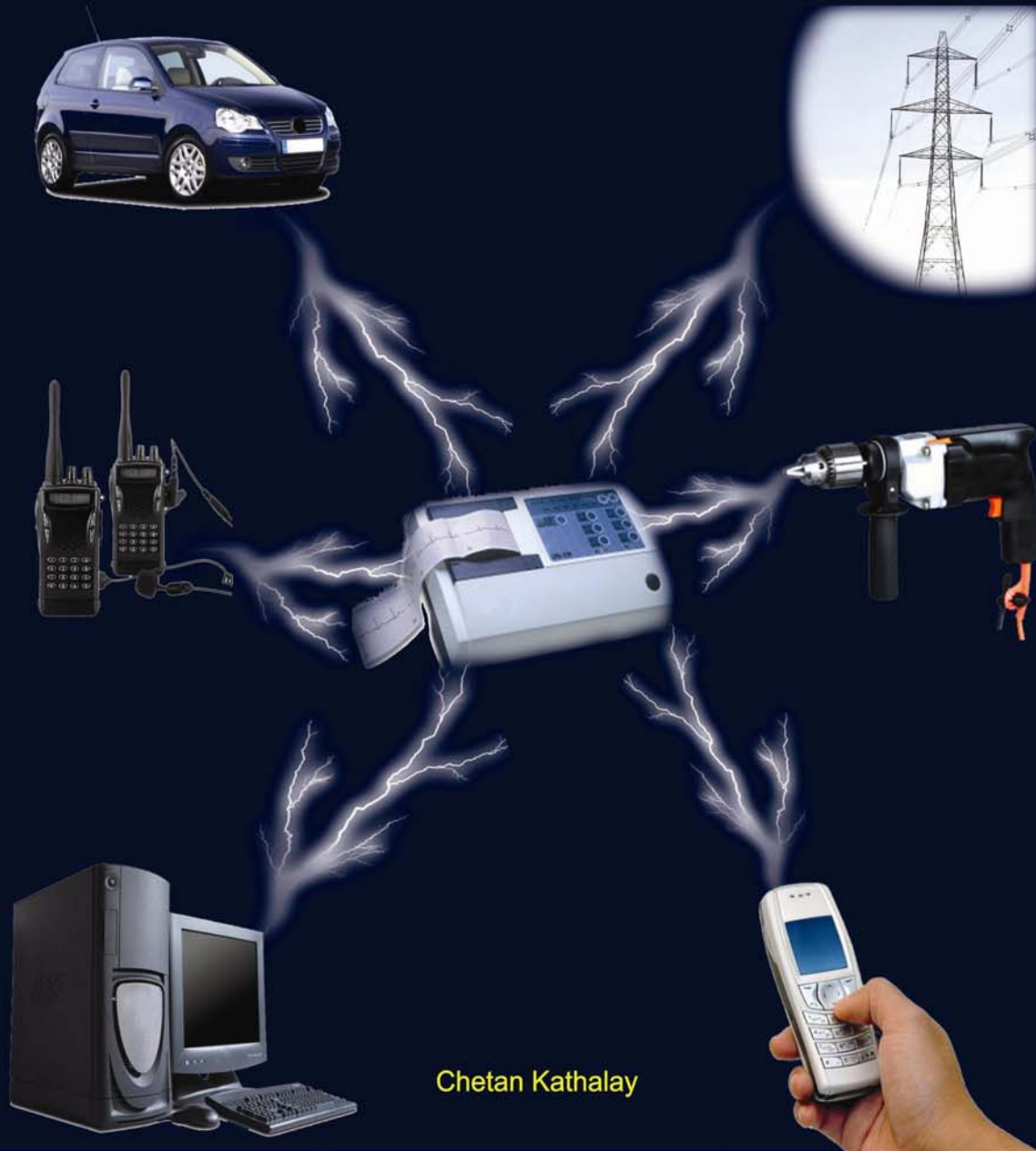


A PRACTICAL APPROACH TO  
**ELECTROMAGNETIC  
COMPATIBILITY**

WITH AN INTRODUCTION TO CE MARKING



Chetan Kathalay

**A PRACTICAL APPROACH TO  
ELECTROMAGNETIC COMPATIBILITY  
(WITH AN INTRODUCTION TO CE MARKING)**

Chetan Kathalay

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To my wife and daughter i

and

To my parents who always encouraged me to learn.



**Declaration as per CCS rule 8(3)**

The views expressed by the author are his own and not that of the government.



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## PREFACE

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The new world has seen an unprecedented proliferation of electronic gadgets. The design engineers have succeeded in achieving the ultimate - reduction in size, reduced power requirements, increased speed, reduced costs - you name it!! On the face of it, the progress seems fantastic. But it comes with a price - that of increased *Electromagnetic Interference* (EMI). All across the globe, EMI and its associated problems have been troubling the systems engineer for quite a while now. Solving these problems has posed a major challenge for them and avoiding them has been a major cause of worry for those involved in design. While engineers elsewhere have come in terms with the problem, engineers in India are still grappling with it. This is because EMI compliance at design stage has never been a priority in India. Faced with stiff challenge from their foreign competitors, who are already manufacturing EMI compliant products, they are now left with no option but to face and sort out EMI issues. There are a miniscule of Indian manufacturers who have succeeded in doing so, but a vast majority still exists who are yet to do it. This book is aimed primarily to help such people who are desperate to find a solution to EMI issues but have not quite found out a way.

The book is based on experiences gained by the author through guidance given to manufacturers during various EMC testing and developmental assistance jobs undertaken and through various courses on EMC design conducted by him. It is also, in some way, an outcome of the frustration expressed by Indian manufacturers regarding the lack of a book published in India, that could explain the practical concepts of EMI measurement and compliance, which they could read and immediately put to use. In the absence of such a book they were left with no other option but to buy costly books published outside India, to refer to college text books or surf incessantly on the internet. This resulted in peace-meal

solutions and conflicting ideas which confused them instead of convincing. This book, because of low cost and practical approach, may serve as a boon for such people.

Normally, if you ask the *experts* in the field about EMC/EMI they will initially throw some technical jargons, which may be enough to desist you. But if you are of persistent type, they will recall some heavy mathematical stuff (Maxwell's equations or Fourier series among the favourite) till you are thoroughly fogged. They will then shake their head and tell you that your knowledge of mathematics is not enough to understand the intricacies of a rather 'complex' subject. In one way they are correct. If you intend to do core research in the area (develop a software which predicts EMI, for example) you may, at some point in time, require a thorough knowledge of mathematics. If the reader is interested only in the mathematical theory of EMI, this book is not for him. But I guess the reader has no such things in mind (at least presently) and is interested only in understanding basics of EMI and practical solutions to EMI problems. He has then chosen the right book since it focuses only on the practical aspects of EMC, without resorting to theoretical and mathematical derivations. Although there are some formulae (there *will be* for a technical subject), but they are mostly basic. Also, a conscious effort has been made to deviate from text book language, which otherwise may make the subject drab and boring.

For better understanding of the subject, the book is divided into two parts – "Part I" deals with the fundamentals, standards and test methodology while "Part II" deals with the design aspects. Part I starts with an introduction to fundamentals of EMC/EMI which will enable the reader to get a foothold of the concept of EMI before going further into the subject. The next chapter gives an introduction to the EMC standards which prescribe the tests to be carried for ascertaining equipment EMI emission and checking its immunity towards emissions of other equipment. The four chapters that follow, deal with test procedures and instrumentation required to measure EMI and expose the equipment to simulated EMI in order to decide compliance.

Part II of the book has five chapters on EMC design namely filtering, shielding, PCB design, grounding and bonding and cable routing which can be considered as the five *pillars* of EMC. The chapter on filtering deals with the design, installation and performance evaluation of line filters which are needed to suppress EMI that is usually conducted on cables in the form of current while the chapter on shielding talks about shielding mechanism and design of shields against EMI that is radiated in the form of electromagnetic waves. The chapter on PCB design discusses the various aspects of proper PCB design required not only to keep the inherent EMI emissions down but also increasing the intrinsic immunity of the equipment against extraneous EMI and improving signal integrity. The chapter on grounding and bonding is especially important since all the above EMI measures work to their full

potential only if the EMI current bypassed by filters and induced in shields is properly *drained* to ground. This is followed by a chapter on cable routing and deals with the interconnection of various modules within a system for improved EMC performance. These chapters on EMC design will serve as a guide to the reader to incorporate EMI suppression measures in the design stage of the product development cycle itself. This will avoid costly retrofits called "*EMI fixes*" that otherwise have to be incorporated at the eleventh hour which not only adds add to equipment cost but also leads to loss of precious time because of the inherent difficulties that are involved in modifying a frozen design.

And last but not the least, the book ends with a introduction to CE marking which is a mandatory compliance mark placed on products intended for export to the European Union and for which EMI compliance is a must (at least for electronic equipment). It is sincerely hoped that the book proves to be useful to the people for whom it is intended.

The author would like to thank Shri Krishna Murari, Director, ETDC, Pune who encouraged him to consider every EMC test job as a project and provide the manufacturer with total EMC solutions and also to Shri P. H. Bhawe, ex-director ERTL (W), Mumbai who put faith in the author and deputed him in EMC test lab at the start of his career.

Chetan Kathalay  
Pune, 2014





## **PART I**

# **EMC TESTING AND STANDARDS**



# 1

## INTRODUCTION TO EMI/EMC

---

### 1.1 INTRODUCTION TO EMI

Pollution is the bane of modern society. It is the undesirable by-product of mankind's scientific and technological progress. Whatever be its type, there is hardly an individual who has not heard of pollution and who has not been affected by it. In general terms, pollution is the introduction of contaminants (chemical substances or energy) that causes an adverse effect. Air pollution, for example, is the introduction of certain undesirable gasses like sulphur-dioxide or carbon-mono oxide, to name a few, which otherwise are not part of the standard atmosphere and which can have adverse effect on human health. The most recent form of pollution is electromagnetic pollution (if we can call it that) i.e. the generation of electromagnetic energy that can have an adverse effect on the *health* of an electrical/electronic equipment.

Thus, any electromagnetic phenomenon (noise or unwanted signal) that may degrade the performance of a device, equipment or a system is referred to as electromagnetic disturbance. The electromagnetic phenomenon can be natural or man-made and includes electromagnetic noise or unwanted signals or even change in propagation medium itself. The International Electrotechnical Commission (IEC) defines electromagnetic interference or EMI as "degradation in performance of a device, equipment or system caused by electromagnetic disturbance". Now, electromagnetic disturbance can occur across the entire range of the electromagnetic spectrum and some of it may fall within the radio frequency range of 3kHz to 300GHz (which is normally used for radio communication) in which case it is referred to as radio frequency disturbance. We can then define RFI or radio frequency interference as "the degradation in reception of a wanted signal caused by radio frequency disturbance".

In simpler terms, EMI/RFI is an electromagnetic pollution caused by the generation of electromagnetic energy that is unwanted or unwarranted. This can interfere with the normal operation of an electronic equipment resulting in the degradation of its health. The electromagnetic phenomenon is the source of EMI, which travels through the intervening

medium and affects the operation of nearby electronic equipment that receives the EMI and becomes a victim.

