	**Central Processing Unit**, the intelligent core of a digital device.
CSA	**Canadian Standards Association**, the main standards organisation in Canada.
Current Loop	A communication method where the signal is represented by a current, usually 20mA or 60mA, flowing in a closed loop.
D/A	Device used to convert Digital signals into the Analog format.
dB	**deciBel**, a measure of attenuation in a signal, based on the logarithmic ratio of the signal magnitude V_1 and V_2 at the two ends. The ratio is expressed as ...... dB = $20\log_{10}V_1/V_2$.
DC	**Direct Current**, an electrical transmission system where Voltage and Current retain a fixed polarity (positive or negative).
DCS	**Distributed Control System**, an industrial control computer usually used for process control applications.
Degradation	An undesired departure in the operational performance of any device, equipment or system from its intended performance.
Differential Mode	The Voltage between two signal conductors, which are isolated from the common reference point or signal common conductor. This is also sometimes called the **Transverse Mode Voltage.**
Digital	A type of signal that has two or more definite states, usually voltage levels. A special case is a **Binary Digital signal**, which has two states (0 & 1).
DIN	**Deutches Institut fur Normierung**, the standards organisation of Germany
DIP	**Dual In-line Package**, a group of switches used on a PCB
DOL	**Direct-on-line**, a method of starting AC Induction motors by switching them directly to the power source via a contactor.
Duct	A channel for the mechanical protection of electrical cables installed inside them. When the duct is made of galvanised steel, it provides protection of the enclosed circuits from inductive coupling, due to magnetic fields.
Earth	The earth itself is taken to be at zero voltage. Any conducting materials connected to earth are said to be "Earthed".
Earth Electrode	A conductor, or group of conductors, which provide a good electrical connection with the Earth.
Electric Field	The field around a charged conductor, due to the high voltage of that conductor relative to earth or relative to another conductor.
Electromagnetic Field	A field which is a combination of both an *electric field* and a *magnetic field*. It is usually abbreviated as an EM Field.
EMC	**Electromagnetic Compatibility**, the ability of electronic equipment or system to function satisfactorily in the electromagnetic environment and without itself introducing any further electromagnetic disturbances that would affect the ability of any other equipment or system to function satisfactorily.
EM Disturbance	**Electromagnetic Disturbance**, any EM phenomenon which may degrade the performance of an electrical device or system.
EM Environment	The totality of the electromagnetic phenomena existing at any given location.
EMI	**Electromagnetic Interference**, the degradation of performance of electronic equipment, transmission channel or system caused by an EM disturbance.
EM Noise	A time varying electromagnetic signal not conveying useful information which may be superimposed on or combined with a wanted signal.

EMI Immunity	The ability of a device, equipment or system to perform without degradation in the presence of electromagnetic interference
EMI Susceptibility	The lack of EMI immunity.
EPROM	**Erasable Programmable Read Only Memory**, a non-volatile memory, commonly used with microprocessors to store program data. The data in the memory can be erased, usually by ultraviolet light. The data is not lost when the power is removed.
EEPROM	**Electrically Erasable Programmable Read Only Memory**, a non-volatile memory, commonly used with microprocessors to store program data. The data in the memory can be erased and updated electronically. The data is not lost when the power is removed.
Equipotential	Of equal voltage (potential).
ESD	**Electrostatic Discharge**, the transfer of an electric charge between bodies of different electrostatic potential.
Farad	Unit of measurement of Capacitance in the metric, whereby a charge of 1 Coulomb produces a potential difference of 1 Volt.
FCC	Federal Communications Commission (USA government body).
Fibre-Optic	A medium, usually made of glass or plastic, for transferring light signals.
Frequency	Refers to the number of cycles per second of an oscillating waveform. Unit of measure : Hertz (Hz).
G-	**Giga**, metric system prefix ..... x 10^9
Ground	Another term for Earth, usually used in USA. A reference point for an electrical circuit, which is connected to the Earth and intended to have the same potential as the Earth. It is usually intended for safety purposes.
Harmonics	Currents, voltages or fields at frequencies which are multiples of the power system frequency.
Henry	Unit of measurement of Inductance in the metric system.
Hz	**Hertz**, unit of frequency - equivalent to one cycle per second.
IC	**Integrated Circuit**, an encapsulated electronic circuit, containing miniaturised electronic components, that is designed to perform in a particular way.
IEC	**International Electrotechnical Commission**, an international standards organisation, which specialises in electrical standards.
IEAust	**Institute of Engineers Australia**, a professional institute for engineers in Australia.
IEE	**Institution of Electrical Engineers**, a professional institute for electrical engineers in UK.
IEEE	**Institute of Electrical and Electronics Engineers**, a professional institute for electronic and electrical engineers in North America.
Impedance	The total opposition that an electric circuit offers to the flow of an alternating current. It is a combination of Resistance (R) and Inductance (L) where $Z = (R + j\omega L)$. Unit of measure : Ohm (Ω).
Inductance	The property of an electric circuit which opposes a change in current flow. In an AC circuit, inductance causes current peak to lag behind voltage peak by 90°. Unit of measure : Henry (H).
Inductive Coupling	The mechanism of transfer of electrical noise signals from a source circuit to another circuit, usually a signal circuit, as a result of the **changing magnetic field (due to di/dt)** associated with the source circuit.
Insulation Resistance	The resistance offered by the insulation of a conductor to an impressed voltage. In the case of an applied DC Voltage, a small leakage current flows through the insulation.
Interface	A common electrical boundary between two separate devices, over which data or other electrical signals can pass between them.
Interference	See EMI and RFI.

I/O — **Inputs and Outputs**, the connections into and out of a control device such as a PLC, DCS, RTU, etc.

ISA — **Instrument Society of America**

ISO — **International Standards Organisation**, an organisation which co-ordinates standards internationally.

Isolation — To separate one circuit electrically from another, usually through a switch, so that it can be safely worked on.

k- — **kilo**, metric system prefix ..... x 10^3.

kVA — **kiloVolt-Amperes**, measurement of ..... Volt x Amp x 10^3.

kW — **kiloWatt**, measurement of ..... Watt x 10^3.

LAN — **Local Area Network**, a data communications system connecting several devices "locally" (a limited area, usually inside a building or plant).

LCD — **Liquid Crystal Display**, a visual display system using liquid crystals.

LCI — **Load Commutated Inverter**, an inverter in which the thyristors are turned off by the electrical behaviour of the load device.

LED — **Light Emitting Diode**, a diode which emits light when current is passing through it.

Linear Device — The output of the device is directly proportional to the input.

LEMP — **Lightning Electromagnetic Pulse**, the intense electric and magnetic field, lasting for a short period, associated with a lightning strike.

LPS — **Lightning Protection System**, the installed equipment designed to protect a structure from damage due to lightning.

m — **metre**, the unit of length in the metric system.

μ- — **micro**, metric system prefix ..... x 10^{-6}

m- — **milli**, metric system prefix ..... x 10^{-3}

M- — **Mega**, metric system prefix ..... x 10^6

Magnetic Field — The field around a conductor which is transferring charge, due to the current flowing in that conductor.

Man-made Noise — Electromagnetic Noise having its source in man-made devices

mho — Unit of measurement of Conductance in the metric system.

min — **minute**, measurement of time = 60 sec.

MOS — **Metal Oxide Semiconductor**, a semiconductor device, using a specific type of construction.

MOV — **Metal Oxide Varistor**, a non-linear semiconductor device used for overvoltage protection.

μP — **Microprocessor**, an "intelligent", miniature, encapsulated processor, used for controlling digital circuit.

MTBF — **Mean Time Between Failures**, a statistical measure of the average period between failures of any component of a device.

MTTR — **Mean Time To Repair**, a statistical measure of the average downtime, after a device has failed, before it can effectively be put back into service.

n- — **nano**, metric system prefix ..... x 10^{-9}

Nm — **Newton metres**, the measurement of Torque in the metric system

NEMA — **National Electrical Manufacturing Association**, a USA association which publishes standards for electric power, construction and testing codes.

NEMP — **Nuclear Electromagnetic Pulse**, the intense electric and magnetic field, lasting for a short period, associated with a nuclear explosion.

Neutral — The name of a return conductor, which is part of the 3-phase power supply system, connected to earth potential at the point of supply.

Noise — The undesirable electrical signals which are induced into an electronic system from other neighbouring electrical equipment carrying high voltages or high currents. See EM Noise.

Natural Noise — Electromagnetic Noise having its source in natural phenomena and not generated by man-made devices.

ohm (Ω) — Unit of measurement of Resistance & Impedance in metric system

Optical Isolation — A technique for galvanically isolating two electronic circuits by means of a light path. The signal is transferred over the isolating barrier by using a light emitting source, such as an LED, and a light sensitive receiver, such as a transistor.

p- — **pico**, metric system prefix ..... x 10^{-12}

PC — **Personal Computer**, a microprocessor based computer designed for personal, office and industrial use, such as a PC-AT with 286, 386 or 486 microprocessor.

PC — **Programmable Controller**, a computer for use in industrial control and which can be programmed by the user to carry out a particular control sequence.

PCB — **Printed Circuit Board**, a flat piece of insulation material which supports a number of electronic components and onto which an electrical circuit has been etched by photographic means.

PLC — **Programmable Logic Controller**, a computer, originally designed for digital sequence control in industrial applications. Modern PLCs can also do calculations and monitor analog inputs or control analog outputs. A PLC can be programmed by the user to carry out a particular control sequence.

QA — **Quality Assurance**, a management and documentation procedure aimed at the close supervision of all aspects of design, manufacture, testing and installation of any device or plant.

QC — **Quality Control**, the supervision procedures of Quality Assurance.

RAM — **Random Access Memory**, a read/write volatile memory with fast access to/from a microprocessor, used for holding temporary data during calculation and/or implementation. The data in the RAM is lost during power down, unless battery backup is provided.

Radio Environment — The electromagnetic environment in the radio frequency range.

Reactance — The opposition to the flow of current when an alternating voltage is applied to an electrical circuit, due to :
the inductance of the circuit ($X_R = j2\pi fL$ ohms)
and/or the capacitance of the circuit ($X_C = 1/j2\pi fC$ ohms)
Unit of measure : Ohm (Ω).

Resistance — The property of a conductor which opposes electric current flow when a voltage is applied across the two ends. It is the ratio of the applied potential (Volts) to the resulting current flow (Amps) ....
Resistance = Voltage/Current. Unit of measure : Ohm (Ω).

RF — **Radio Frequency**, which refers to high frequency waveforms above the audible range.

RFI — **Radio Frequency Interference**, the degradation of the reception of a wanted signal by interference in the radio frequency range.

RF Disturbance — Electromagnetic disturbance having components in the radio frequency range.

RMS — **Root Mean Square**

RMS Voltage — **The Root Mean Square Voltage**, the DC heat equivalent of an AC voltage or current. For sinusoidal waveforms V_{RMS} = sqrt2 x V_{PEAK}

ROM — **Read Only Memory**, a non-volatile microprocessor memory, with relatively slow access, which holds a program to control the sequence of a control device. The program is stored in the ROM during manufacture and cannot be changed by the user. The program is not lost during power down.

RTU — **Remote Terminal Unit**, an Input/Output terminal device, which can be mounted remotely (far away) from a programmable controller. Communication between them can take place via a wire, fibre, radio, modem, carrier or any other suitable medium.

SA (SAA)	**Standards Australia (ex Standards Association of Australia)**, the main standards organisation in Australia.
SCR	**Silicon Controlled Rectifier**, a alternative name for a Thyristor
Screen	The conducting material placed around an electrical circuit to shield it from the effects of electric or magnetic fields. To be most effective against *electric fields*, the screen material should be a good conductor and should be earthed at least at one point. To be most effective against *magnetic fields*, the screen material should be of magnetic material (eg steel), should be a good conductor and should be earthed at both ends.
sec	**Second**, a measurement of time.
Shield	Another name for a Screen ..... see **Screen** above.
S/N Ratio	Signal to Noise Ratio, which is the ratio of the signal level to the level of the noise or interference.
Spike	A word commonly used to describe a *transient overvoltage*, an interference voltage of brief duration and, usually, of high magnitude.
STP	**Shielded Twisted Pair**, usually comprising an insulated pair of copper wires, twisted together to reduce the effect of EMI. A conductive shield around the twisted pair, earthed at one end only, provides screening against capacitively coupled noise.
Surge	A word commonly used to describe a *transient overvoltage*, an interference voltage of brief duration and, usually, of high magnitude.
SPU/SPD	**Surge Protection Unit** or **Surge Protection Device**, a device used for protecting electronic equipment from damage from surges.
SPZ	**Surge Protection Zone**, a zone protected from external surges and noise.
Telemetry	The transfer of measured data over a long distance. (*From Greek : Tele*)
Thyristor	Semiconductor "switch" with 3 terminals, being the Anode (A), Cathode (K) and Gate (G).
Transient Overvoltage	An excessive increase in voltage between two or more conductors, usually lasting for a short duration of time, usually from a few μsecs to millisecs.
Transverse Mode	see **Differential Mode Voltage**.
Twisted Pair	A cable, usually used for communications, consisting of a pair of insulated conductors which are twisted together to reduce interference.
UTP	**Unshielded Twisted Pair**, usually comprising an insulated pair of copper wires, twisted together to reduce the effect of induced noise. No conductive screen is provided.
UL	**Underwriters Laboratory Inc**, a public testing Institute in USA.
UPS	**Uninterruptible Power Supply**, a device used to provide a backup power supply for important equipment during a power supply interruption.
VDE	**Verband Deutcher Elektrotechniker**, German Standards which are generally in harmony with the equivalent IEC standards.
Volts	The unit of measure of electrical potential.
VSD	**Variable Speed Drive** – controls the speed of an electric motor, usually comprising non-linear switching power electronic devices, which generate noise.
VVVF	**Variable Voltage Variable Frequency (Converter)**, where both the voltage and the frequency output of the converter are controlled to control the speed and limit the flux in the AC motor.

0 Contents

BIBLIOGRAPHY & RECOMMENDED ADDITIONAL READING

1. Lightning Phenomena

1.1 Beck E, McNutt HR, Shankle DF, Tirk CJ : "Electric Fields in the Vicinity of Lightning Strokes", IEEE Transactions, Vol PAS-88, No 6, June 1969, pages 904 to 910.

1.2 Chauzy S : "A Review of the Principal Processes of Thundercloud Electrifications", Paper 20/12/A, All Africa Conference on Lightning, Harare, 1990.

1.3 Swift DA : "Physics of the Lightning Discharge : a Critical Review of Data and Theories", Paper 4/8/C, All Africa Conference on Lightning, Harare, 1990.

1.4 Williams ER : "The Electrification of Thunderstorms", Scientific American, November 1988, Pages 48 to 65.

2. Earthing

2.1 Chisholm WA, Janischewskyj W : "Lightning Surge Response of Ground Electrodes", IEEE Transactions on Power Delivery, Vol 4, No 2, April 1989, Pages 1329 to 1337.

2.2 Gupta BR, Thapar B : "Impulse Impedances of Grounding Grids", IEEE Transactions, Vol PAS-99, No 6, November/December 1980, Pages 2357 to 2362.

2.3 Kosztaluk R, Loboda M, Mukhedkar D : "Experimental Study of Transient Ground Impedances", IEEE Transactions, Vol PAS-100, No 11, November 1981, Pages 4653 to 4660.

2.4 Liew AC, Darveniza M : "Dynamic Model of Impulse Characteristics of Concentrated Earths", Proceedings of the IEE, Vol 121, No 2, February 1974, Pages 123 to 135.