## 1.2 HISTORY OF EMI

It all started in 1882 when Thomas Elva Edison and Westinghouse opened the first electricity generating station in Manhattan and Pittsburg respectively. By that time commercial telephony was also gaining momentum. With the increasing deployment of power and telephones, overhead power and telephone lines shared long parallel runs on poles. Electric trolleys (trams) were widely used in the early 1890's and the trolley's speed control induced noise into the telephone lines interfering with the voice. This was one of the earliest instances of conducted EMI which resulted in the formation of the first "inductive coordination" committee overseeing the mutual deployments of power and telephone companies and devise ways to avoid such problems. The first instance of radiated EMI occurred in 1901 when Marconi and Lee de Forest were competitors in America's Cup yacht race off the New York coast and had hired separate press agencies to cover the event from another boat. When they both attempted transmission using their broadband arc transmitters and wide-open receivers, they interfered with each other and neither shore station could hear anything. After realizing what was happening, the two teams agreed to take turns transmitting and receiving, but by then a third wireless operator had begun transmitting and nobody could communicate useful information!

By 1904, various AC and DC devices like wireless telephones / telegraphs, dynamos, electric monorail etc were being used. The International Electrotechnical Commission (IEC) was set up in 1906 to generate standards of nomenclature and ratings in order to harmonize differing electrical norms. In 1912, the US Congress passed the radio act that required licensing of operators which led to the formation of an international society –the Institute of Radio Engineers(IRE) in the same year.

In 1920, the first commercial radio station was built by Dr Conrad with a transmitting power of 100 watt. People used to listen to transmission using Westinghouse radio receivers. By 1924 there were 600 commercial stations in the US. To regulate these radio transmissions and to standardize definitions, symbols and testing, the radio act of 1927 was passed and Federal Radio Commission was established.

Broadcast AM (amplitude modulated) radios became very popular by 1930 but they were plagued by interference generated mostly from motors, railroads, trolleys and electric signs. In 1932, when RF interference started becoming widespread, the IRE began addressing vehicle EMI problems. In 1934, IEC recommended the formation of the International Special Committee on Radio Interference or CISPR (which in French actually stands for "Comite International Special des Perturbation Radioelectrique" and many pronounce it as "SISPER") to address quantification and measurement of interference from 150kHz – 1,605kHz. CISPR worked on the design of measuring receivers, artificial mains networks, field strength measurement procedures and techniques for measuring radio noise. A "board of listeners" was formed to assess the relative annoyance of various repetition rates to radio reception and it was concluded that interference sources with a higher pulse

Coupling is the process by which the energy from an EMI source is transferred to the victim. This transfer of energy can be in the form of a current (if the source and victim are galvanically connected to each other) or it can take place through air (or space) in the form of radiation. The amount of energy transferred depends upon impedance matching between the source and victim. If the output impedance of the source is comparable to the input impedance of the victim, then the coupling is more efficient. To reduce the coupling it is imperative to maximize the impedance mismatch either by design (like increasing source-victim distance or source-victim geometry) or by introducing certain components that will enhance this mismatch or using both! But before going into the details of EMI coupling, it is useful to understand the modes in which EMI occurs and propagates. Basically there are two modes of EMI namely, the differential or symmetric or normal or balanced mode and the common or asymmetrical or unbalanced mode.

### 1.9.1 EMI modes

#### 1.9.1.1 Common mode (CM) voltage and current

Common mode voltage or asymmetrical or unbalanced voltage is defined as the "voltage between artificial midpoint of two conductor line and ground (or earth)" OR as "the mean of the phasor voltages appearing between each conductor and a specified reference", usually earth or frame. Voltages on phase and neutral as referenced to ground or Earth are essentially common mode. As shown in the Fig. 1.16 if  $V_1$  and  $V_2$  are voltages on phase and neutral respectively, then expression 1.2 gives the common mode voltage. EMI voltages induced by external electric fields are generally common mode in nature. The common mode voltage 'VCM' is given by

$$V_{CM} = (V_1 + V_2) / 2 \quad \dots 1.2$$

Common mode current is defined as "vector sum of currents flowing through two (or more) conductors at specified cross sections". In simpler terms, common mode currents are those currents which flow in the same direction on live and neutral and return via earth (see Fig. 1.17). EMI currents induced by external magnetic fields are generally common mode in nature. If  $I_1$  and  $I_2$  are currents on live and neutral, then the common mode current 'ICM' is given by vector sum of the two.

$$I_{CM} = I_1 + I_2 \quad \dots 1.3$$

#### 1.9.1.2 Differential mode (DM) voltage and current

Differential mode or normal mode or symmetrical mode or balanced voltage is defined as "the voltage between two wires of a two conductor line". In the Fig. 1.16 the voltage  $V_{DM}$  is the differential mode voltage and is the vector difference (expression 1.4) of the voltages on phase and neutral. The normal mains voltage is differential in nature.

$$V_{DM} = V_1 - V_2 \quad \dots 1.4$$

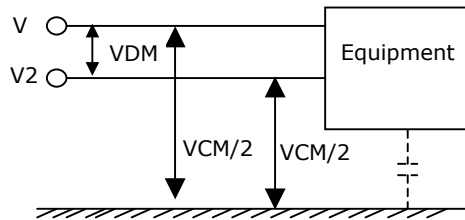


Fig. 1.16 : CM and DM voltage

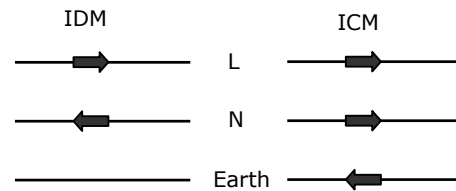


Fig. 1.17 : CM and DM currents

Differential mode currents are defined as "half the vector sum of currents flowing in any two of a specified set of active conductors at a specified cross-section". In simpler terms differential mode currents are those currents which flow in opposite directions on phase and neutral. The normal power currents are differential in nature as given by.

$$I_{DM} = (I_1 - I_2) / 2 \quad \dots 1.5$$

### 1.9.1.3 Unsymmetrical mode

The voltages  $V_1$  and  $V_2$  in Fig. 1.16 are sometimes termed as unsymmetrical voltages and are defined as

$$V_1 = V_{CM} + V_{DM}/2 \quad \dots 1.6$$

$$V_2 = V_{CM} - V_{DM}/2 \quad \dots 1.7$$

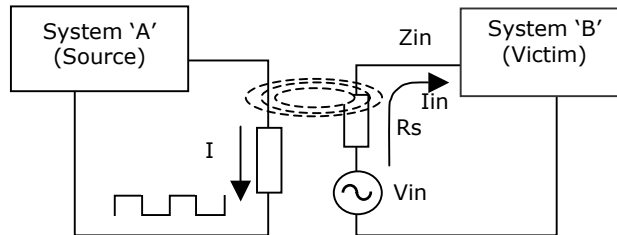
### 1.9.2 EMI coupling mechanisms

Having understood the modes in which EMI occurs, let us now take a detailed look at the various coupling mechanisms. It is important to note that in typical interference situations, it is impossible to single out one mechanism. The problem is normally a result of a combination of more than one mechanism and a good EMC engineer is one who can identify the mechanism which is more dominant in a particular scenario and apply EMC design methodology keeping the dominant mechanism in mind. EMI generated by the source reaches the victim via any or all of the following coupling modes :-

- Inductive coupling.
- Capacitive coupling.
- Galvanic coupling.
- Electromagnetic coupling.
- Field-to-cable common mode coupling.
- Field to cable differential mode coupling.
- Cable-cable coupling.

#### 1.9.2.1 Inductive coupling

In low impedance , high current systems, coupling of EMI is usually inductive. This is also referred to as magnetic field coupling.



**Fig. 1.18 : Inductive coupling**

As shown in the Fig. 1.18, a changing current "I" in system 'A' produces a magnetic field (shown dotted) that couples to system 'B' and induces a voltage "Vin" given by

$$V_{in} = M(dI/dt) \quad \dots 1.8$$

Where 'M' is the mutual inductance between the two circuits. This voltage forces a current



' $I_{in}$ ' in system 'B' given by exp 1.9, where the term ' $Z_{in}/R_s$ ' ( $Z_{in}$  parallel with  $R_s$ ) is the input impedance of system 'B'.

$$I_{in} = V_{in} * Z_{in} / R_s \quad \dots 1.9$$

$$I_{in} = M (dI / dt) * Z_{in} / R_s \quad \dots 1.10$$

A common example of inductive coupling is that 50Hz power currents through a transformer.

### 1.9.2.2 Capacitive coupling

This is also referred to as electric field coupling and occurs in high impedance circuits where voltage plays a dominant role. As shown in the Fig. 1.19 a changing voltage "V" in system 'A' couples to system 'B' and induces a voltage " $V_{in}$ " through a stray capacitance (shown dotted) formed by circuit wires and intervening space. The most common example of this type is the coupling of EMI through a transformer by a stray capacitance between primary and secondary.

The induced voltage in system 'B' is given by:

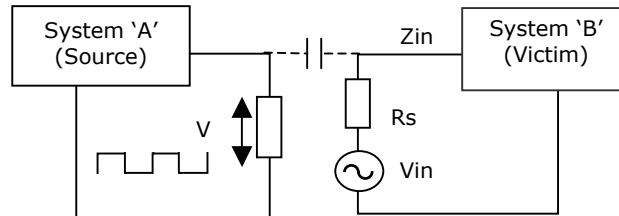
$$V_{in} = C * dV / dt * Z_{in} / R_s \quad \dots 1.11$$

Where in ' $C$ ' is the stray capacitance and ' $Z_{in}/R_s$ ' represents the input impedance of system 'B'.

To appreciate the amount of voltage induced, consider the voltage source 'V' as a square wave where 5V is being switched at 100 MHz. Assuming the stray capacitor of 1pF (the usual figure) and ' $Z_{in}/R_s$ ' = 50 $\Omega$ , the voltage induced is given by :-

$$\begin{aligned} V_{in} &= 1 * 10^{-12} * 5 * 100 * 10^6 * 50 \\ &= 25 * 10^{-3} = 25\text{mV} \end{aligned} \quad \dots 1.12$$

Since EMI voltages are generally measured in micro-volts, 25mV is obviously a very high value.



**Fig. 1.19 : Capacitive coupling**

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### 1.9.2.3 Radiation or electromagnetic coupling

Capacitive and inductive coupling occurs in the near field region where either the electric field or magnetic field is dominant. But if the victim lies far away from the source i.e. at distances greater than  $\lambda/2\pi$  where ' $\lambda$ ' is the wavelength corresponding to highest frequency, then it is said to be in the far field region and the coupling will be via electromagnetic field and as such is referred to as electromagnetic or radiation coupling. Such coupling occurs between a radio receiver and the transmitter.