2.5 Saraoja EK : "Lightning Earths", Lightning (ed Golde RH), Vol 2, Academic Press, 1977, Pages 577 to 598.

2.6 Van Alphen JC : "The Earthing of the Neutral in Low Voltage Distribution Systems", SAIEE Transactions, March 1982 Pages 45 to 48.

2.7 Van Coller JM, Jandrell IR : "A Consideration of the Effectiveness under Lightning Surge conditions of a Single Trench Earth when used as an Interconnection between two buildings", Proceedings of SAUPEC-92, Durban, July 1992, Pages 1.30 to 1.33.

2.8 Van Coller JM, Jandrell IR : "Behaviour of Interconnected Building Earths under Surge Conditions", Paper 3.06, 21 ICLP, Berlin, September 1992, Pages 117 to 122.

2.9 Fisher & Porter : "Site Preparation Guide for Digital Electronic Instrumentation Instruction", F+P Instruction Bulletin 53E9049, Feb 1985.

2.10 Measurement Technology Ltd : "A User's Guide to Intrinsic Safety", MTL Application Note AN9003-4, March 1983.

2.11 Allen-Bradley : Programmable Controller Wiring and Grounding Guidelines

2.12 WJ Furse & Co Ltd : Consultants Handbook - "Recommendations for the Protection of Structures against Lightning", Publication CHB/12/92

3. Surge Protection and Shielding

3.1 Arpin KJ : "EMI Control in Light-duty Cables via Shields and Connectors", EMC Technology, Vol 5, No 5 September/October 1986, Pages 19 to 25.

3.2 Barbosa CF, Rossi JAD, Nallin FE : "Telecommunications Cable Shield Effect upon Lightning induced Overvoltages" 21 ICLP, Berlin, September 1992, Pages 419 to 423.

3.3 Bodle DW, Martzloff FD, Boehne EW, Kotter FR, Miller BD, Ridge GS, Stadfeld N (Jr), Thwaites HW : "Bibliography on Surge Voltages in AC Power Circuits rated 600 Volts and less", IEEE Transactions, Vol PAS-89, No 6, July/August 1970, Pages 1056 to 1061.

3.4 Chesworth ET : "Electromagnetic Interference Control in Structures and Buildings", EMC Technology, Vol 5, No 1, January/February 1986, Pages 39 to 54.

3.5 Darveniza M, Sargent MA, Limbourn GJ, Ah Choy L, Caldwell RO, Currie JR, Holcombe BC, Stillman RH, Frowd R : "Modelling for Lightning Performance Calculations", IEEE Transactions, Vol PAS-98, No 6, November/December 1979, Pages 1900 to 1908.

3.6 Eriksson AJ, Geldenhuys HJ : "A Lightning Surge Disturbance Environment for Electronic Systems : Guideline Standards for Surge Withstand Compliance and Testing", available from the Enertek, CSIR, 1990.

3.7 Ette AII : "Lightning Protection : Traditional and Scientific Perspectives", Paper 1/32/B, All Africa Conference on Lightning, Harare, 1990.

3.8 Flisowski Z, Mazzetti C : "Weighting Factors in the Probabilistic Approach to the Lightning Hazard Assessment", 21 ICLP, Berlin, September 1992, Pages 453 to 458.

3.9 Gostache G : "Transient Skin-effects on Wire Leads", EMC Technology, Vol 3, No 1, January - March 1984, Pages 26 to 30.

3.10 Hasse P, Wiesinger J : "Lightning Protection for Information System : A Part of EMC", Paper 7.01, 21 ICLP, Berlin, September 1992, Pages 369 to 374.

3.11 Jandrell IR, Reynders JP, Van Coller JM : "Consideration of the Transient Skin Effect in Co-axial Systems and an Analysis of this Effect in Various Types of Conductor", Paper 83.12, 7 ISH, Dresden, August/September 1991, Pages 143 to 146.

3.12 Kern A, Lang U, Wiesanger J, Zischank W : "The Longitudinal Voltage of Cable Tubes with a Screening Mesh caused by Partial Lightning Currents", Paper 27.10, 7 ISH, Dresden, August/September 1991.

3.13 Kern A, Zischank W : "The Effect of Parallel Wires on the Longitudinal Voltage Drop along Shielded Cables", Paper 7.14, 21 ICLP, Berlin, September 1992, Pages 425 to 430.

3.14 Lewis WH : "Recommended Power and Signal Grounding for Control and Computer Rooms", IEEE Transactions, Vol IA-21, No 6, November/ December 1985, Pages 1503 to 1516.

3.15 Monserrate JL : "Grounding Secure Facilities", EMC Technology supplement, November/December 1988, Pages 15 to 17.

3.16 Martzloff FD, Hahn GJ : "Surge Voltages in Residential and Industrial Power Circuits", IEEE Transaction, Vol PAS-89, No 6, July/August 1970, Pages 1049 to 1056.

3.17 Montandon E : "Swiss PTT, Telecommunications Centers, Bonding and Routing Practice with Respect on Lightning Protection and EMC", Paper 7.05, 21 ICLP, Berlin, September 1992, Pages 393 to 398.

3.18 Noack F, Brocke R, Göhlsch T : "Interaction between Pulse Generators and Voltage Surge Protectors for use on Low-voltage Mains during their Pulse Test", Paper 5.13, 21 ICLP, Berlin, September 1992, Pages 287 to 292.

3.19 Shenfeld S : "Magnetic Fields of Twisted-wire Pairs", IEEE Transactions, Vol EMC-11, No 4, November 1969, Pages 164 to 169.

3.20 St John AN : "Grounds for Signal Referencing", IEEE Spectrum, June 1992, Pages 42 to 45.

3.21 Vance EF : "Electromagnetic Interference Control", IEEE Transactions, Vol EMC-22, No 4, November 1980, Pages 319 to 328.

3.22 Vance EF : "Cable Grounding for the Control on EMI", EMC Technology, Vol 2, No 1, January - March 1983, Pages 54 to 58.

3.23 Van Coller JM, Jandrell IR : "Selection of the Correct Transient Suppression Circuit Topology to afford Protection of Electronic Equipment against Lightning Surges", Electricity + Control, January 1993, Pages 39 to 41.

3.24 Zaengl WS : "General Report - Group 7 : Protection of Electronic Equipment and Systems", Paper 7.0, 21 ICLP, Berlin, September 1992, Page 367.

3.25 WJ Furse & Co Ltd : Electronic Systems Protection Handbook - "A Guide to Protecting Electronic Equipment from Lightning and Transient Overvoltages"

4. Standards

4.1	AS 1028 - 1992	Power Reactors and Earthing Transformers
4.2	AS 1307 - 1987	Surge Arrestors
4.3	AS/NZS 1768 - 1991	Lightning Protection
4.4	ANSI 78	Lightning Protection Code (USA)
4.5	AS 1852 - 1980	International Electrotechnical Vocabulary
4.6	AS 2279 - 1991	Disturbances in Mains Supply Networks
4.7	AS 3000 - 1991	SAA Wiring Rules
4.8	SAA HB45 - 1993	Handbook on Electromagnetic Compatibility Standards and Regulations
4.9	IEEE 518 - 1982	IEEE Guide to the Installation of Electrical Equipment to Minimize Electrical Noise to Controllers from External Sources
4.10	IEC 801	Electromagnetic Compatibility (EMC) for Industrial Process Measurement and Control Equipment
4.11	IEC 1024.1 - 1990	Protection of Structures against Lightning Part 1 : General Principles
4.12	IEC 1024.1.1 - 1993	Section 1 : Selection of Protection Levels for Lightning Protection Systems
4.13	IEC 81(sec)57 - 1993	Protection against LEMP (Released for Voting May 1993)

The interference generated by the above sources can be transferred into the electronic control system either **directly** via the power system or signal wiring (*conducted interference*) or **indirectly** via the electric and magnetic fields (*coupled interference*). Whatever the cause or the mechanism of interference, these transient over-voltages can damage or introduce errors into the electronic equipment of the control system.

This book concentrates on the first four types of interference listed above, which represent the majority of problems encountered with industrial control systems. The damaging effects on electronic equipment of these types of interference can be prevented by the careful attention to the design and selection of the following :

- The power supply connections and earthing system
- The strategy for earthing the electronic equipment
- The method of installing and terminating the cabling interfaces
- The type of shielding used for the cables and electronic equipment
- The design of the surge protection system

The remaining problems with RFI and ESD are not often encountered. They contain energy at frequencies in the MHz and GHz ranges, which requires very precise shielding and high frequency filtering, which is beyond the scope of this book.

One of the best ways to avoid the effects of interference and transient over-voltages is to ***remove the source of the interference***. Unfortunately, this approach is not always economically viable, or even possible, so it is usually necessary to design an earthing, shielding and surge protection system which effectively diverts the destructive energy away from the electronic equipment and into the ground.

Many of the fundamental principles for avoiding problems with interference and surges are not fully understood or properly applied in practice. Consequently, the main goals of this manual and the associated training course are as follows :-

- To analyse the causes of commonly encountered interference and surges. The level of interference associated with Lightning is usually the most severe .... the worst case !!! If the control system can withstand a lightning surge, then it will probably perform reliably for most other types of interference.
- To learn about the techniques for installing Lightning Protection and the associated national and international standards. These standards have been based on the collective experience of a broad cross-section of users throughout the world, particularly from the high lightning areas. They have been prepared to encourage users to apply sound solutions to the problems associated with surges.
- To explain the mechanisms of *conducted interference* and *coupled interference* and to present a clear picture of how the interference penetrates into the electronic circuits of an instrumentation and control system.
- To provide a clear understanding of the purpose and methods of earthing electronic equipment to reduce the effects of interference.
- To provide a clear understanding of the purpose and methods of shielding electrical equipment and cables, to exclude electric and magnetic fields.
- To introduce the concept of Surge Protection Zones for electromagnetic shielding.
- To explain how surge protection devices work and how and where they should be applied to the control system circuits.
- To try to develop a practical step by step approach to the design of a "good" earthing, shielding and surge protection system for electronic control equipment.

The Integration and Differentiation functions as applied to Process Control.

Objectives

1. To demonstrate the Intregal and Differential functions as applied to a P.I.D. process control loop.

Integrator

a) That the output of an Integrator will ramp in proportion to the magnitude of the input signal.

b) If the input returns to zero the Integrator output will remain at its present value, i.e. zero input results in zero rampping output, i.e. steady state.

Differentiator

a) That the output of a Differentiator will assume a value dependent on the rate of change of the input signal.

b) If the input maintains a steady value the Differentiator output returns to zero, i.e. zero rate of change of the input results in a zero output.

Integrator

Application

The Intregal functions as applied to a P.I.D. process control loop is used to remove 'offset' between the process 'setpoint' and the process variable being measured for use in the control feedback loop.

Method

Construct the circuit of Fig1. or use the J&B P.I.D. Controle board.
Adjust the J&B 'integrator' rotory switch to '12' and the gain to '0.1'.
Switch the 'integrator' to 'IN', and the 'proportional' and 'differential' to 'OUT'.

Connect a CRO and DVM to both the input and output circuits.

Apply a 0.5V DC input signal and monitor, and record,(draw a family of graphs) the output for a period to allow the output to' saturate' ;
repeat for values through to 5.0V DC.

Explain the implication of the results when applied to a 'closed loop' control system and the 'error signal' and the controller output to the F.C.E.

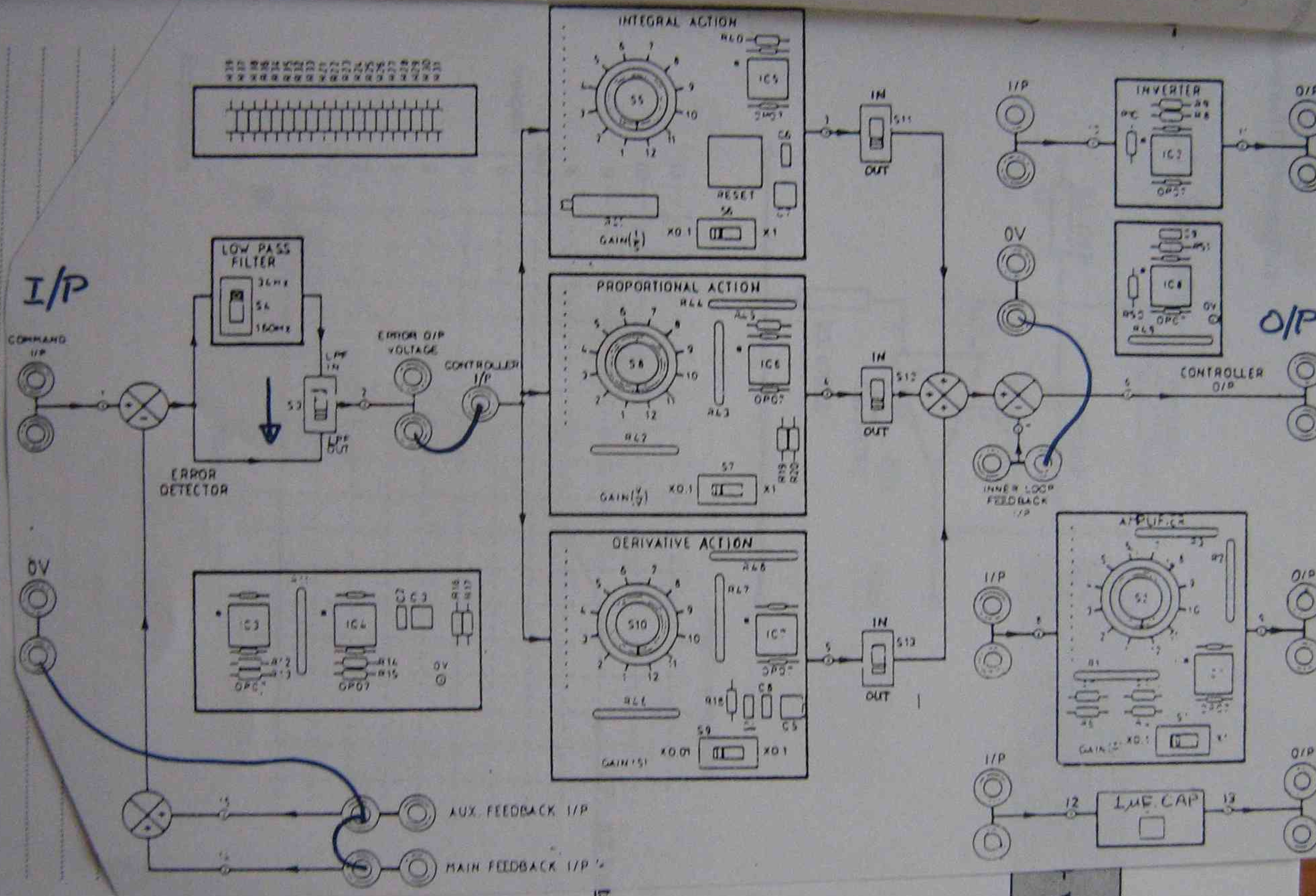
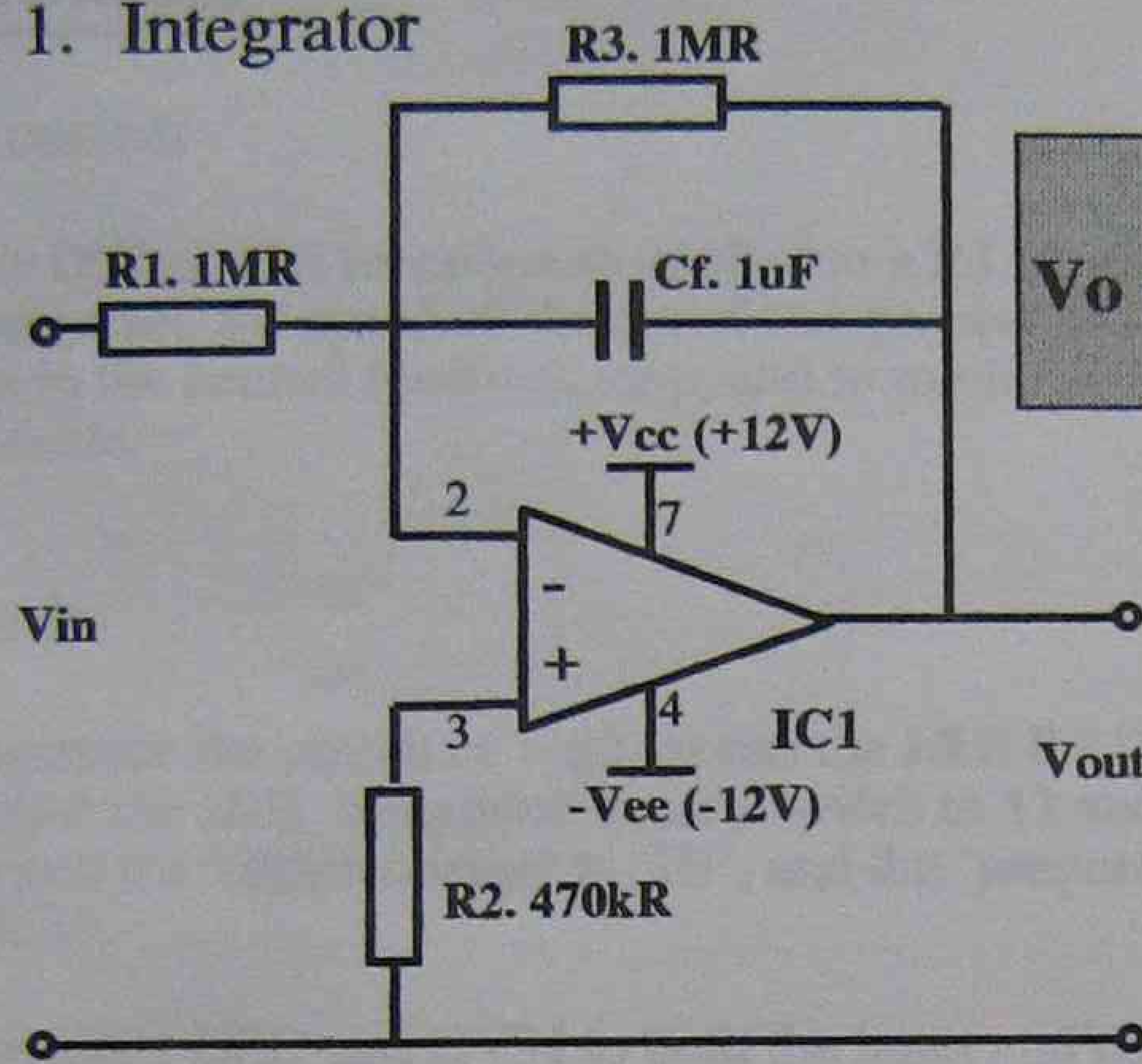
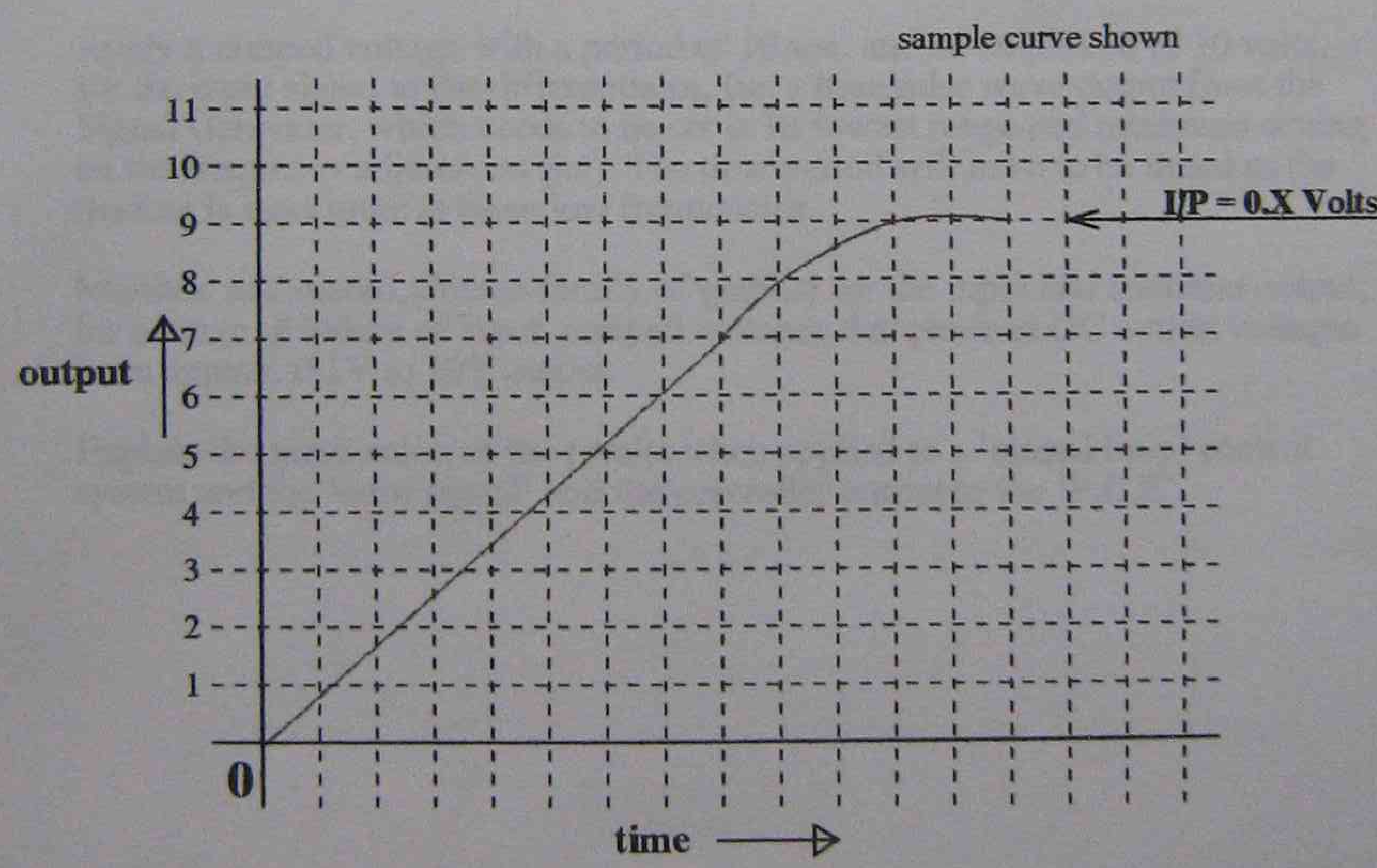

INTEGRAL ACTION
S5
RESET
GAIN($\frac{1}{5}$)
X0.1
X1
LOW PASS FILTER
36Hz
S4
160Hz
LPF IN
LPF OUT
I/P
COMMAND I/P
ERROR DETECTOR
ERROR O/P VOLTAGE
CONTROLLER I/P
PROPORTIONAL ACTION
S8
S7
IN
OUT
INVERTER
IC7
O/P
0V
IC8
O/P
CONTROLLER O/P
INNER LOOP FEEDBACK I/P
DERIVATIVE ACTION
S10
S9
X0.01
AMPLIFIER
S2
IC3
IC4
OP07
AUX. FEEDBACK I/P
MAIN FEEDBACK I/P
1µF. CAP

Fig. 1. Integrator



$$V_o = -\left(V_{in}/R_1C_f\right)t + V_o$$



Explanation

....

....

....

....

....

....

....

Differentiator

Application

The Differential functions as applied to a P.I.D. process control loop is used to counteract the speed of change of the process variable (PV) being measured for use in the control feedback loop, and to minimise 'overshoot' of the process variable.

Method

Construct the circuit of Fig2. or use the J&B P.I.D. Controle board.
Adjust the J&B 'integrator' rotory switch to 12 and the gain to 0.01.
Switch the 'differentiator' to 'IN', and the 'proportional' and 'integrator' to 'OUT'.

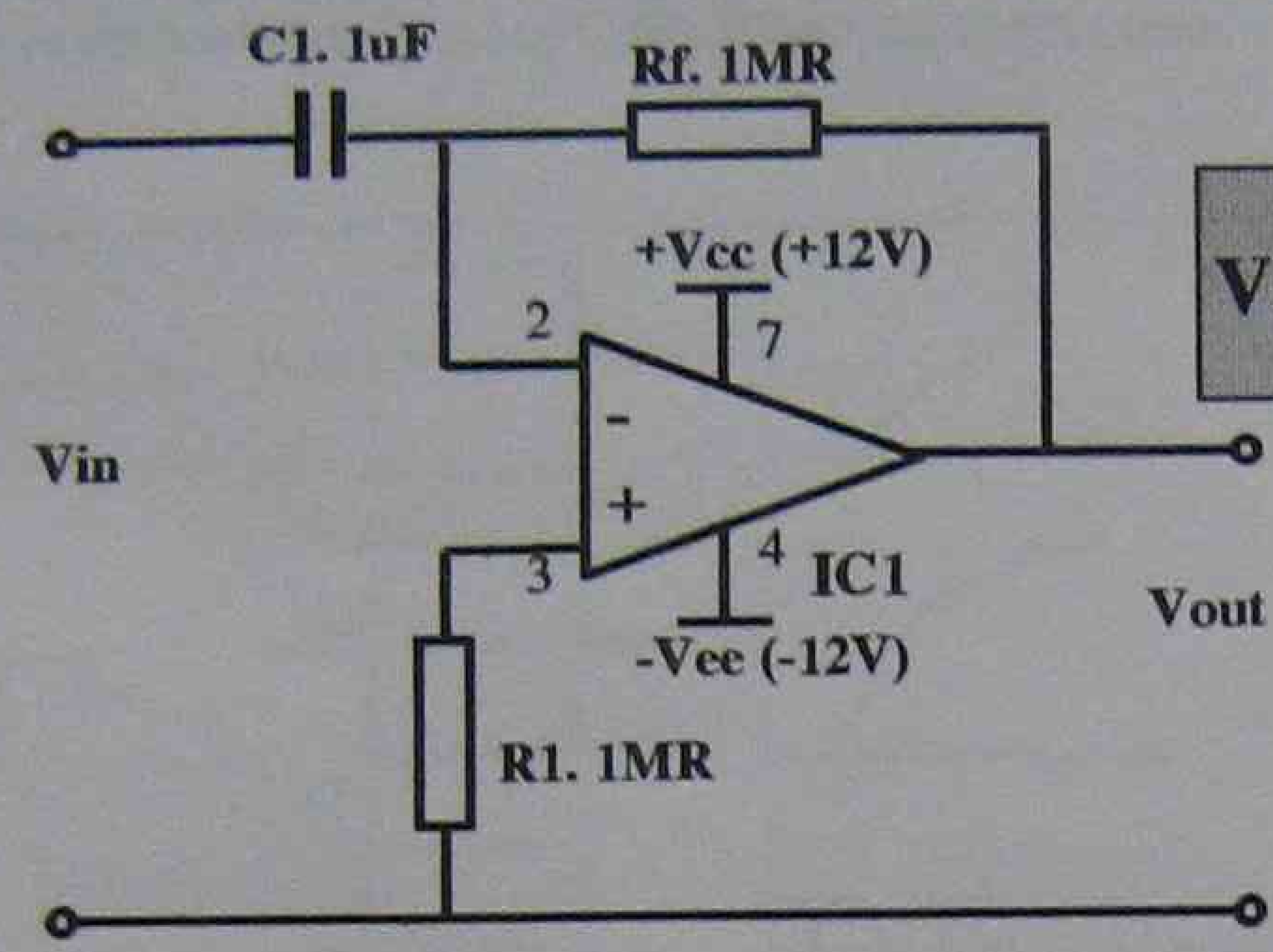
Connect a CRO and DVM to both the input and output circuits.

Apply a ramped voltage with a period of 10 sec. and an amplitued of 10 volts, for the input signal to the differentiator, (ie. a triangular wave output from the Signal Generator, which needs to be set to its lowest range and minimum setting on the frequency adjustment pot). The time period will have to be timed as the readout is inaccurate at these low frequencies.

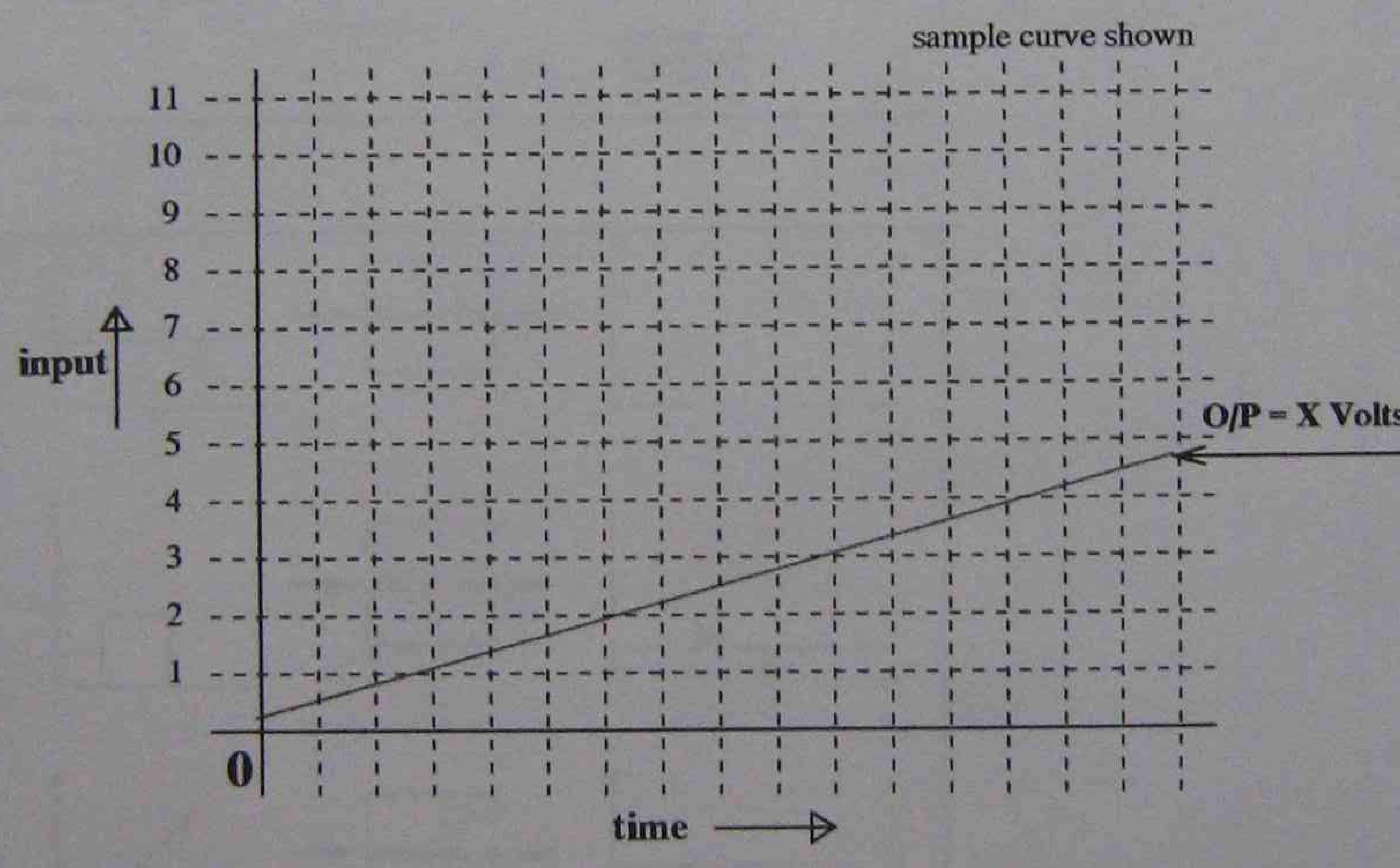
Monitor, and record,(draw a family of graphs) for the input and resultant output, for a range of values of input ramped voltages that produce DC output voltages from approx. 0.1V to 10V output.