# 2

## EMC STANDARDS

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### 2.1 INTRODUCTION

The word "standard" is used by us almost every day. Many-a-times we use the term loosely, inadvertently like a "standard time" or a "standard photograph" or a "standard hospital bed" and we do not even notice it. When two people talk about standard, they mean something recognizable and real which can be easily identified by both of them. When they talk for instance about a "standard hospital bed", it is assumed that it will -at its bare minimum- be made of metal, be white in color and will have a mechanism for reclining and we just have to say "standard hospital bed" without elaborating on its features. A "standard" therefore can become a "means of comparison". "Cold" may be "colder" or "warmer" depending on which part of the world one comes from. For example -5 degrees C will be warm for a person from Siberia, but quite cold for a person from Arabia. So how does one compare then? When one says a "good" TV, what does it actually mean? We either should have a TV with a certain characteristics which all TV manufacture will compare their TV with OR we may have a "document" which explains certain characteristic of a TV which makes it good or bad. Well this document can then be called a "standard". A standard can be defined as a *"technical specification, adopted through consensus, by a standard making body that provides rules, guidelines or characteristics for activities (or their results), aimed at the achievement of the optimum degree of order in a given context"*.

What then is an EMC standard? Well, it can be defined as "a technical specification adopted by a standardization body for the purpose of establishing rules, guidelines, methods or characteristics for assessing the EMC performance of a product". The objective of EMC standards is to ensure reasonable electromagnetic compatibility between electrical, electronic, electromechanical and RF communication systems for trouble-free co-existence by limiting emission of EMI and ensuring that these systems have adequate level of immunity to EMI generated by other equipment. EMC standards also provide a means of comparing the EMC characteristics of various equipment so that the user may choose an equipment appropriate to his requirement. The standard contains a list of definition of words,

forefront of developing and publishing EMC standards. In fact, the IEC and the FCC have done some of the pioneering work in studying EMI phenomenon, developing methods and equipment to simulate these phenomena and receivers to measure EMI.

#### **2.4.1 International electrotechnical commission (IEC)**

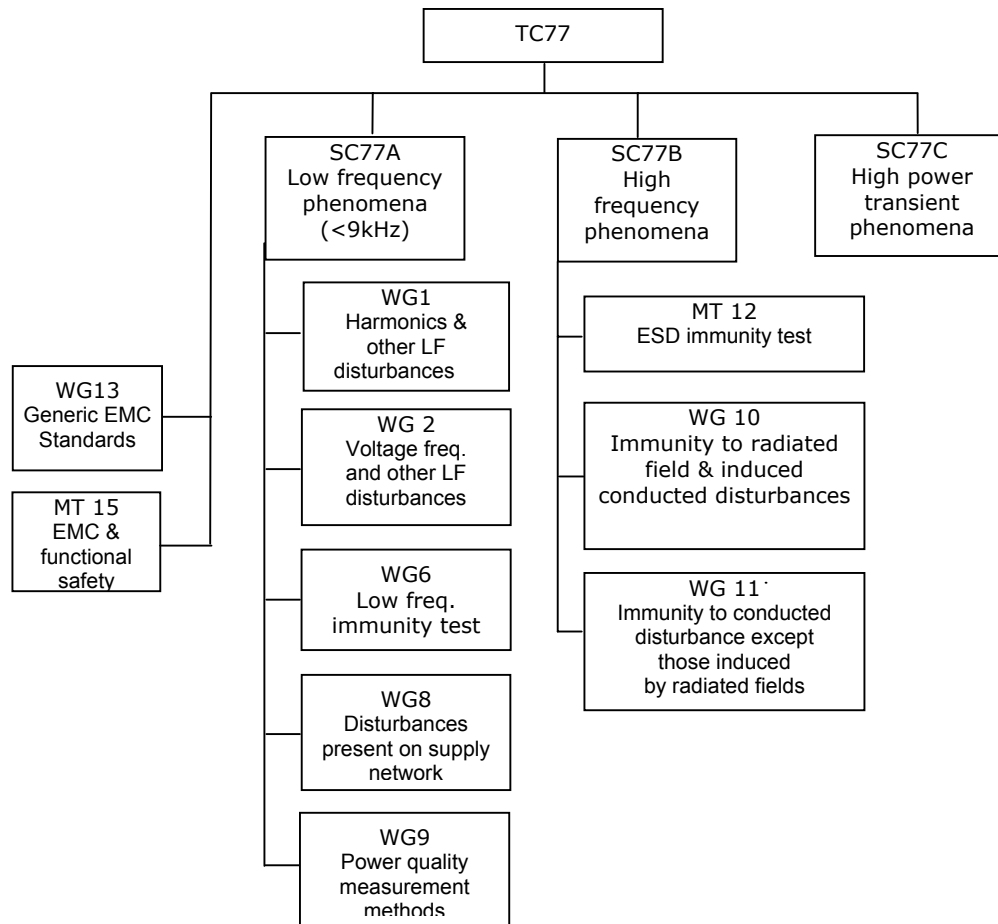
The IEC was founded in 1906 and is headquartered in Geneva. It is the world's leading organization that prepares and publishes international standards for all electrical, electronic and related technologies. IEC activities – collectively known as "electro-technology" – cover all electrical, electronic and associated technologies on land, at sea and in the air, as well as related disciplines such as terminology, electromagnetic compatibility, performance, safety and the environment. As well as providing an excellent framework for improving safety and optimizing energy use, IEC's international standards support trade between countries by providing a reference for the functioning of the World Trade Organization's (WTO) agreement on reducing technical barriers to trade.

Being an international organisation, the IEC has members from all over the world. IEC members are known as "national committees (NCs)" and there is one for each country. Each NC is fully representative of all interested parties in the area of electrotechnology at a national level. NCs typically comprise of representatives from industry, governmental agencies, academia, trade associations, end-users and standards developers. IEC NCs are constituted in various ways. Some are public sector only, some are a combination of public and private sector, and some are private sector. Furthermore, there are two membership categories viz. full member and associate member. Full membership grants countries the right to participate fully in all IEC's standardization activities, including the right to vote on all matters. It also gives access to all IEC international standards and documents. Associate membership provides more limited participation in IEC's standardization activities, while giving the same access rights as full members.

Standards activities in IEC are carried out by around 200 technical committees (TCs) and sub-committees (SCs) which work in various areas of electro-technical standardisation. The technical committees and sub committees present their works in the form of standards and technical reports. All NCs are free to take part in the work of any TC, either as participating or "P" members, with an obligation to vote at all stages and to attend meetings or as observing or "O" members, with the obligation to vote on final draft international standards. The products, or publications, that result from the work of technical committees and subcommittees fall into two broad categories viz. normative and informative. Normative publications are international standards, technical specifications, publicly available specifications, and industry technical agreements. Informative publications are technical reports, technology trend assessments, and guides.

The development of an IEC standard typically starts with participants at the national level feeding their ideas and proposals to their NCs, who then bring these forward as new work projects. If approved by the IEC membership, these are taken forward to the appropriate IEC technical committees and subcommittees who transform the ideas and proposals into international standards and other types of publications.

introduction to the phenomenon, a description of the various transients/RF to be simulated, the severity levels to which the equipment under test should be exposed to, the design of generators and coupling networks to generate and couple transients onto power line and on equipment enclosure, the method of presentation of results and calibration of the generators and couplers. IEC 61000-5 deals with installation and mitigation guidelines while IEC 61000-6 are the generic standards (see section 2.4.8) IEC 61000-6-1 to 61000-6-4



**Fig. 2.2 : TC-77**

The structure of TC 77 is as shown in Fig. 2.2. It is divided into subcommittees SC 77 A, B and C with area of activity as shown. Each subcommittee consists of various working groups "WGs". Thus, there exists a fair amount of specialisation within the TC 77 itself. The two most frequently referred basic standards are the IEC61000-3 series and the IEC 61000-4

and 4kV, one of which is selected according to installation conditions and type of line. All lower test level voltages must also be applied.

**2.4.7.6 IEC 61000-4-6 : Conducted disturbances induced by radio frequency (RF) fields**

High power RF transmitters and other RF sources can induce disturbance in cables which then flows in the form of a current. This test simulates the effect of such RF current on equipment operation. The test is carried out over frequency range of 80MHz to 230MHz and the standard specifies severity levels of 1,3 or 10V (unmodulated) depending on the installation environment. The applied RF is modulated to 80% with a 1kHz sine wave.

**2.4.7.7 IEC 61000-4-8 : Power frequency magnetic fields**

This test analyzes the effect of magnetic fields on equipment installed in the vicinity of transmission lines. Continuous and short duration power frequency magnetic field is applied via an induction coil adequately sized to surround the EUT in three orthogonal positions. Severity levels specified are 1,3,10, 30 or 100 A/m continuous and 300 or 1000 A/m short duration (1 to 3s).

**2.4.7.8 IEC 61000-4-9 : Pulse magnetic field**

Electronic equipment installed in electrical plants may be affected by transitory magnetic fields. The pulse magnetic field test simulates this phenomenon. At least 5 positive and 5 negative pulses are applied via an induction coil adequately sized to surround the EUT in three orthogonal positions, repetition period not less than 10s. Severity I prescribed are 100, 300 and 1000 A/m.

**2.4.7.9 IEC 61000-4-10 : Damped oscillatory magnetic field**

This test is applicable to electronic equipment installed in electricity generating stations and switchyards and simulates oscillatory magnetic fields generated due to faults. Oscillatory wave of 0.1 or 1 MHz damped to 50% of peak after three to six cycles at a repetition rate of 40 or 400 per second, applied via an induction coil adequately sized to surround the EUT in three orthogonal positions for 1s. Severity levels of 10, 30 and 100 A/m are specified.

**2.4.7.10 IEC 61000-4-11 : Voltage dips, short interruptions and voltage variations**

Power drawn for utility suffers from various voltage conditions like short interruptions or

short term increase or decrease in voltage. This test simulates various conditions of transient interruptions and dips (also called sags or brown outs) and is applicable to electrical and electronic equipment fed by low-voltage power supply networks and having an input current not exceeding 16A per phase. (400Hz AC networks excluded). Dips and short interruptions initiated at any phase angle of the input voltage, to a level of 0%, 40% 70% and 80% of the nominal voltage for a duration of 0.5 to 250 50Hz periods of 50Hz.

**2.4.7.11 IEC 61000-4-12 and IEC 61000-4-18 : Oscillatory waves**

These tests simulate oscillatory surges generated in power generating stations or switchyards due to faults or operation of fault prevention switchgear or control gear. IEC 61000-4-12 prescribes testing for "ring wave" oscillatory transient which is a 100kHz wave

#### **2.4.14 Automotive emission standards**

**2.4.14.1 CISPR 12 :** Vehicles, boats, and internal combustion engine driven devices – Radio disturbance characteristics – Limits and methods of measurement for the protection of receivers.

Limits in this standard are designed to provide protection for broadcast receivers from automotive interference in the frequency range of 30 MHz to 1000 MHz when used in the residential environment. Calls for conducted and radiated emission measurement.

#### **2.4.14.2 CISPR 25**

Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers.

The standard applies to any electronic/electrical components intended for use in vehicles, trailers and devices and contains limits and procedures for the measurement of radio disturbances in the frequency range of 150 kHz to 2500 MHz.

#### **2.4.15 Automotive susceptibility/immunity standards**

##### **2.4.15.1. ISO 11451: Vehicle test methods**

This standard gives various test methodologies for testing entire vehicles for EMC.

*Part 1 (ISO 11451-1):* This part gives general principles and terminology.

*Part 2 (ISO 11451-2):* Off-vehicle radiation sources

This part gives vehicle test method for determining the immunity of passenger cars and commercial vehicles to electrical disturbances from off-vehicle radiation sources, regardless of the vehicle propulsion system (e.g. spark ignition engine, diesel engine, electric motor). It can also be readily applied to other types of vehicles.

*Part 3 (ISO 11451-3):* On-board transmitter simulation.

This part specifies methods for testing the immunity of passenger cars and commercial vehicles to electromagnetic disturbances from on-board transmitters regardless of the vehicle propulsion system.

*Part 4 (ISO 11451-4):* Bulk Current injection.

Bulk current injection (BCI) test methods and procedures for components for passenger cars and commercial vehicles regardless of the propulsion system is specified by this part.

##### **2.4.15.2 ISO 11452 : Component test methods**

This standard gives EMC test methodologies for components installed in vehicles.

*Part 1 (ISO 11452-1): General principles and terminology*

*Part 2 (ISO 11452-2): Absorber-lined shielded enclosure method.*

This is an absorber-lined shielded enclosure method for testing the immunity (off-vehicle radiation source) of electronic components for passenger cars and commercial vehicles regardless of the propulsion system.

*Part 3 (ISO 11452-3) : TEM cell method.*

# **3**

## **CONDUCTED EMISSION MEASUREMENT**

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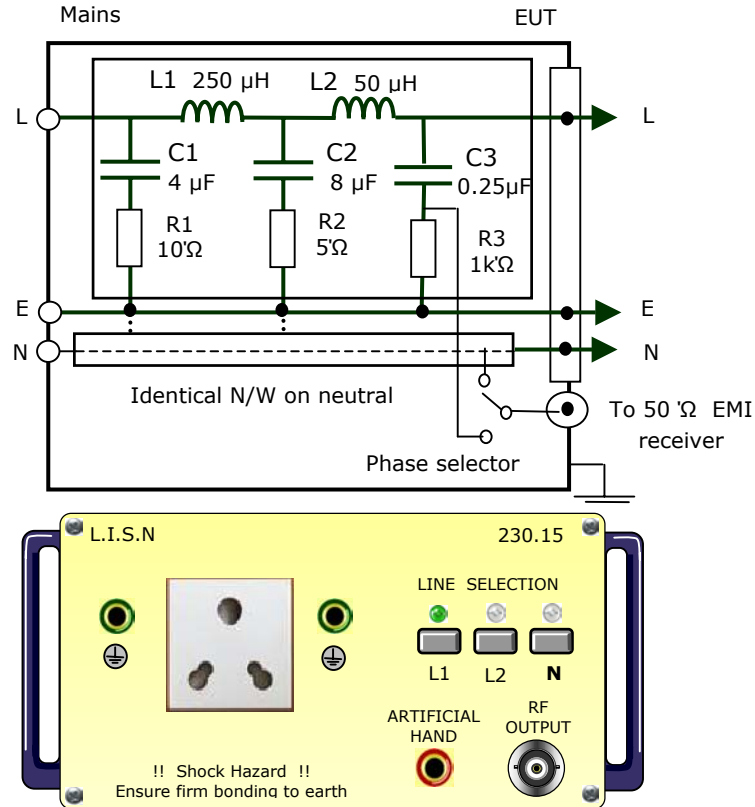
### **3.1 INTRODUCTION**

Conducted emission (CE) is the EMI emitted by an equipment in the form of a current through any conductor that interfaces the equipment with the outside environment. Conducted emission measurement is generally carried out over a frequency range from a few kilohertz (kHz) to tens of megahertz (MHz). In this range, the cable length may not be sufficient to act as efficient antenna and as such EMI travels in the form of a current along the conductive path provided by the cable. It must be noted that the term conducted emission is actually used by MIL standard 461 while IEC/CISPR based standards use terms like terminal disturbance voltage or conducted disturbance voltage. We will however stick to the term conducted emission or CE during the course of this chapter.

CISPR-based standards specify CE measurement from 150kHz to 30MHz on the mains cable. The three most commonly referenced standards CISPR 11, CISPR 14-1 and CISPR 22 and corresponding EN standards (EN 55011, 55014-1, 55022) specify measurement in this frequency range. CISPR 13 (for broadcast receivers) and CISPR 15 (for lighting equipment) also require a similar test, although CISPR 15 calls for measurement from 9kHz to 30 MHz. In addition to mains cable, the standard CISPR 22 also calls for measurement on telecom cables. There are certain standards which call for CE measurement below 9kHz. Such measurement include power frequency harmonics (EN 61000-3-2) which is measured from fundamental mains frequency to its 40th harmonic. Conducted EMI at such frequencies is usually categorized as low frequency while that between 9kHz to 30MHz is categorized as high frequency.

For high frequency conducted emission measurement, most of the EMC standards require the emission from the equipment under test (EUT) to be sensed by calibrated transducers. The transducer output is then scanned by a EMI receiver (a tunable RF

the EUT is fed with a pure mains supply. This is essential because the AC mains supply, which is generally drawn from public utility, may already have certain level of 'ambient' conducted EMI from stray sources. Without the LISN, it will be difficult to distinguish between ambient EMI and the actual conducted emissions from the EUT. Thirdly, the LISN stabilizes the impedance of mains to  $50\Omega$  to match with the input impedance of the EMI receiver. The circuit diagram of a typical V-type LISN/AMN is as shown in the Fig. 3.5. This is a  $50\mu\text{H}/50\Omega + 5\Omega$  LISN as specified by CISPR 16-1-2 for the measurement range of 9kHz to 150 kHz.



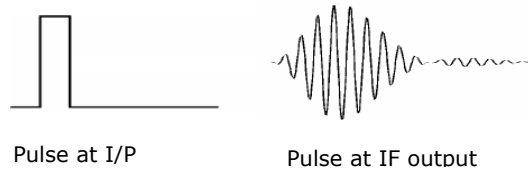
**Fig. 3.5 : V-type LISN (AMN)**

For measurement in the range 150kHz–30MHz, the standard specifies a  $50\mu\text{H}/50\Omega$  LISN (although the former can also be used provided impedance requirements are met). In this variant, the resistors R1, R2 and capacitor C1 are absent and so is the inductor L1. The value of C2 is 1 $\mu\text{F}$  while that of C3 is 0.1 $\mu\text{F}$ . A third variant, the  $5\mu\text{H}/50\Omega + 1\Omega$  is specified for the frequency range of 150kHz to 100MHz, wherein L1, C1 and R1 are absent while the value of R2 is 1 $\Omega$ , that of C2 is 2 $\mu\text{F}$ , value of L2 is 5 $\mu\text{H}$ , while value of C3 is 0.1 $\mu\text{F}$ . This type of LISN can be used for high mains current above 100A per phase, since the low series inductor of 5 $\mu\text{H}$ , causes less voltage drop. The Fig. 3.5 shows a single phase LISN, with the LC network on the line, although there exists an identical network on the neutral (which has



### 3.5.5 Detectors

Due to the band-pass characteristics of any receiver (the IF filter has a defined bandwidth which does not allow all frequency components to pass through), a pulse appearing at the input produces an I/F output as shown in the Fig. 3.17.

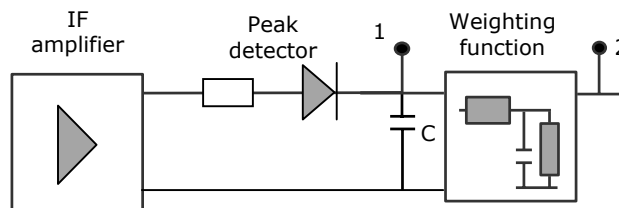


**Fig. 3.17 : IF response to pulse**

The duration of the IF-pulse depends upon the bandwidth of the receiver. The inverse of the IF-pulse duration is equal to the half of the receivers' 6 dB bandwidth. The frequency of the oscillations corresponds to the IF of the receiver. The IF-pulse is amplified and forwarded to the demodulator and detector circuitry. EMI receivers incorporate, at the minimum, three type of detectors as dictated by CISPR 16 and other EMC standards viz. peak, quasi-peak (QP) and average. Other type of detectors specified are the RMS and the RMS-average. The Fig. 3.18 shows a basic detector circuit used by most EMI receivers. Average and QP detectors are realized by a peak detector followed by appropriate weighting functions. In case of un-modulated sine wave voltages at receiver input, all the detectors give equal output readings. The scenario is different for pulsed input and in such a case, the output of the QP and average detector depends on the pulse repetition frequency (PRF) of the input. QP and average detectors give proportionally higher output for input with higher PRF.

### 3.5.6 Peak Detector

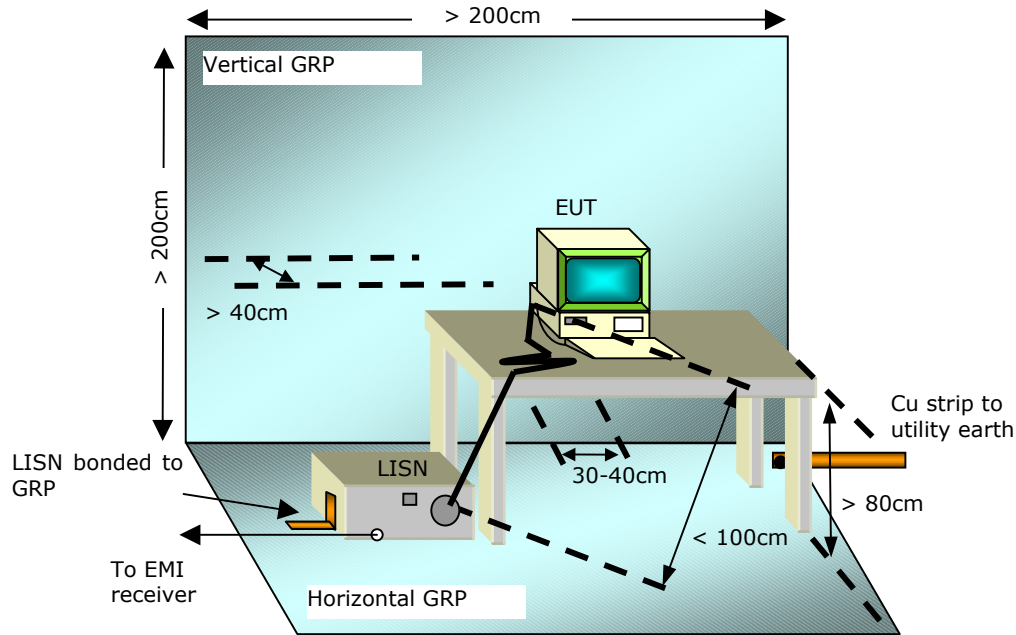
A peak detector is characterized by very short time constant for charging and an extremely long time constant for discharging (CISPR 16-1-1 specifies the ratio of discharge time constant to the charge time constant for CISPR band 'B' as  $1.25 \times 10^6$ ).