Explain the implication of the results when applied to a 'closed loop' control system and the 'error signal' and the controller output to the 'F.C.E'.

Fig. 2. Differentiator



$$Vo = -RfC1\left(Vin/t\right)$$



Explanation

....

....

....

....

....

....

....

Integration and Differentiation Lab

the charts below show typical responses for input waveforms to integrators and differentiators. Using the equipment already setup verify these output responses.

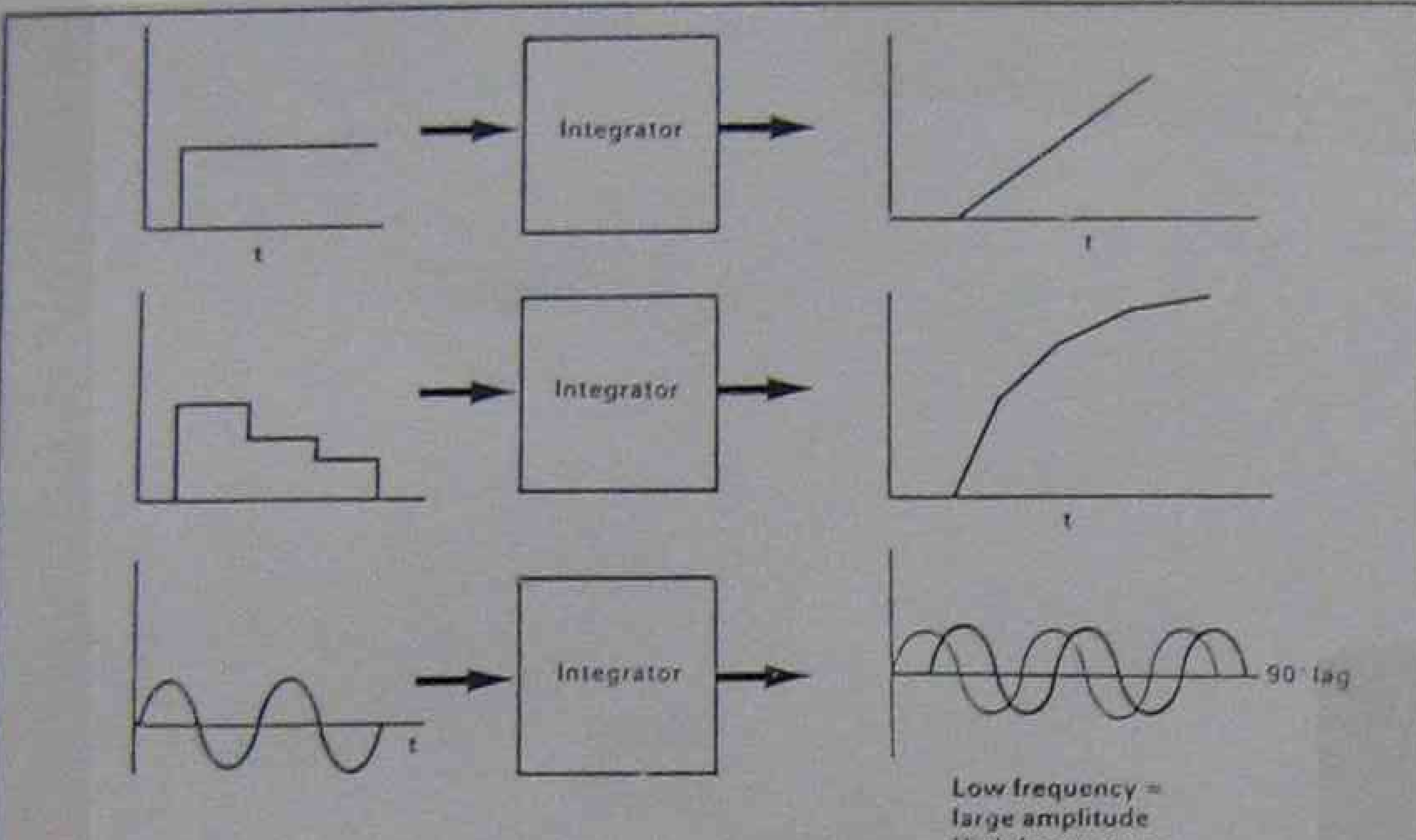


Fig 73

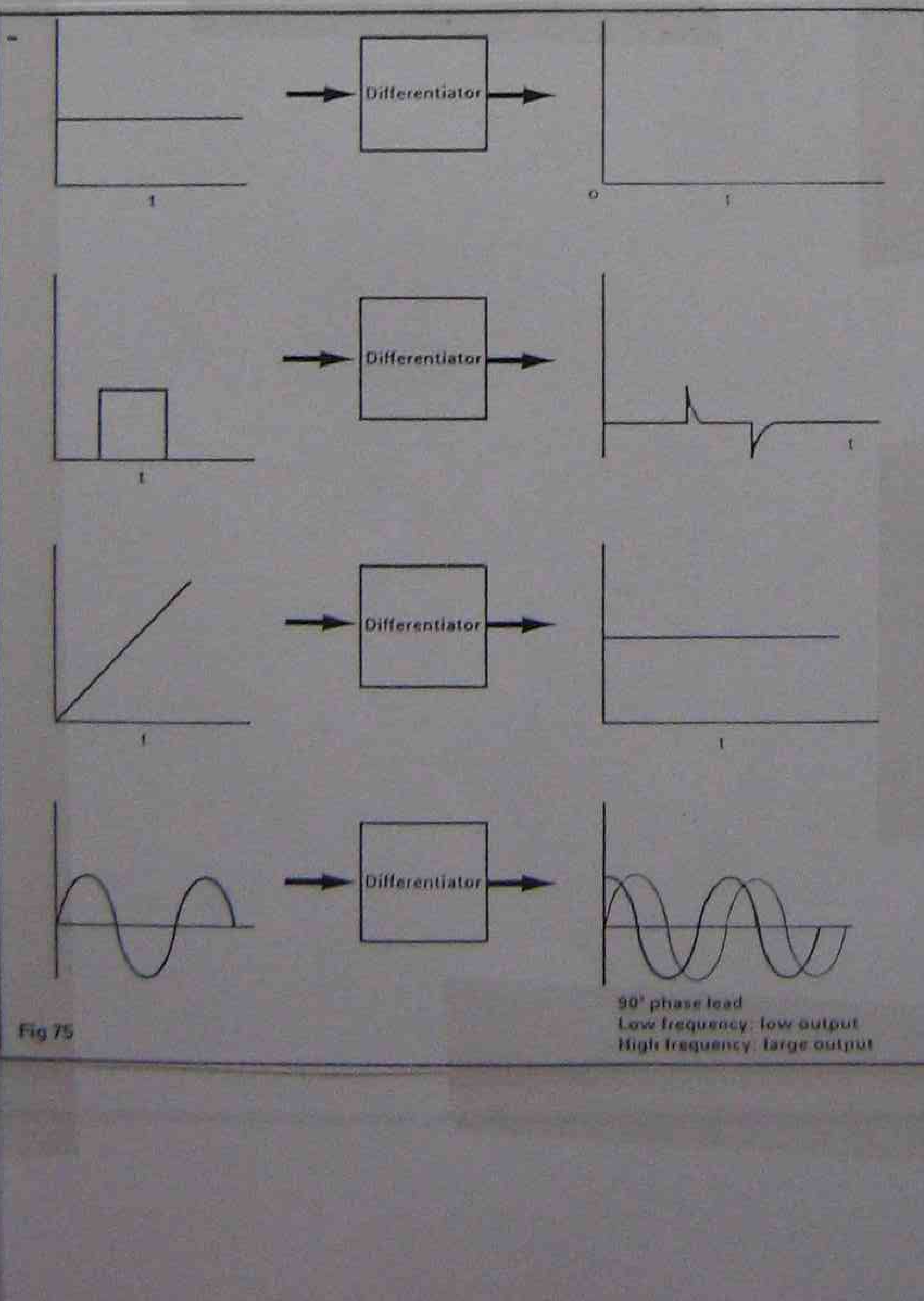


Fig 75

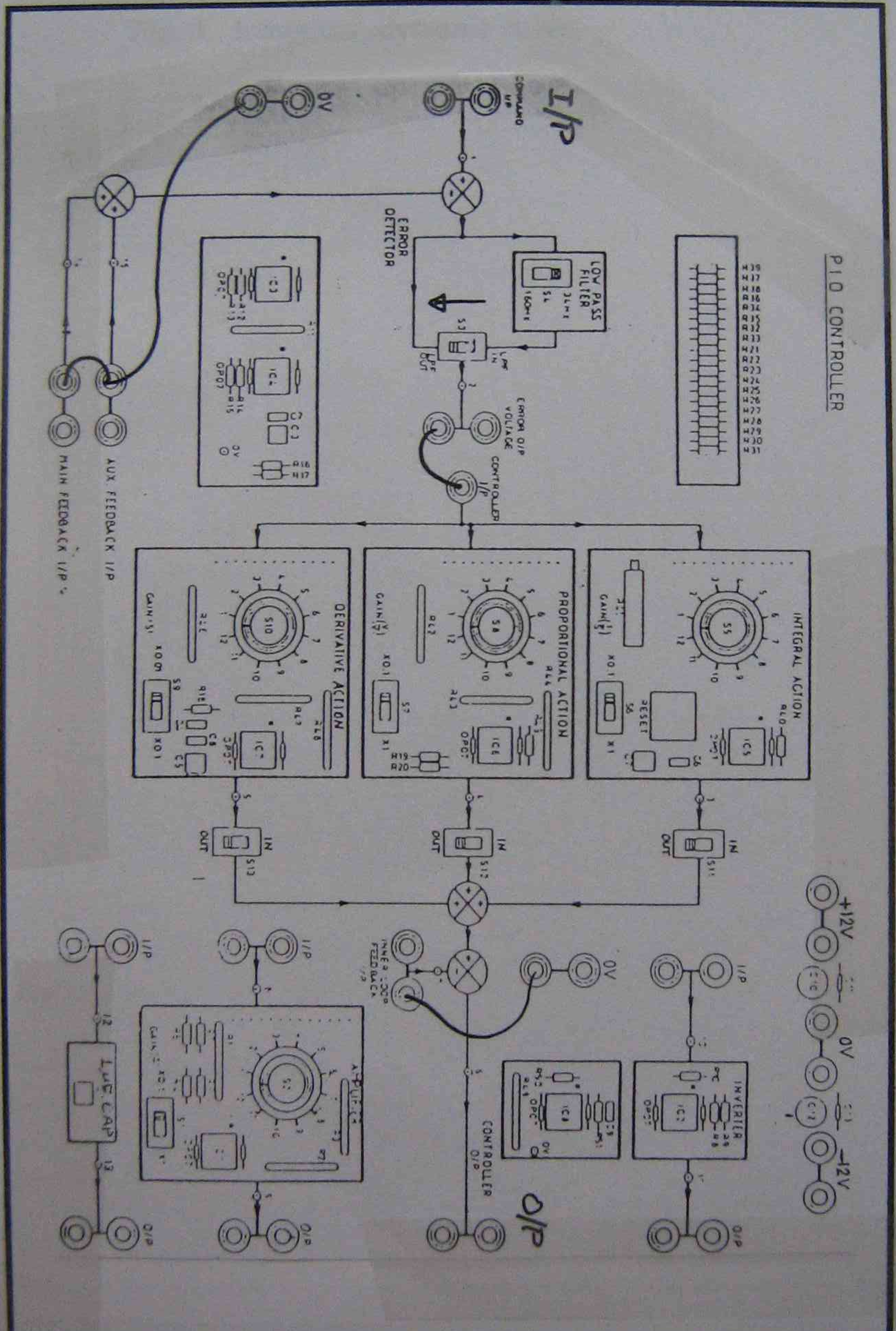
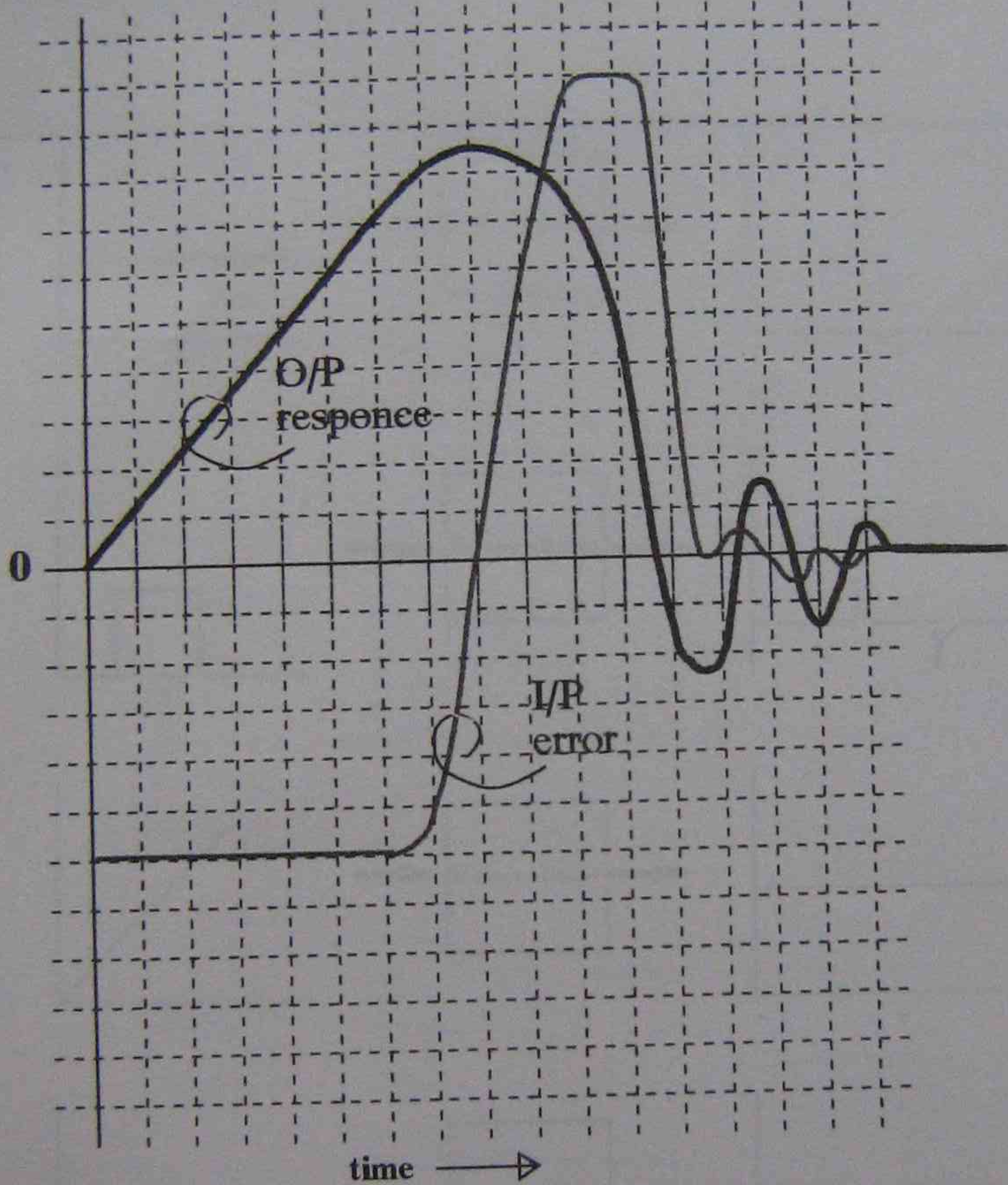
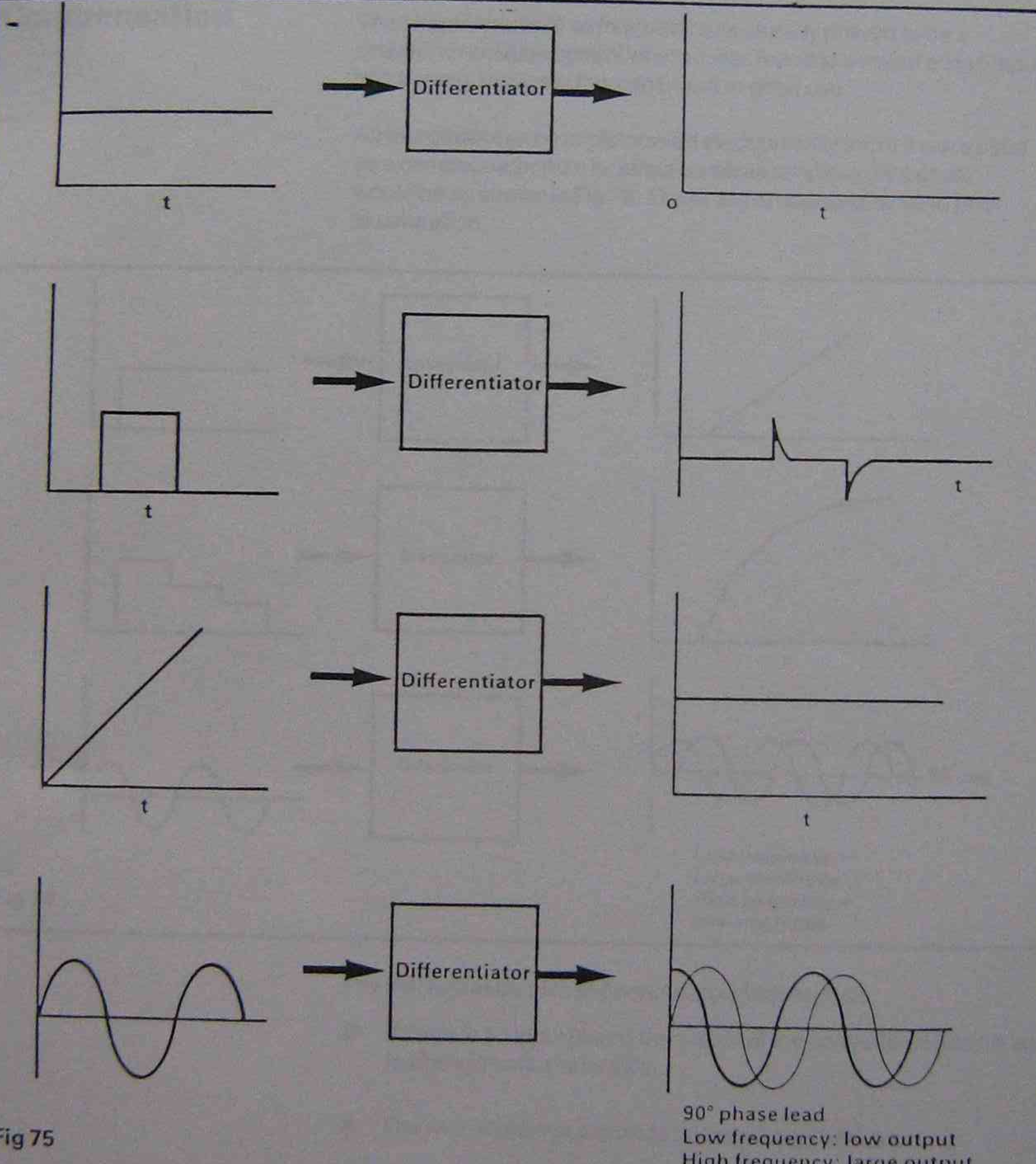