**Fig. 3.18 : Basic detector**

As shown in the Fig. 3.18, the output at point '1' (before the weighting function) is the output of a peak detector. In the absence of the weighting function (essentially a pulse shaping network) the capacitor 'C' has no path to discharge. The peak detector therefore

should be placed on a conducting floor used as the GRP but not in electrical contact with it. The distance between the boundary of the EUT and the closest surface of the AMN/LISN must be 80 cm.



**Fig. 3.25 : CISPR laboratory set-up**

The mains lead from the EUT to the AMN/LISN should preferably be 1 m long and raised at least 10 cm from the GRP for the whole of its length. Longer mains leads may be bundled non-inductively in the figure of '8', but this introduces considerable variations into the results, and it is preferable to shorten them to the standard length. Many-a-times a standard wooden jig is used so that bundling can be done in a repeatable manner. Mains-powered peripherals that are necessary for the operations of the EUT but which are not themselves under test should be powered from a separate AMN/LISN. Other connected leads should be terminated in their normal loads but should not extend closer than 40 cm from the GRP. The set-up for floor-standing equipment is the same except that in place of the table, the EUT is placed on an insulating support 0.1m high.

The laboratory set-up for MIL std 461F for the test CE 102 is similar to CISPR standard and is as shown in the Fig. 3.26. Since the testing is done in a shielded chamber, GRPs are not required. The EUT is kept on a table 80-90 cm high. The LISN is kept on the table but on a metallic ground plane which is bonded to the chamber wall. The length of the mains chord is specified as 2 m and it should be routed 10cm away from table edge. For EUTs which are installed permanently on a ground plane, the standard requires that the entire table be covered by a ground plane (of resistance not greater than 0.1 mΩ per square)

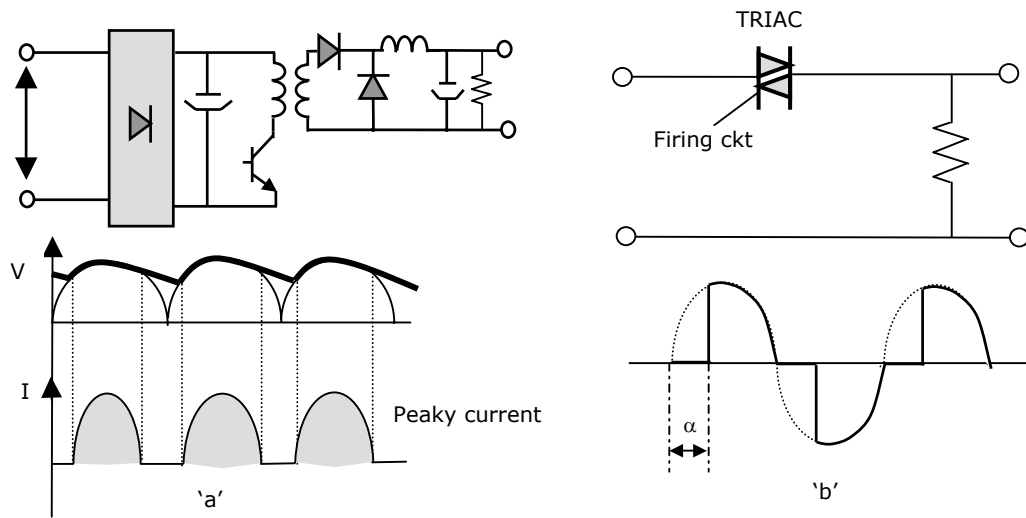


Fig. 3.30 : Harmonics

### 3.13.2 Rationale for reducing harmonics

The presence of harmonics on power line is detrimental to the health of any electrical/electronic equipment. One of the ill-effects is the reduction of power factor (PF) i.e power factor falls below unity. Now, PF is the ratio of the real power (the "watts") and the apparent power (the "VA") as given in exp 3.14.

$$PF = \text{Watts} / VA = V * I / V_{rms} * I_{rms} \quad \dots 3.14$$

If the current (or voltage) is non-sinusoidal, then it can be represented by the sum of several sine waves in multiple frequencies, as given by Fourier series.

$$I = A_1 \sin \omega t + B_1 \cos \omega t + A_2 \sin 2\omega t + B_2 \cos 2\omega t + A_3 \sin 3\omega t + B_3 \cos 3\omega t + \dots \quad \dots 3.15$$

The RMS value of current is given by the expression

$$I_{rms} = \sqrt{A_1^2 + B_1^2 + A_2^2 + B_2^2 + \dots} \quad \dots 3.16$$

In the absence of harmonics, the higher frequency components (i.e.  $A_2, B_2, A_3, B_3 \dots$ ) are zero. In the presence of harmonics, these components have some finite value and hence the RMS value of the current (or voltage) (expression 3.16) increases, hence the PF decreases.

Again, PF is given by cosine of the phase angle between voltage and current. When voltage and current are in phase, (see Fig. 3.31a), their peaks coincide i.e. the phase separation is zero, the power factor is unity and all current contributes to useful power. When power factor is less than unity, some part of the mains current is not in phase with the voltage i.e. its peak either precedes or follows the voltage peak (see Fig. 3.31b and 3.31c). This part of the current (shown shaded in Fig. 3.31) is incapable of providing useful power. It however causes  $I^2R$  losses resulting in wasteful heating of devices like transformers and

# 4

## **RADIATED EMISSION (RE) MEASUREMENT**

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### **4.1 INTRODUCTION**

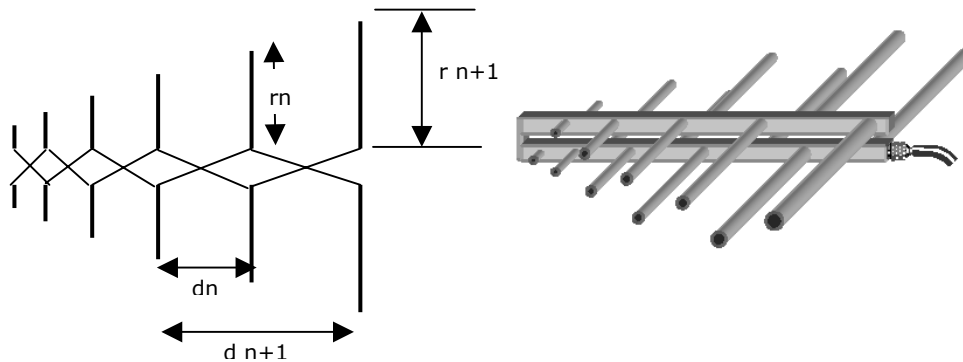
Use of electromagnetic energy in the form of radio waves has become part and parcel of modern life. We are surrounded nowadays by gadgets that use electromagnetic waves in the radio frequency (RF) region for communication (e.g. cellular mobiles) or for wireless operation (e.g. blue tooth) or for processing material (e.g. microwave oven) etc. Each of these devices have been allocated a particular range of frequencies in which they can transmit or receive electromagnetic energy. To avoid interfering one another, these devices must strictly operate in its allocated frequency band. If transmitted RF energy of any of these devices "spills" outside its band, it may interfere with devices operating in adjacent bands. For example if RF energy from a police wireless handset (due to a fault or otherwise) spills into a band meant for radio or TV, one can actually hear police conversations which may cause nuisance. At times while listening to radio, we may notice a continuous hum that becomes audible when a compact florescent lamp (CFL) is switched 'ON'. We all know that the CFL is not a RF transmitter which makes us wonder why it is disturbing the radio. Well the CFL is certainly not an intentional transmitter but the radio frequency energy is generated un-intentionally in its ballast which interferes with the radio. This intentional or unintentional generation of RF energy in the form of radiated electromagnetic waves is called as radiated emission which is defined as "the phenomenon by which energy emanates into space from a source in the form of electromagnetic waves, that tends to interfere with the operation of other equipment". EMC standards seek to keep this interference in check by prescribing measurement of radiated emission and imposing "limits" on the amount of radiated emission a particular class of equipment generates. For intentional emitters, the limits are imposed on "out-of-band" emissions.

In such tests, measurements are carried out over certain frequency range. A graph of frequency Vs the amplitude of emission is obtained. Limits are then superimposed on the graph to ascertain that the emissions are below limit, in which case the equipment is deemed compliant. The results may also be presented in tabular form.

It is also specified by MIL 461F for RE 102 testing and by automotive standard like CISPR 12 (for vehicles) and CISPR 25 (for components). It is a modified dipole antenna wherein the dipoles have been "flared" into a conical shape which gives the antenna its name. The conical elements serve to make the radiation pattern nearly spherical and the antenna nearly omni-directional. The horizontal and vertical radiation patterns approximate to a sphere centered at the feed and diameter equivalent to antenna length. If viewed in three dimensions the radiation pattern would resemble the shape of an apple. Since the antenna is balanced, a balun is required to interface it with an unbalanced coaxial cable. The balun also serves to match the high antenna impedance of  $200\Omega$  with the  $50\Omega$  impedance of the coaxial cable. A high quality balun is required so as to meet stringent VSWR requirements given by the standards, especially when the antenna is used to transmit high power during radiated susceptibility tests. For better impedance matching, ferrite beads are slipped over the cable connecting the balun to the coaxial connector, which absorb surface currents and keep VSWR low. The ferrite assembly is usually inside the mounting rod. The length of the antenna is about 1.35m, maximum width of the cone about 0.52m and cone angle is 26 degrees. The antenna is foldable i.e. the conical elements can be detached from the balun for ease of transportation when RE measurements are required to be done at manufacturer's site or in-situ. Nowadays, collapsible conical elements are also available wherein the elements fold like an umbrella which makes the antenna even more portable.