P I D CONTROLLER
I/P
COMMAND I/P
0V
ERROR DETECTOR
LOW PASS FILTER
ERROR O/P VOLTAGE
CONTROLLER I/P
AUX. FEEDBACK I/P
MAIN FEEDBACK I/P
DERIVATIVE ACTION
PROPORTIONAL ACTION
INTEGRAL ACTION
RESET
IN
OUT
INNER LOOP FEEDBACK I/P
CONTROLLER O/P
O/P
INVERTER
AMPLIFIER
LAG LAP
+12V
0V
-12V

Fig. 3. Integrator, dynamic curve



Explanation



t
Differentiator
o
t
t
Differentiator
t
t
Differentiator
t
Differentiator
90° phase lead
Low frequency: low output
High frequency: large output

Fig 75

Integral Compensation

The characteristic of an integrator has already proved to be a problem in position control where it was found to convert a step input into a ramp. Ironically this can be put to good use.

An integrator can be implemented electronically and if it were used as a compensator then its effect on some simple error signals would be as shown in Fig 73. These are of course only valid prior to saturation.

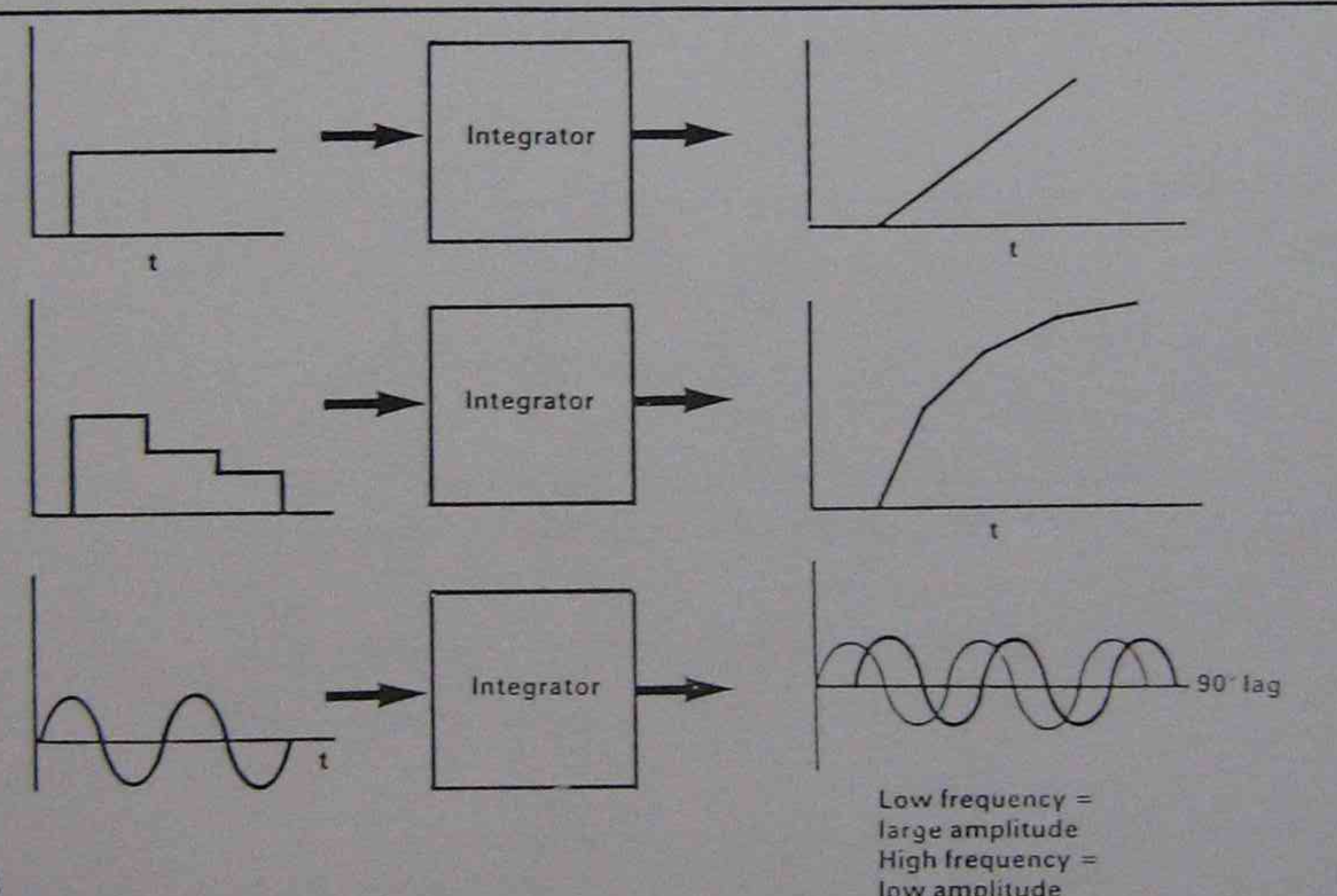


Fig 73

The first two examples show very important aspects

- If there is an input (error) the output of the controller will continue to change until it saturates.
- The rate of change depends on the size of the input.

This means that a large error would produce high rate of application of the correcting signal and that would continue at a reducing rate until the error was forced to zero.

Obviously if the drive lacks the power to overcome the error the integrators output will remain saturated.

Integral Gompensation

The characteristic of an integrator has already proved to be a problem in position control where it was found to convert a step input into a ramp. Ironically this can be put to good use.

An integrator can be implemented electronically and if it were used as a compensator then its effect on some simple error signals would be as shown in Fig 73. These are of course only valid prior to saturation.

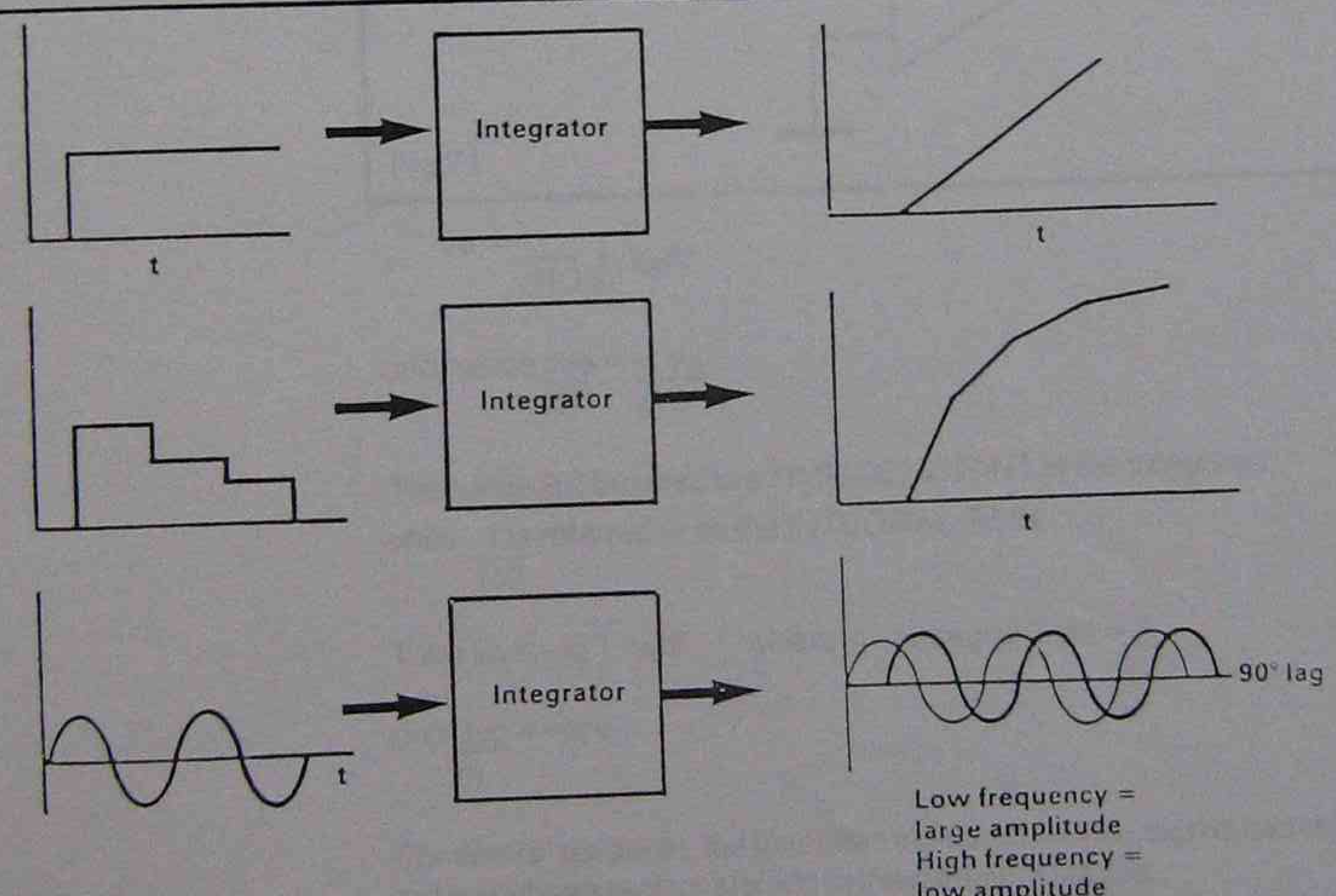


Fig 73

The first two examples show very important aspects

- If there is an input (error) the output of the controller will continue to change until it saturates.

- The rate of change depends on the size of the input.

This means that a large error would produce high rate of application of the correcting signal and that would continue at a reducing rate until the error was forced to zero.

Obviously if the drive lacks the power to overcome the error the integrators output will remain saturated.

A basic integrator was configured in curriculum CA02 and the AS4 circuitry is based on Fig 74.