#### 4.3.2.3. Log-periodic Antenna

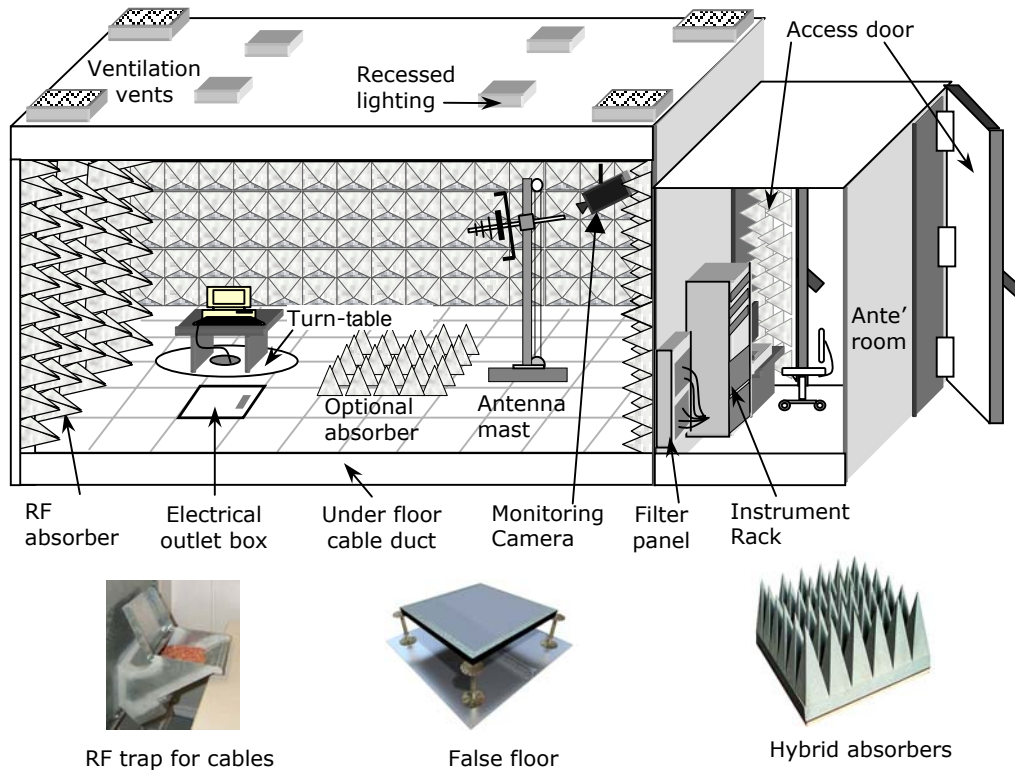
A typical Log-periodic antenna (also called as log periodic dipole array or LPDA) is as shown in the Fig. 4.5. This is the preferred antenna type specified by CISPR 16-1-4 for electric component of electromagnetic field measurement in the frequency range of 250 to 1000 MHz for automotive as well as non-automotive testing.



**Fig. 4.5 : Log-periodic antenna**

Although it resembles a yagi antenna, the log-periodic antenna is radically different and is much more broad-band. It is actually a series of dipoles where the length " $r_{n+1}$ " and distance " $d_{n+1}$ " of next dipole to previous one " $r_n$ " and " $d_n$ " are in same proportion (expression 4.1), while adjacent dipoles are fed with opposite phases. During measurement, the dipole whose length is closer to  $\lambda/2$  (where  $\lambda$  is the wavelength being measured) will start to resonate. This dipole is now the active dipole and receives energy, the shorter dipoles

of lights, cameras and even ventilation ducts in the absorbers. Normally at lower frequencies (below 200MHz), the pyramid absorber dimensions become impractical so ferrite tiles are preferred, while pyramid absorber are preferred for higher frequencies. In order to cover both the ranges, manufacturers typically use hybrid absorbers wherein ferrite tiles are first fixed on the walls and pyramid absorbers are fixed over the tiles. When these absorbers are in place, RF energy is scattered and absorbed thus avoiding reflections.



**Fig. 4.14 : Anechoic chamber**

The word "an-echoic" comes from the fact that in such a chamber there is "no echo" (reflections). Since the pointed absorbers are not aesthetically pleasing, they are nowadays covered by white tiles made up of nonconductive material like high density thermocole or styrofoam which not only increases the optical reflectivity but also provide laboratories to print their insignia! Depending upon the position of RF absorbers, anechoic chambers come in two types viz semi-anechoic and fully anechoic. Semi-anechoic chambers (SAC) do not have RF absorbers on the floor whereas fully anechoic chambers (FACs) have absorbers on the floor as well. Many-a-times absorbers on the floor are movable. They can be wheeled in during radiated susceptibility testing and removed during radiated emissions measurement. As far as the floor is concerned, a false floor with metal supports is normally installed at a suitable height, above the floor shielding panels. The false floor is

# **5**

## **CONDUCTED IMMUNITY / SUSCEPTIBILITY TESTING**

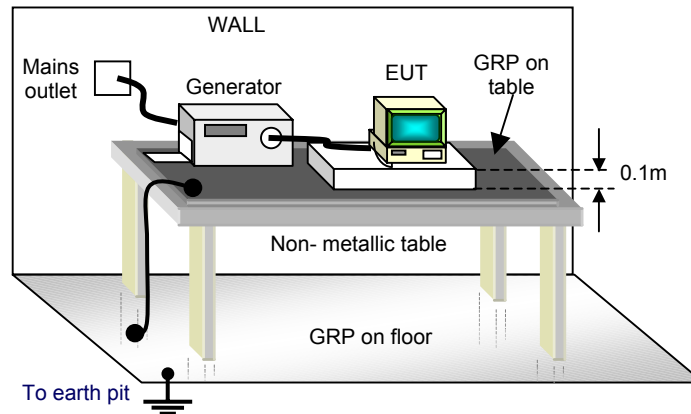
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### **5.1 INTRODUCTION**

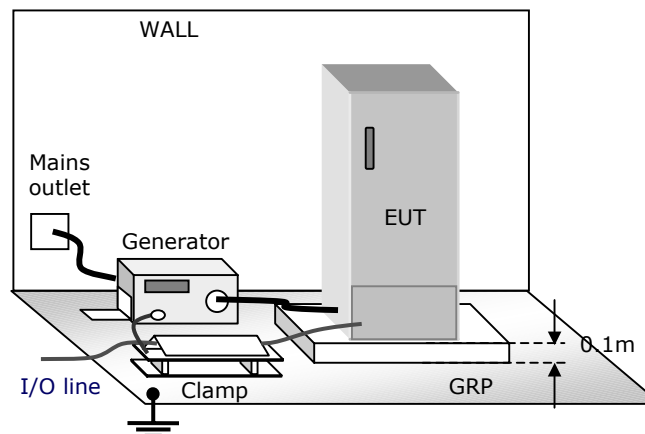
To establish electromagnetic compatibility an equipment must also be subjected to immunity/susceptibility tests in order to ensure that its operation is not disrupted in the presence of continuous radio-frequency noise and transient pulses which may be present in its operating environment. The source of transient pulses may be natural phenomena like electrostatic discharge (ESD) and lightning strikes or it may be artificial like conducted repetitive transients and ringing transients generated by fault currents. While the source of continuous RF fields can be radiated noise generated by RF transmitters and power lines. Conducted transients are of short duration of micro seconds or nanoseconds and whose amplitude is high enough to disrupt the operation of electronic circuits. Some transients like surges have the capacity to destroy and damage components. Except for ESD, the source of the transients is usually not near to the equipment and in majority of cases, these are coupled to the equipment via interconnecting mains or I/O cables. Most of the transients therefore are conducted in nature, and it comes as no surprise that a majority of immunity standards call lay stress on conducted immunity tests which involve coupling of transients on power / control lines. Except for pulsed and damped magnetic fields, not many standards call for radiated transient tests. ESD is a special case which involves both conductive (direct discharge) and radiative (in-direct discharge) transient immunity test.

Conducted immunity tests involve the application of a single transient or a series of transients or continuous wave EMI on power and communication cables (superimposed over mains/control voltage) accompanied by monitoring the function of the equipment under test (EUT) so as to ascertain whether its operation has disrupted, the extent of disruption and whether the disruption is acceptable or not. This chapter discusses the mechanism involved in generating conductive EMI, the standard tests that have been devised by IEC to deal with them and some practical issues in carrying out such tests. It must be noted here that all the generators, coupling devices and calibration accessories, made as per respective standards, are available in the market as proprietary items and that the test laboratory or the

words "unless otherwise specified by product standard", implying that product standards may specify a different length. The mains and all other cables (under test) are also kept 0.1m above the GRP. If a coupling clamp is used for testing on I/O lines, it is firmly bonded to the ground plane and is located 0.5m away from all metallic surfaces (including the EFT/B generator) other than the GRP. The EUT is connected to the earth system in accordance with the manufacturer's installation specifications. So under normal conditions the EUT will get protective earth (PE) from the CDN and this PE is connected to the GRP on the mains side (i.e. the decoupled side) of the CDN. The EUT cabinet (or body) is connected directly to GRP only if the manufacturer specifies separate earthing for the EUT cabinet and the length of any such connection is specified in the report. It must be noted here that since EFT/B is a broadband phenomenon with spectral components up to hundreds of MHz, any deviation from standard test set-up would mean alteration of stray capacitances between the EUT and its surroundings which in-turn may alter test results and affect the test repeatability.



**Fig. 5.7 : EFT/B Lab set-up for table-top equipment**



**Fig. 5.8 : EFT/B Lab set-up for floor-standing equipment**

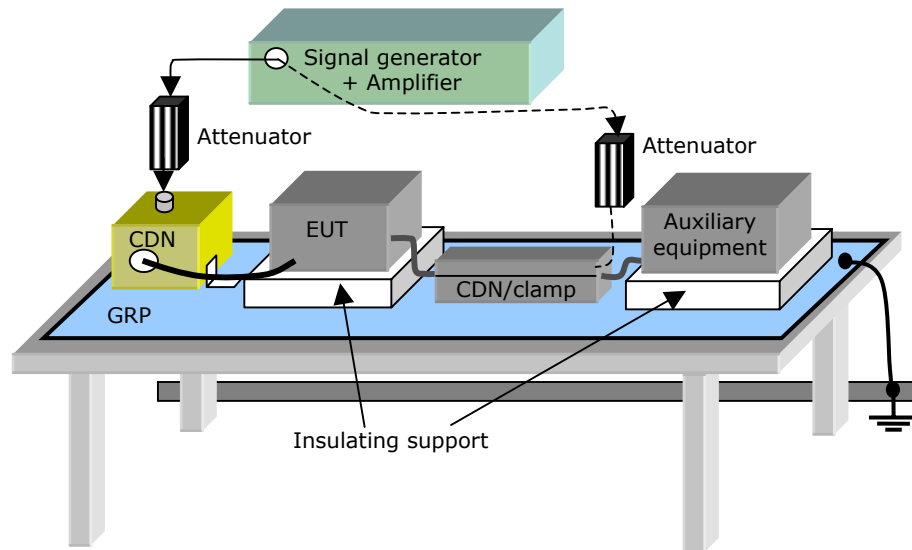


manganese–zinc (MnZn). These rings are split into two semicircular parts. One half is in the body of the clamp whilst the other half is in the clamp cover. The coupling transformer consists of a single wire loop that extends over the whole length of the twenty-six ferrite rings on mains side. The loop also goes through ten high frequency ferrite rings made up of nickel–zinc (NiZn) and a semicircular copper foil (connected to the loop and embedded in the clamp body) on the EUT side of the clamp. This is another difference over the absorbing clamp in which coupling transformer is only on the ferrite rings on EUT side.

The reason why the loop extends over the entire length of the clamp is because, the equipment cable, under normal installation conditions, may be exposed to external RF over its entire length. The loop is terminated on each side with an  $50\ \Omega$  impedance. This creates both a voltage and a current. The voltage gives capacitive (electric) coupling through the copper foil and the current gives inductive (magnetic) coupling via the ferrite rings and hence the name electromagnetic clamp. The EM clamp, as with a CDN, must be bonded to the ground reference plane (GRP) while testing.

### 5.5.7 Laboratory set-up for conducted RF susceptibility

The Fig. 5.26 shows basic laboratory test set-up for carrying out a conducted RF susceptibility test. The EUT, the CDN, the coupling device etc must be kept on a ground reference plane or "GRP" made up of copper/aluminum sheet.



**Fig. 5.26 : Conducted RF immunity test setup**

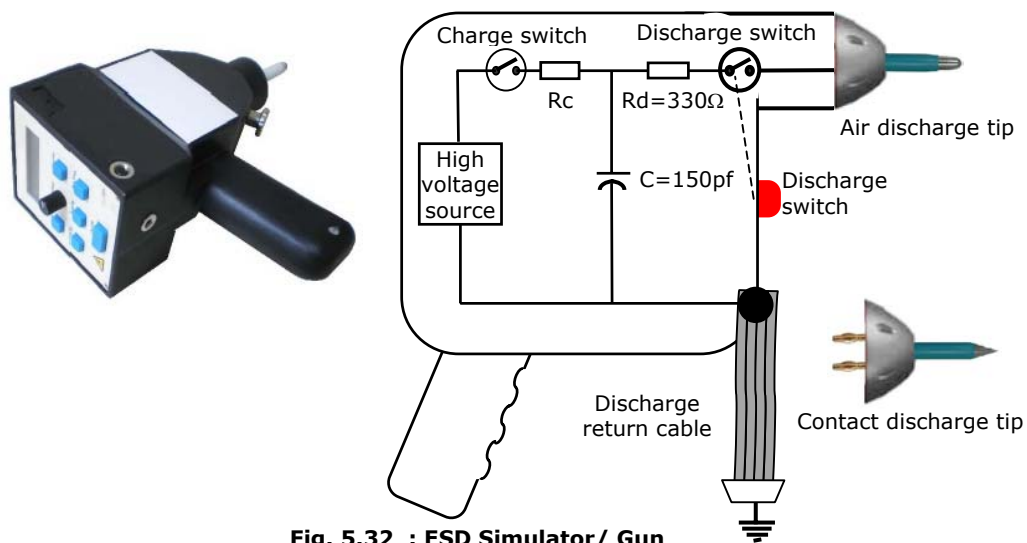
For table top equipment, the GRP can be located on a table while for floor standing equipment the GRP is on the floor. The GRP is essential so as to establish a common ground reference, since the output of the signal generator and the amplifier is referenced to earth. The GRP also provides a return path for stray capacitance to earth. The CDN/ clamp is firmly bonded to the GRP by a very short non-inductive strap, while the EUT is kept 10 cm above

### 5.6.6 ESD simulator

ESD simulator is essentially a "gun" which has the circuit (as shown in Fig. 5.32.) incorporated into it. This type is specified by IEC 61000-4-2. A HV supply (capable of generating up to 16.5 kV) is used to charge an energy storage capacitor 'C' through a charging resistor 'Rc' in the range of 50–100 MΩ, the charging being controlled by a charging switch. The energy storage capacitor (along with a the distributed capacitor between the generator and its surroundings) must have a value of 150 pf. This capacitor is discharged through a resistor of 330 Ω via a 'discharge tip'. When the discharge switch is pressed (i.e closed), the charge appears on the tip.

The automotive standard ISO 10605 specifies a capacitor of 330pF and discharge resistor of 2kΩ. ESD standards normally specify two type of discharge tips. The one for air discharge has a rounded shape more like the human finger, while the other, for contact discharge, is pointed. The other end of the storage capacitor (and the HV source) is connected to a discharge return terminal which in turn is connected to GRP via a "return" cable.

Now, the sharp rise time of the ESD wave-shape means that its spectrum can extend to about 1.5 GHz. In order to maintain proper ESD current wave shape as specified by the standard, the discharge return cable must provide low resistance at high frequencies. ESD simulator manufacturers typically achieve this by using a FRC cable whose individual wires are shorted at each end by using a steel plate. This design introduces "inductance compensation" allowing the cable to be used at high frequencies associated with the discharge. The ends are then connected to the gun and the GRP. The gun must have two modes of operation the "contact" and "air" discharge modes while it must also be capable of giving a single discharge at repetition rate of 1 pulse/sec and also continuous discharge at 20 pulses/sec for exploratory purpose.



**Fig. 5.32 : ESD Simulator/ Gun**

# 6

## RADIATED SUSCEPTIBILITY / IMMUNITY TESTING

### **6.1 INTRODUCTION**

An electronic equipment of today is constantly exposed to radiated EMI present in the environment, the more recent culprit being the ubiquitous mobile phone. Other "disturbers" include intentional radio frequency (RF) sources like walkie-talkies, radio/TV transmitters and RF sources used for purposes other than communication (like induction heating or medical diathermy). The equipment is also exposed to unintentional RF sources generated from SMPS, drives, arcing etc. It has therefore become imperative to test the equipment to radiated EMI in order to establish electromagnetic compatibility. Radiated susceptibility/immunity testing involves exposing the equipment to simulated magnetic or RF electromagnetic fields. In the former case it is called as magnetic field immunity and in the latter case it is called as RF electromagnetic field immunity. The amplitude and frequency range of the simulations are dictated by the standard being followed. The operation of the EUT is then monitored for degradation. The extent of allowable degradation (referred to as "performance criterion") is again dictated by the standard in question and allowable degradation depends upon operational reliability requirements.

### **6.2 GENERAL TEST SET-UP**

A typical test setup for carrying out radiated susceptibility/immunity testing is as shown in the Fig. 6.1 where the required simulation frequency is generated by a signal generator and amplified to the desired severity level by an RF amplifier. It is then fed to an antenna or a radiating system in order to generate the radiated field to which the EUT is exposed to. The most important requirement for radiated susceptibility/immunity test is a shielded enclosure, which contains the simulated field within a small area and does not allow it to escape. This is because many frequencies, especially those falling in the radio frequency region, cannot be generated in open, for example, for generating frequency used in

this condition and to extend the frequency range of GTEM up to tens of gigahertz, the characteristic construction of a square pyramid is used.

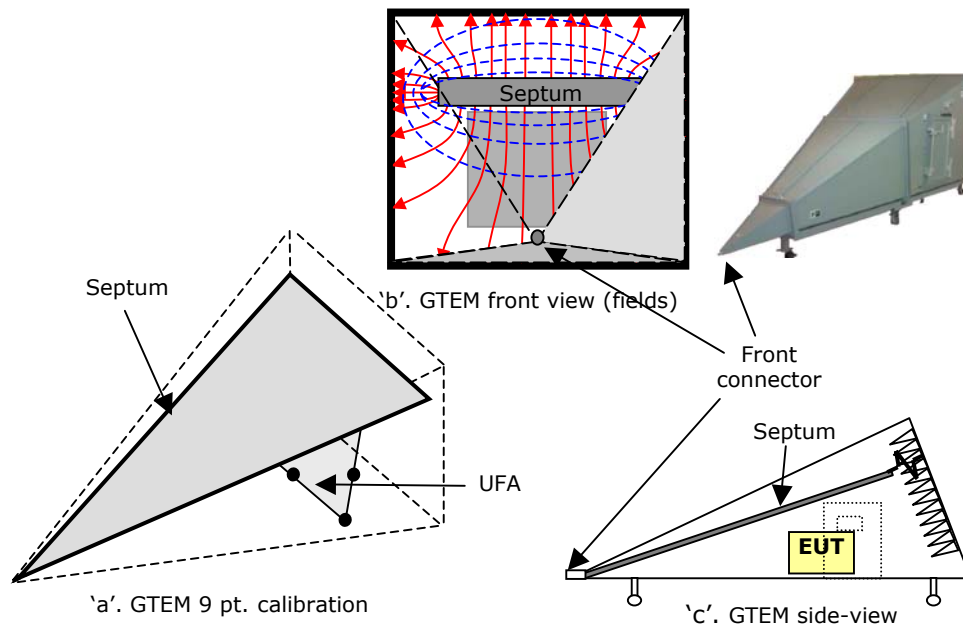


Fig. 6.4 : GTEM cell

### 6.10 MAGNETIC FIELD IMMUNITY TEST

This test verifies the immunity of the EUT against magnetic fields. IEC 61000-4-8 calls for power frequency magnetic field immunity tests which tests immunity of equipment to magnetic fields generated by power frequency currents flowing in nearby conductors under normal (long term) and fault condition (short term). The set up (Fig. 6.5) consists of a square loop of 1 meter diameter inside which the EUT is kept. The loop is fed by the required current, generated by a motorised variac (that takes supply from the AC mains) followed by current transformer, to produce a magnetic field at power frequency of 50Hz/60Hz. A standalone test system is available wherein the variac, the transformer and the controller are enclosed in a single box which has terminals for connections to the loop antenna. The standard specifies four levels viz 3A/m, 10 A/m, 30 A/m and 100 A/m for long duration test of 1 minute and two levels 300A/m and 1000A/m for short duration tests of 3 seconds. Since the loop is of 1 meter diameter, the field produced is equal to the current flowing through the loop. For example, to produce a 30 A/m field, current flowing through the loop should be 30 A. The EUT should be tested in all three orthogonal directions either by rotating the loop or the EUT. The EUT performance is monitored during the entire period of the test for degradation. The standard calls for calibrating the loop antenna with a loop sensor at regular intervals not exceeding one year.

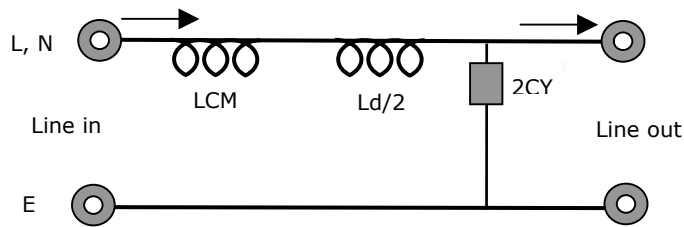
# 7

## **FILTERING**

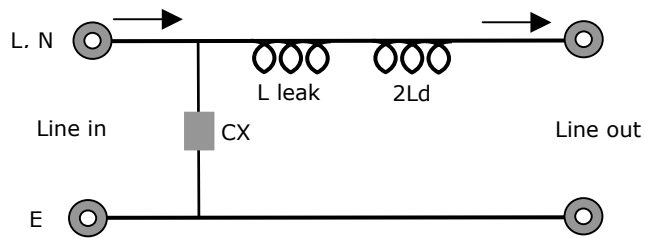
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### **7.1 INTRODUCTION**

In order to achieve electromagnetic compatibility, conducted emissions leaving an equipment via mains and/or I/O cables should be below certain limit and at the same time the equipment should have sufficient immunity against conducted EMI entering via these cables. Filtering is a method of attenuating conducted EMI that is entering or leaving the equipment through the power, signal and control lines by introducing line filters and other suppression components so that an equipment can comply with conducted emission and immunity tests as prescribed by EMC standards. EMI filters or line filters are referred to as EMI 'fixes' because these have to be 'added' to 'fix' the problem when other design strategies like cable routing, grounding, PCB design etc (that do not require additional components per se) are insufficient in controlling the conducted EMI. It is imperative to note that conducted EMI problems cannot be solved by proper designing alone, although this is the first line of defense. The right approach is to try and eliminate problems by proper design strategies first and resort to line filters only if problems still persist. This will put less stress on filter performance requirements and consequently reduce the cost burden of adding fixes. This approach is useful in case of equipment that incorporate components such as SMPS, DC-DC converters, drives, inverters, high power RF generators etc, which are known to be prolific emitters of EMI. Line filters are mostly of passive types although active filters are also employed for certain low frequency emission (such as reducing harmonics of line frequency). This chapter concentrates on passive filters used for reducing high frequency EMI (above 9kHz) on power mains (AC/DC) and data lines. For deciding component values for continuous wave EMI, two design approaches are discussed –one based on the frequency ranges over which various filter components operate and other based on actual measurement of conducted EMI and choosing component values to get the desired attenuation. Various measures and components for transient suppression are also discussed and so are filter mounting methods.