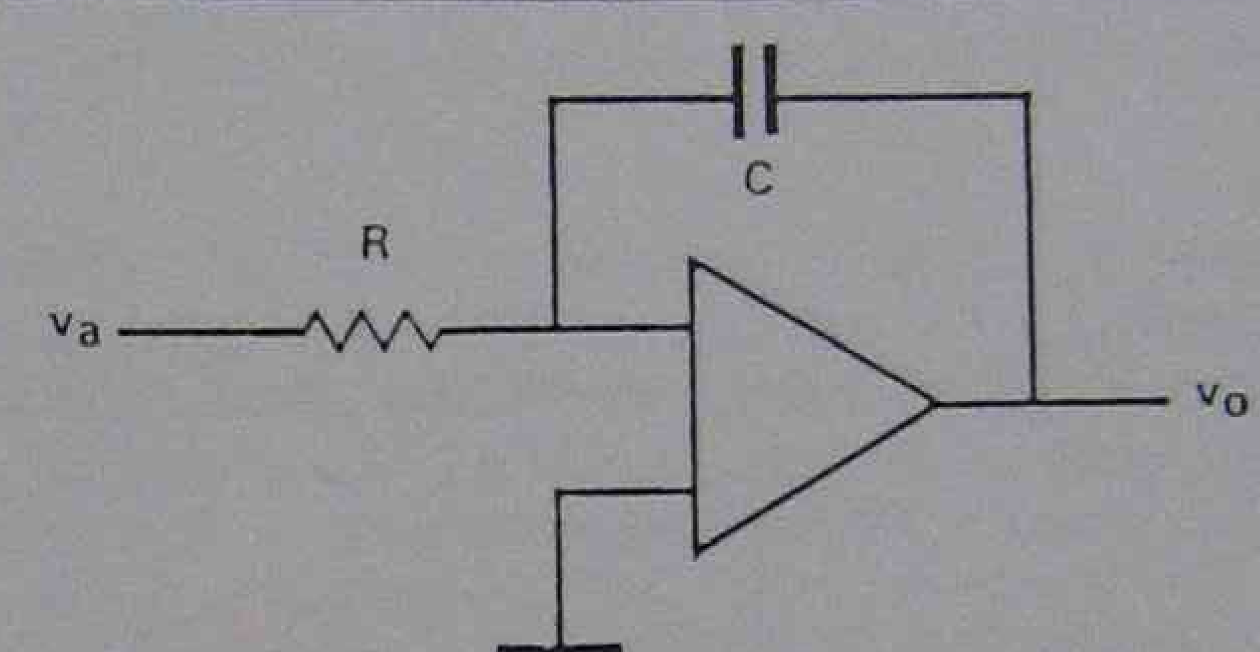


Fig 74

$$vo = \frac{-1}{RC}\int v_a dt$$

and hence $\frac{dvo}{dt} = \frac{-1\, v_a}{RC}$

The value RC is called the TIME CONSTANT of the integrator while $\frac{1}{RC}$ is referred to as the INTEGRAL GAIN.

Thus $vo = -k_i \int v_a dt$ where k_i = Integral Gain $= \frac{1}{RC}$

and $\frac{dvo}{dt} = -k_i v_a$

For control purposes the inversion indicated by the - sign is cancelled out by subsequent inversions in the summing stages.

The Integral Gain k_i will affect the rate at which the integrators output changes for a given input v_a and has units of $\frac{1}{\text{seconds}}$

For example, if $k_i = 2\frac{1}{s}$ and $v_a = 2V$.

vo changes at a rate of $2\frac{1}{s} \times 2V = 4\frac{V}{s}$

The AS4 controller provides a range of k_i values from 0.1 to $12\frac{1}{s}$.

Because of the possibility of saturation a 'reset' button is also provided to allow the output to be manually forced to zero at any time.

A basic integrator was configured in curriculum CA02 and the AS4 circuitry is based on Fig 74.

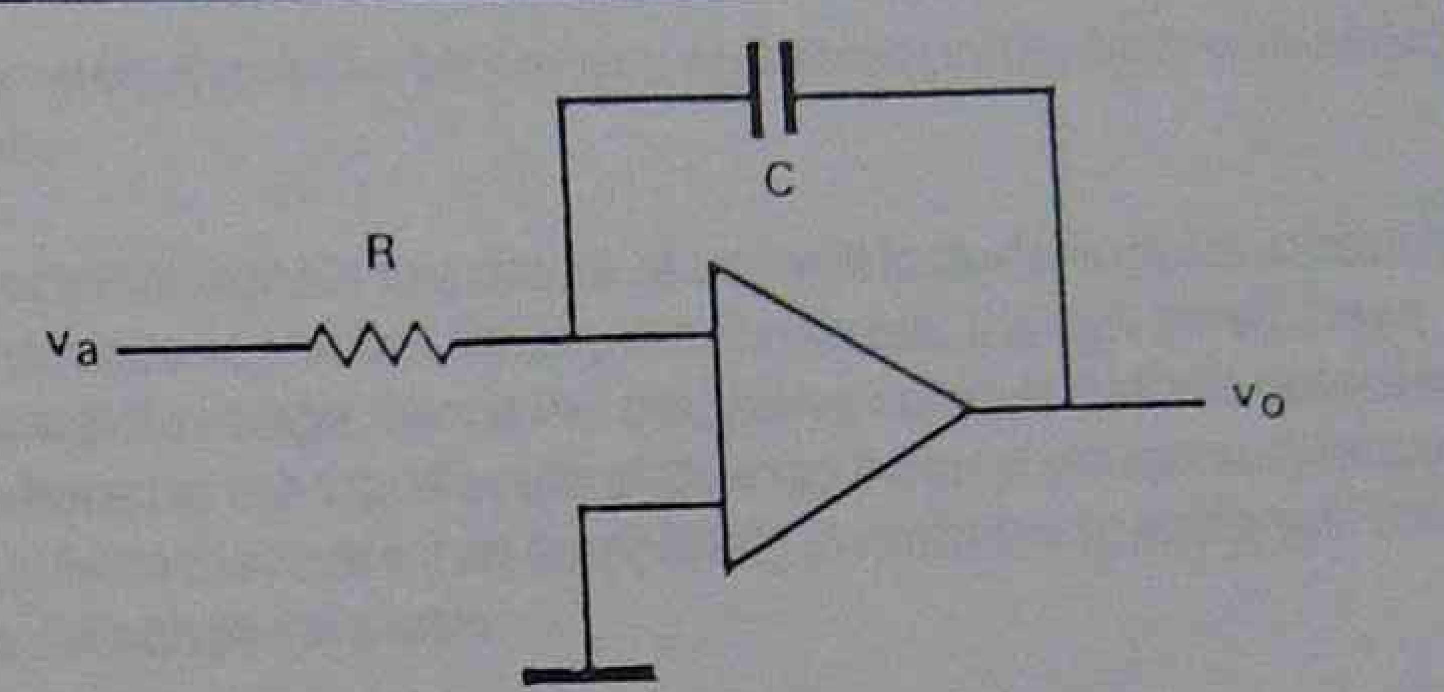


Fig 74

$$vo = \frac{-1}{RC} \int v_a dt$$

and hence $\frac{dvo}{dt} = \frac{-1}{RC} v_a$

The value RC is called the TIME CONSTANT of the integrator while $\frac{1}{RC}$ is referred to as the INTEGRAL GAIN.

Thus $vo = -k_i \int v_a dt$ where k_i = Integral Gain $= \frac{1}{RC}$

and $\frac{dvo}{dt} = -k_i v_a$

For control purposes the inversion indicated by the - sign is cancelled out by subsequent inversions in the summing stages.

The Integral Gain k_i will affect the rate at which the integrators output changes for a given input v_a and has units of $\frac{1}{\text{seconds}}$

For example, if $k_i = 2 \frac{1}{s}$ and $v_a = 2V$.

vo changes at a rate of $2 \frac{1}{s} \times 2V = 4 \frac{V}{s}$

The AS4 controller provides a range of k_i values from 0.1 to $12 \frac{1}{s}$.

Because of the possibility of saturation a 'reset' button is also provided to allow the output to be manually forced to zero at any time.

For derivative action everything looks perfect providing that we include a proportional path to overcome the problem of no response to a constant error.

Unfortunately there can be serious problems particularly with servo systems.

The electrical signals are not ideal and will include various amounts of high frequency noise. By implication these, though small, have high rates of change. Since the derivative compensator's output is proportional to the input's rate of change it can produce very large outputs from the noise that completely swamp the true signal. This will be demonstrated later.

In an attempt to solve this problem various stages of LOW PASS FILTERING have to be added to remove the noise. This is at best a compromise however because not only is some of the input information lost, but the filters produce phase lags that eventually, with a lot of filtering, cancel out any phase lead that the derivative compensator is trying to introduce!

The AS4 controller has various filter stages but predominantly the 34Hz/160Hz one preceeding the various compensators.

Returning to the derivative action the basic circuit is shown in Fig 76 for which the following relationship applies,

$$v_o = -RC\frac{dv_a}{dt} \qquad (v < v\ \text{saturation})$$

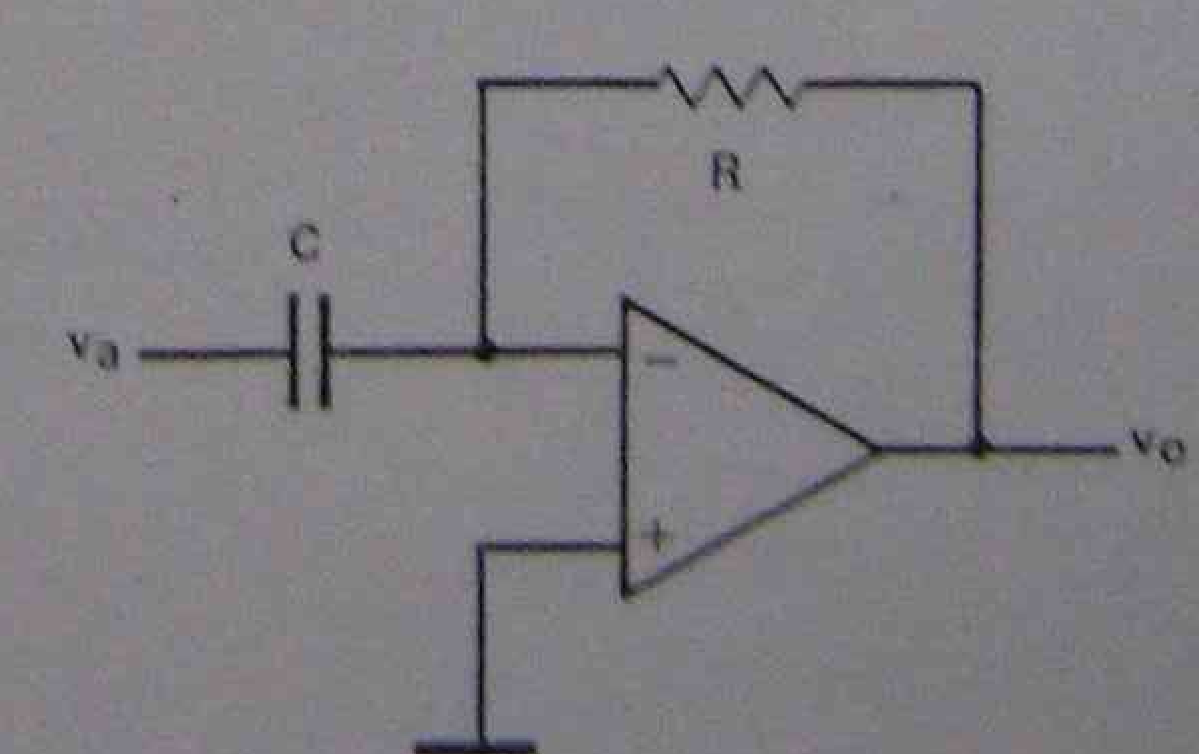


Fig 76

For derivative action everything looks perfect providing that we include a proportional path to overcome the problem of no response to a constant error.

Unfortunately there can be serious problems particularly with servo systems.

The electrical signals are not ideal and will include various amounts of high frequency noise. By implication these, though small, have high rates of change. Since the derivative compensator's output is proportional to the input's rate of change it can produce very large outputs from the noise that completely swamp the true signal. This will be demonstrated later.

In an attempt to solve this problem various stages of LOW PASS FILTERING have to be added to remove the noise. This is at best a compromise however because not only is some of the input information lost, but the filters produce phase lags that eventually, with a lot of filtering, cancel out any phase lead that the derivative compensator is trying to introduce!

The AS4 controller has various filter stages but predominantly the 34Hz/160Hz one preceeding the various compensators.

Returning to the derivative action the basic circuit is shown in Fig 76 for which the following relationship applies,

$$v_o = -RC\frac{dv_a}{dt} \qquad (v < v \text{ saturation})$$

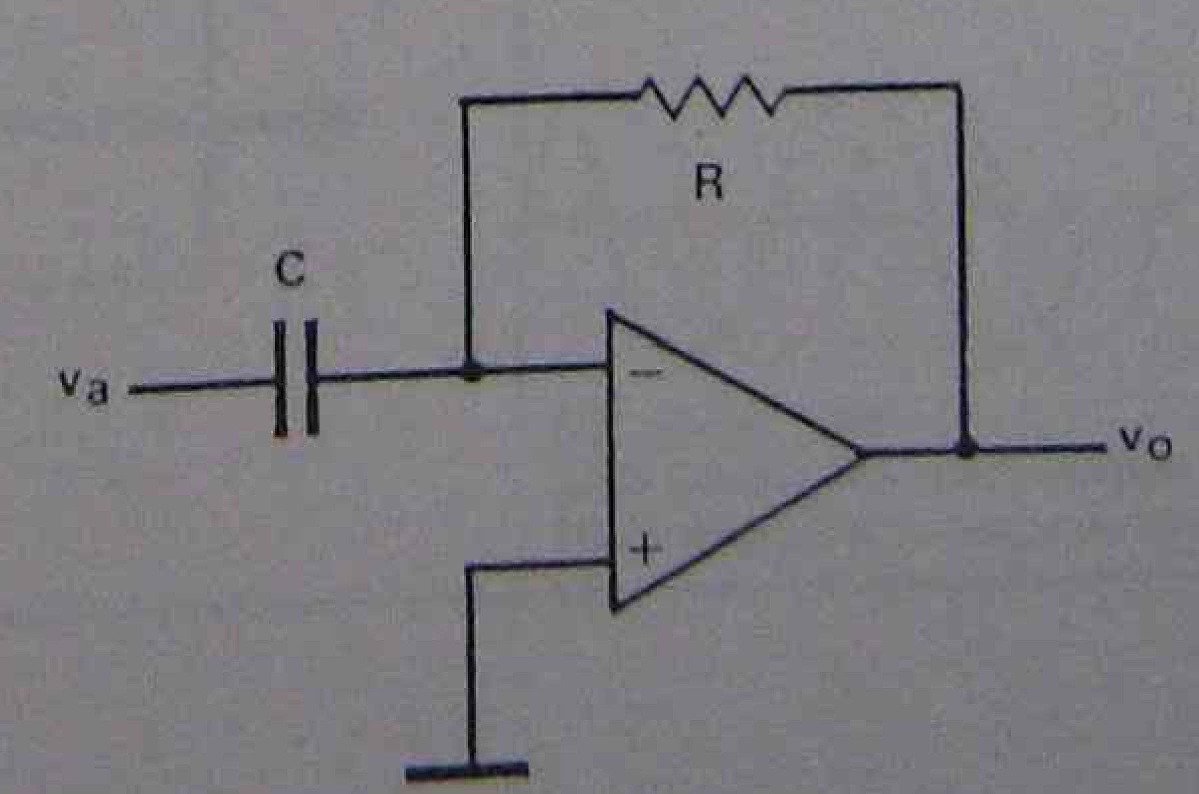


Fig 76

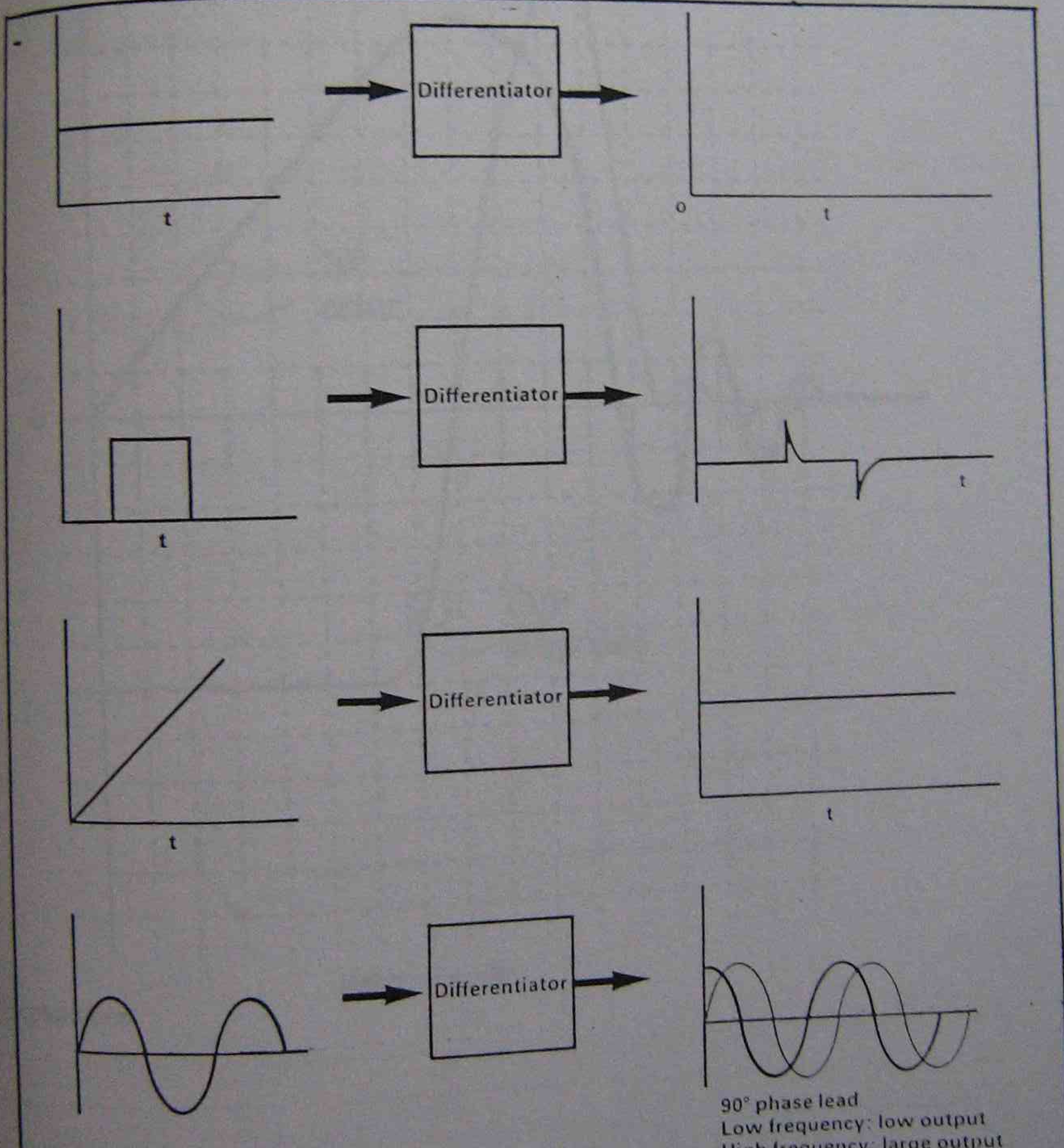
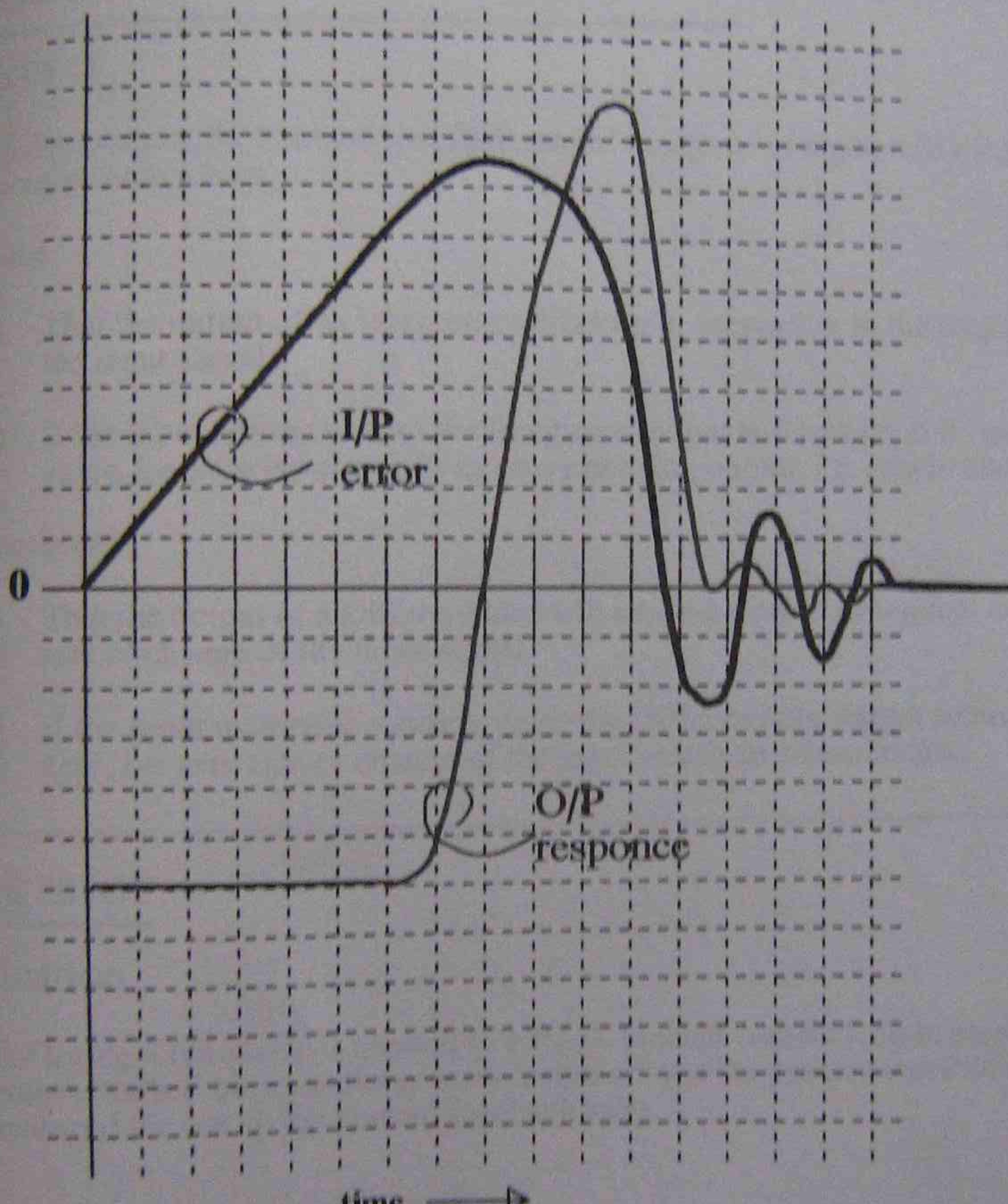

t
Differentiator
o
t
t
Differentiator
t
t
Differentiator
t
Differentiator
90° phase lead
Low frequency: low output
High frequency: large output

Fig 75

Fig. 4. Differentiator, dynamic curve



Explanation

The Integration and Differentiation functions as applied to Process Control.

Objectives

1. To demonstrate the Intregal and Differential functions as applied to a P.I.D. process control loop.

Integrator

a) That the output of an Integrator will ramp in proportion to the magnitude of the input signal.

b) If the input returns to zero the Integrator output will remain at its present value, i.e. zero input results in zero rampping output, i.e. steady state.

Differentiator

a) That the output of a Differentiator will assume a value dependent on the rate of change of the input signal.

b) If the input maintains a steady value the Differentiator output returns to zero, i.e. zero rate of change of the input results in a zero output.

Integrator

Application

The Intregal functions as applied to a P.I.D. process control loop is used to remove 'offset' between the process 'setpoint' and the process variable being measured for use in the control feedback loop.

Method

Construct the circuit of Fig1. or use the J&B PID controller board.

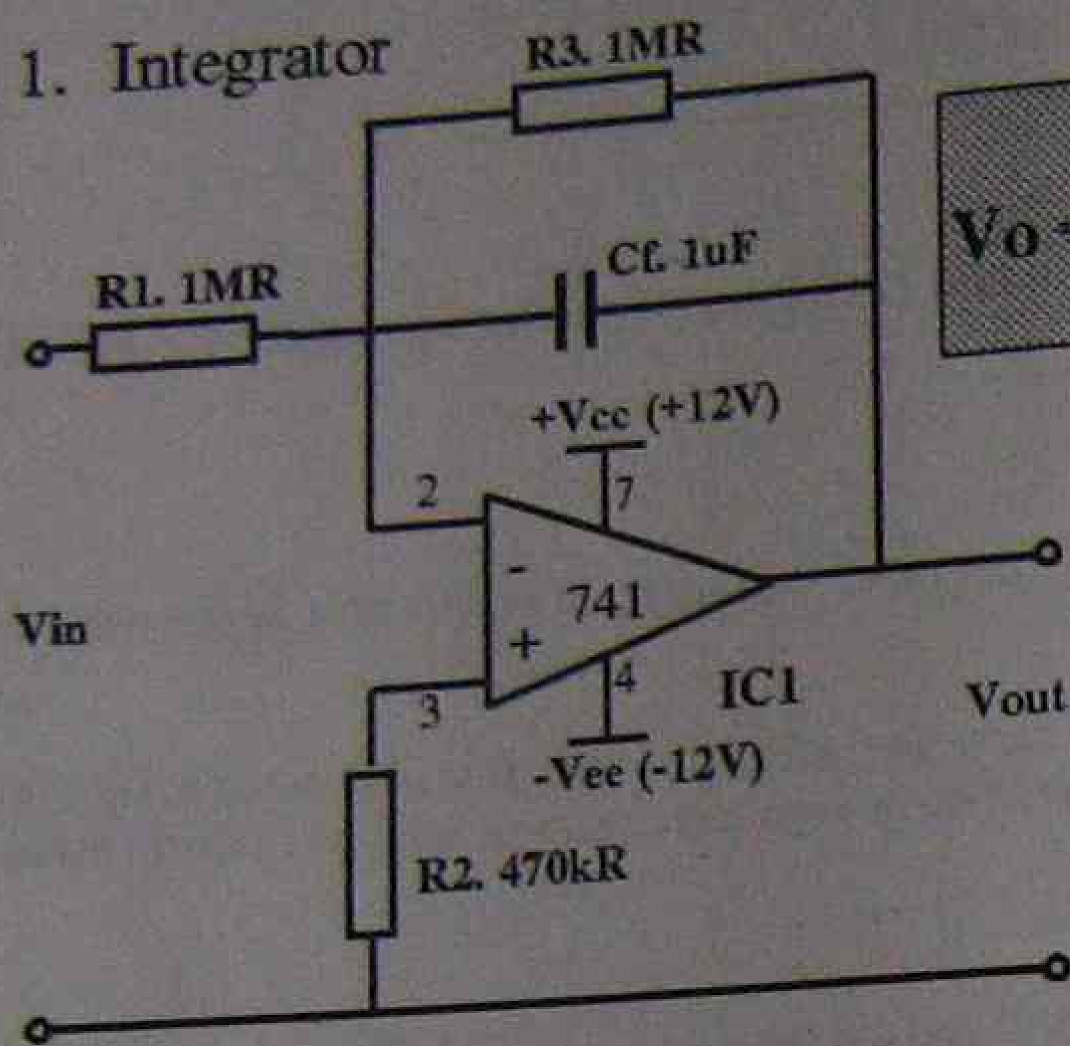
Connect a CRO to the input and both a CRO and DVM to the circuit output at the points indicated in the diagram. DO NOT FORGET to adjust the switches on the PID function outputs.

Apply a 0.5V DC input signal and monitor, and record, the output for a period of 10 seconds;
repeat for voltage values up to 5.0V DC.

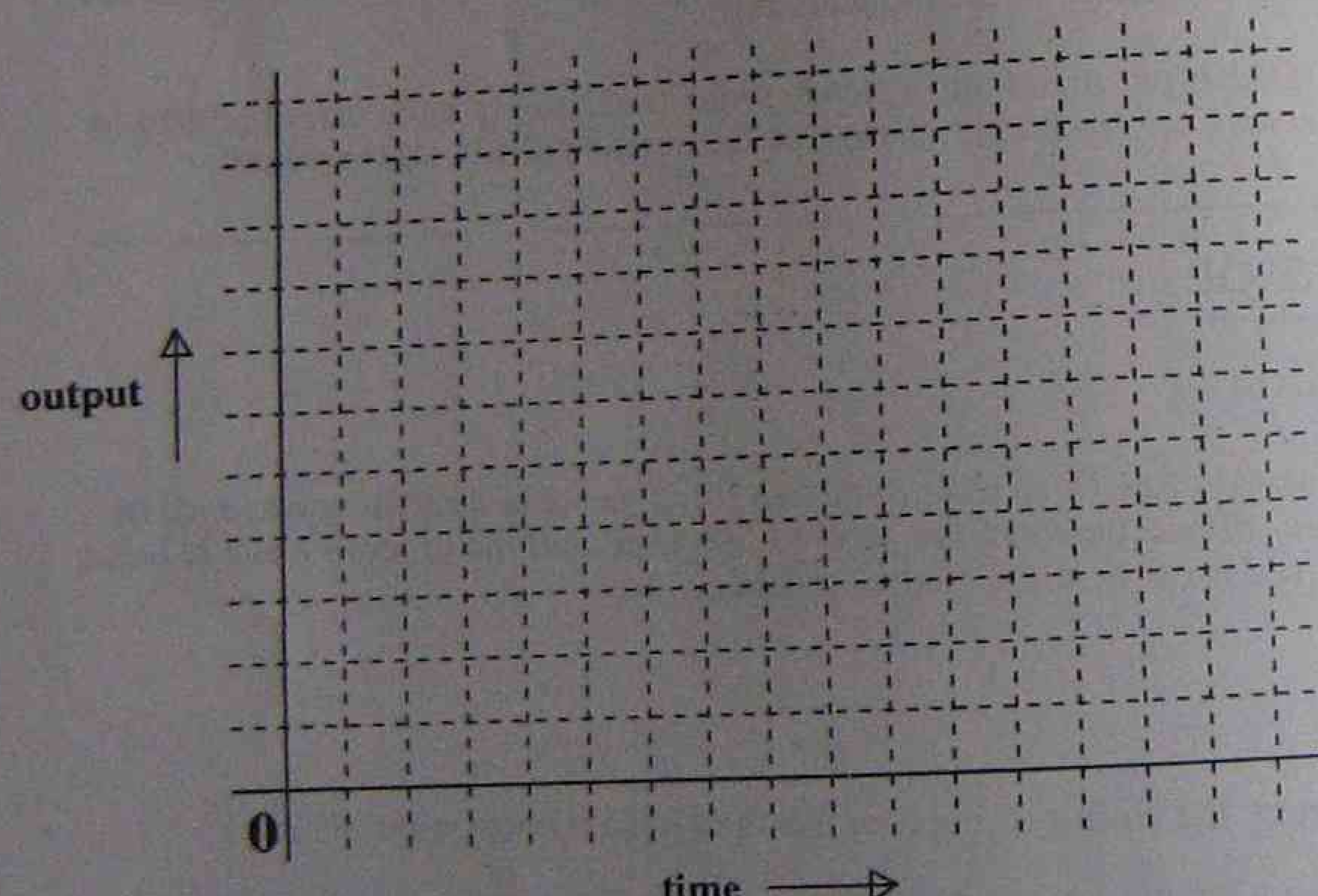
Adjust the settings to obtain the best CRO display to demonstrate the function.

Explain the implication of the results.

Fig. 1. Integrator



$$V_o = -\left(V_{in}/R_1C_f\right)t + V_o$$



Explanation

....

....

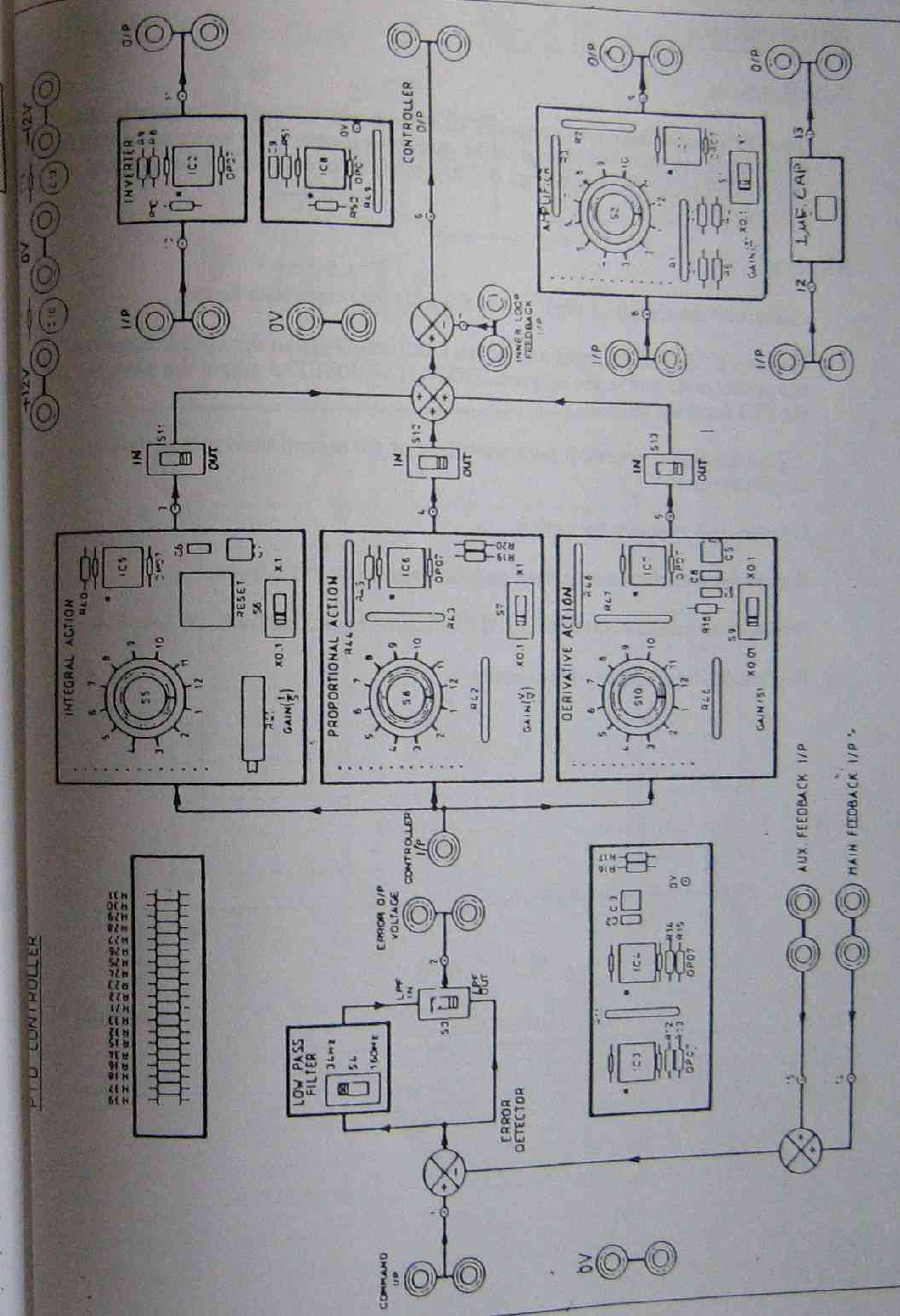
....

....

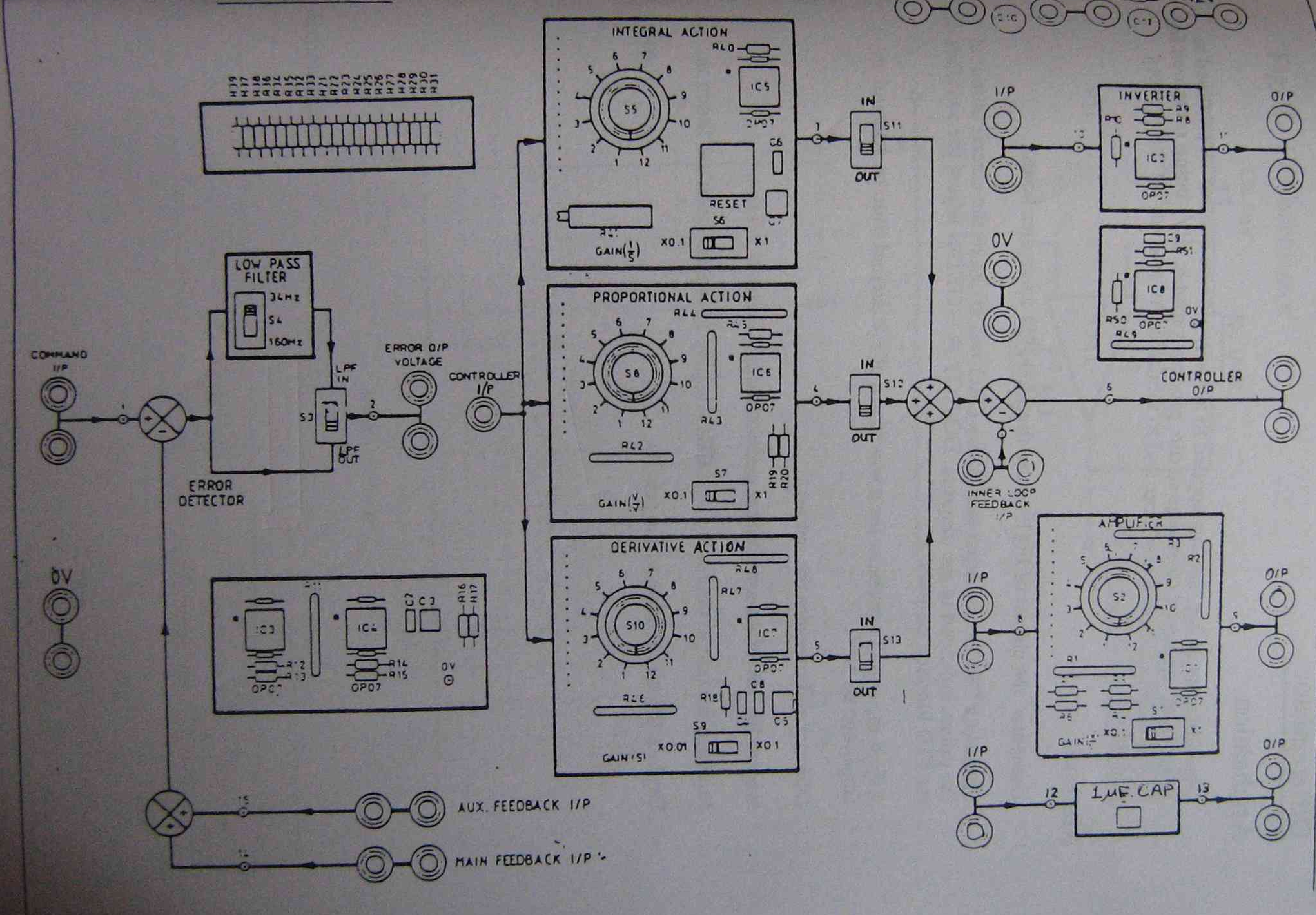
....

....

....



P.I.D CONTROLLER



Differentiator

Application

The Differential functions as applied to a P.I.D. process control loop is used to counteract the speed of change of the process variable (PV) being measured for use in the control feedback loop, and to minimise 'overshoot' of the process variable.

Method

Construct the circuit of Fig1. or use the J&B PID controller board.

Connect a CRO to the input and both a CRO and DVM to the circuit output at the points indicated in the diagram. DO NOT FORGET to adjust the switches on the PID function outputs.

Adjust the signal generator for a waveform of 1.0 second time period and an amplitude of 10V.

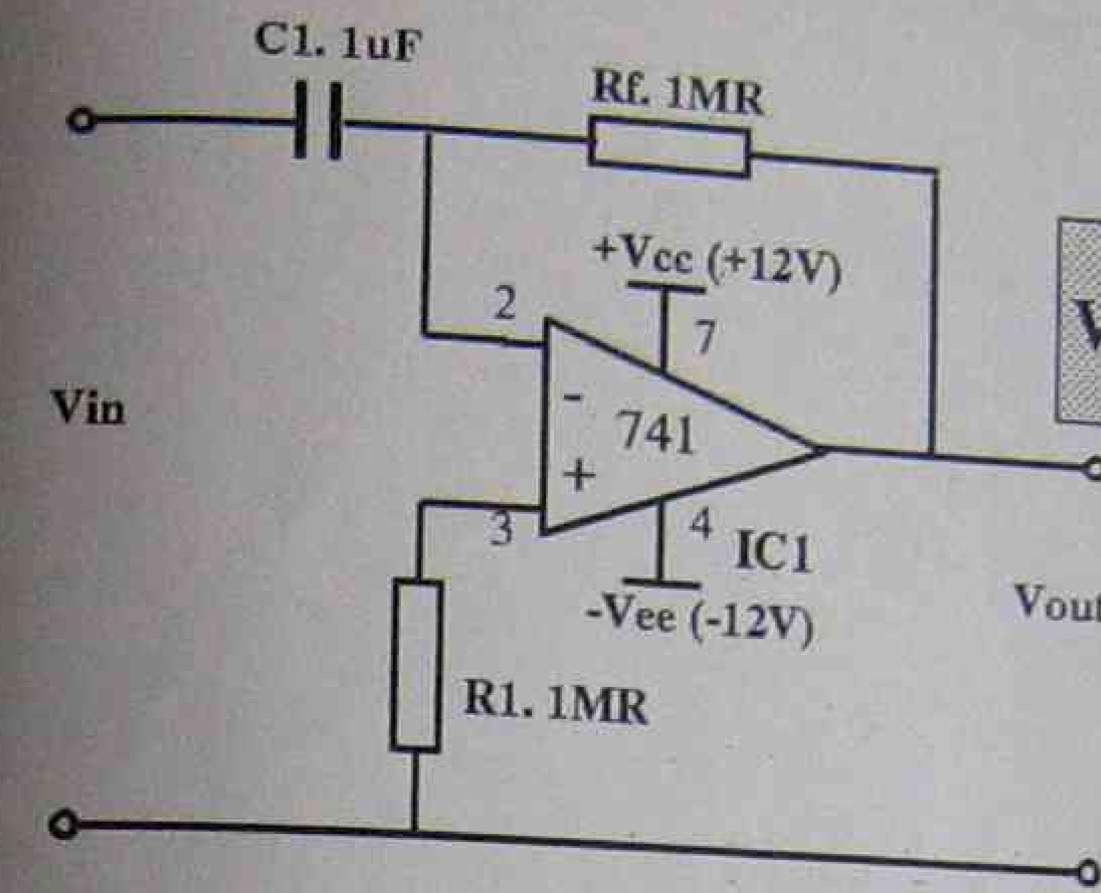
Observe and measure the output,

Repeat for waveforms with time periods from 0.1 sec to 1.0 sec.

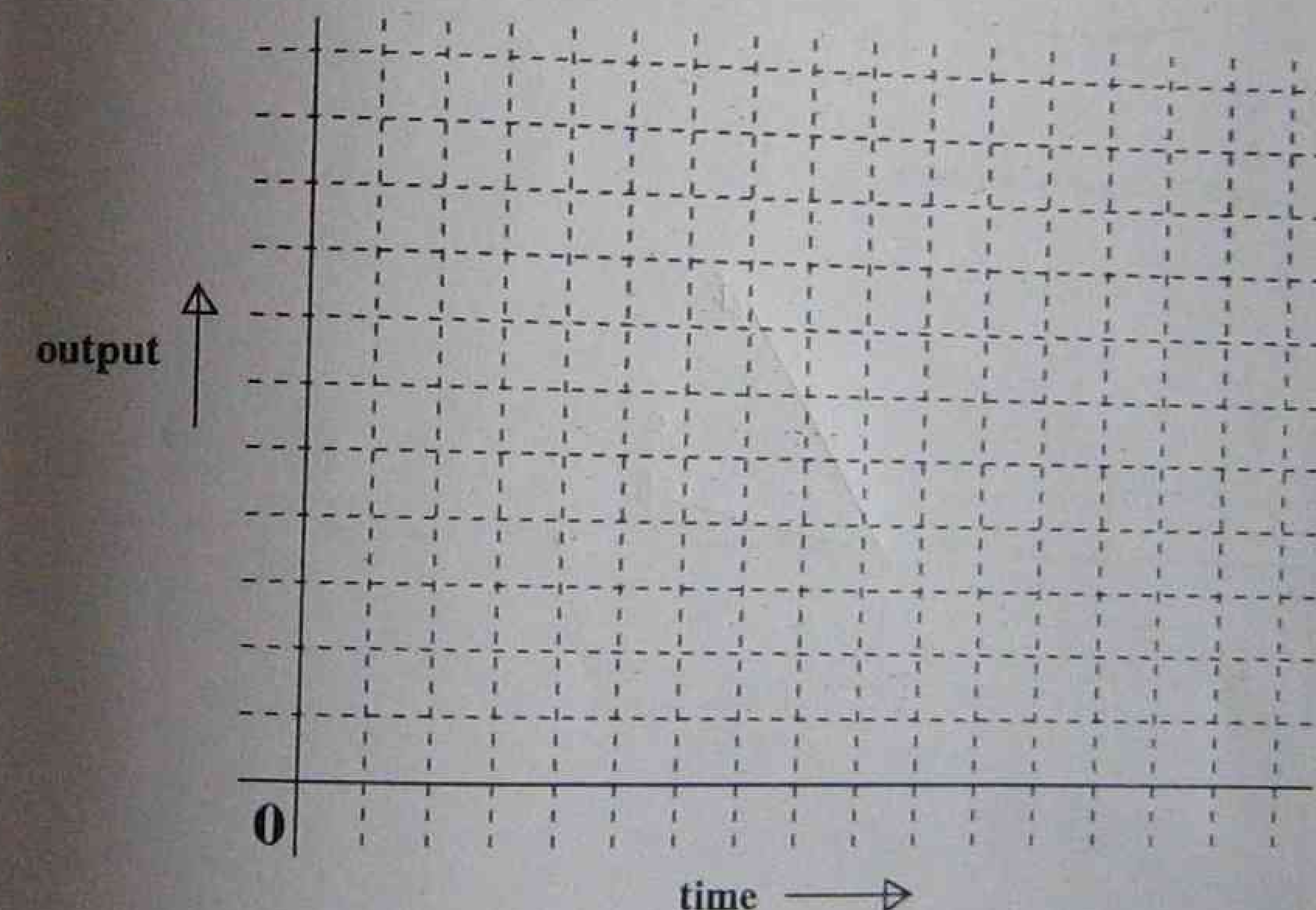
Increase the rate to obtain the best CRO display to demonstrate the function.

Explain the implication of the results.

Fig. 2. Differentiator



$$\boxed{V_o = -R_fC_1\left(V_{in}/t\right)}$$



Explanation