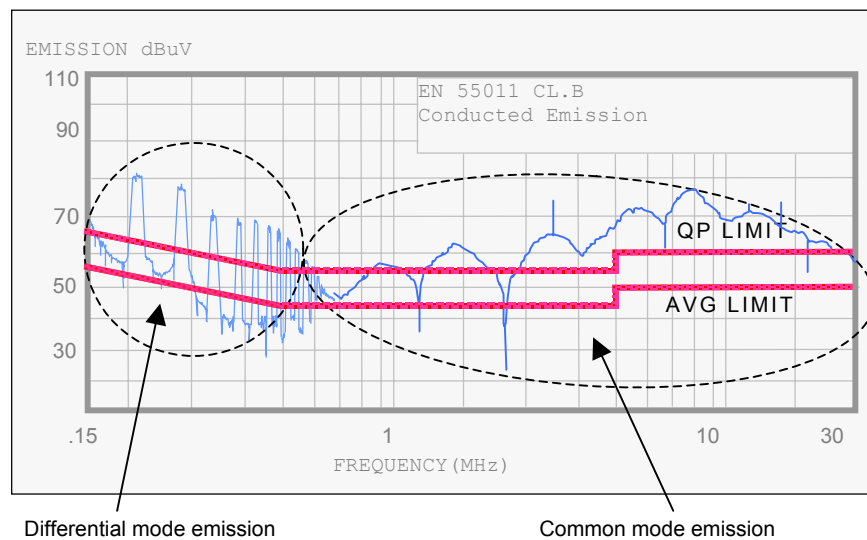
**Fig. 7.17 : Common mode equivalent circuit**



**Fig. 7.18 : Differential mode equivalent circuit**

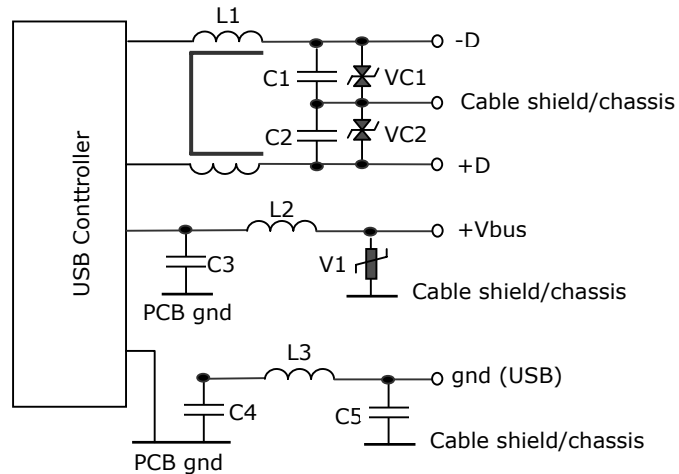
### 7.6.2 Filter design approach-1

This is the simplest approach based on the range of frequencies over which filter components act. A typical conducted emission graph is shown in the Fig. 7.19. It is seen that the conducted emissions are above the limit over almost the entire frequency range. The aim is to reduce the emissions so that they are below the average (AVG) limit.

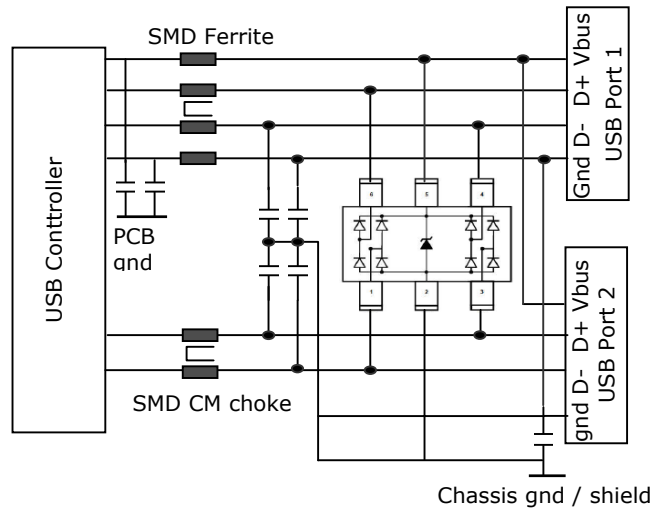


**Fig. 7.19 : Typical conducted emission graph**

in a range of rated voltages from 5 VDC to 24 VDC and clamping voltages ranging from 20V to 200V. This is followed by capacitors C1 and C2 (100nF MLCC) and SMD common mode choke L1 (of the order of 10  $\mu$ H) which attenuates the asymmetrical USB harmonics as well as conducted RF noise. The choke is bifilar wound and provides pure common mode inductance whereby the symmetric USB signals are not affected. The filter for Vbus consists of a SMD varistor V1, SMD chip bead ferrite L2 and MLCC capacitor C3 (100 nF) between cable and PCB ground. A similar filter on gnd line maintains isolation between the USB cable shield and PCB ground.



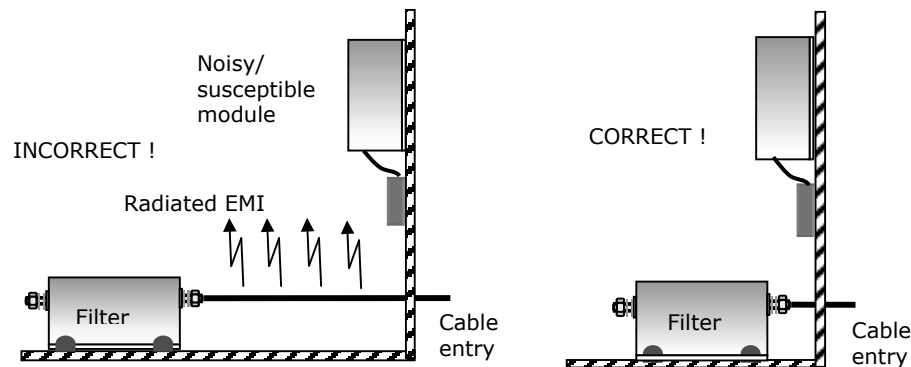
**Fig. 7.50 : Protection of USB ports with SMD varistors and ESD suppressors**



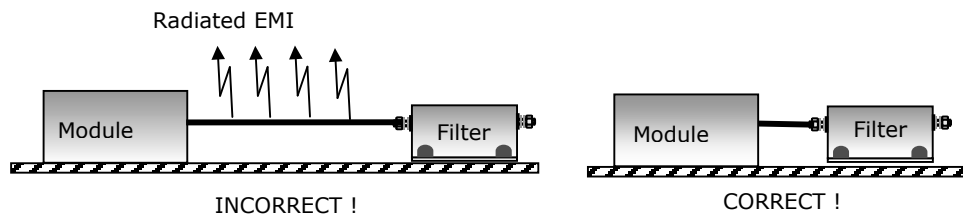
**Fig. 7.51 : Protection of two USB ports with TVS array**

Almost all of the commercial available filters come in a metallic box which is invariably not painted. During installation on a mounting plate in a typical control panel, the mating surfaces must be stripped off any nonconductive material like paint etc or an area slightly larger than the mating area should be masked during painting or powder coating process as shown in Fig. 7.59. The filter should then be firmly bonded using mounting screws, the bond should be tight allowing maximum 'surface' contact between the filter base and the mounting plate.

The location of filter inside a electronics panel or cabinet is crucial. Filters should be mounted precisely at that point where power mains enters the cabinet as shown in Fig. 7.60. This is to reduce exposed lengths of unfiltered mains which can radiate EMI and pollute the cabinet or radiations from modules within the cabinet may couple on to it. Similarly filters for individual modules should be mounted as close to the module as possible (Fig. 7.61)



**Fig. 7.60 : Filter position from mains entry**



**Fig. 7.61 : Filter position from module**

The separation between cables leading to the filter input and those coming from the filter output should be maximized. They should never be routed through the same conduit, they should not cross under any circumstances or even come near (Fig. 7.62). This is to avoid direct coupling of EMI from the input cable to the output cable via stray capacitance that is formed if the wires are near to each other or via the mutual inductance between the wires. This coupling bypasses the EMI rendering the filter ineffective.



# 8

## SHIELDING

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### 8.1 INTRODUCTION

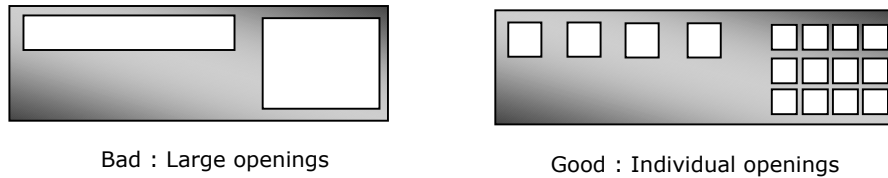
Shielding is a method of reducing radiated EMI entering or leaving a component, equipment or system. A typical shield works either way i.e. it reduces radiated emissions from an equipment and at the same time increases immunity by attenuating radiated EMI entering the equipment.

There are two ways for explaining the shielding mechanism, one is the circuit theory and the other is the field theory. We will consider the field theory approach essentially because shields are employed against radiated EMI and it is easier to understand radiation related concepts in terms of field theory. This theory of shielding tells how a wave or field behaves and interacts with different materials to yield a value of merit referred to as shielding effectiveness which is then used to gauge the attenuation of the field through the shield barrier material.

Shielding works partly by reflection, which is the result of mismatch between impedance of the wave and the impedance of the shielding material and partly by absorption suffered by the wave as it travels through the shield material. The more efficient the shielding material in providing impedance mismatch and absorption, the more is the shielding effectiveness. Metals are the best option for shielding material not only because they provide the sudden impedance discontinuity for a wave traveling through space or air but also because they provide good attenuation to high frequency waves. The second part of the previous sentence appears a bit confusing –metals are good conductors then how come they provide high attenuation to waves? Well, the answer is that metals (non magnetic ones) are good conductors only at DC or power frequencies (50/60Hz) where they are mostly resistive. However, as the frequency increases, inductive effect starts to manifest itself so that the resistance is now replaced by an impedance which progressively increases with frequency and therefore, high frequency waves find it more difficult to travel through the metal.

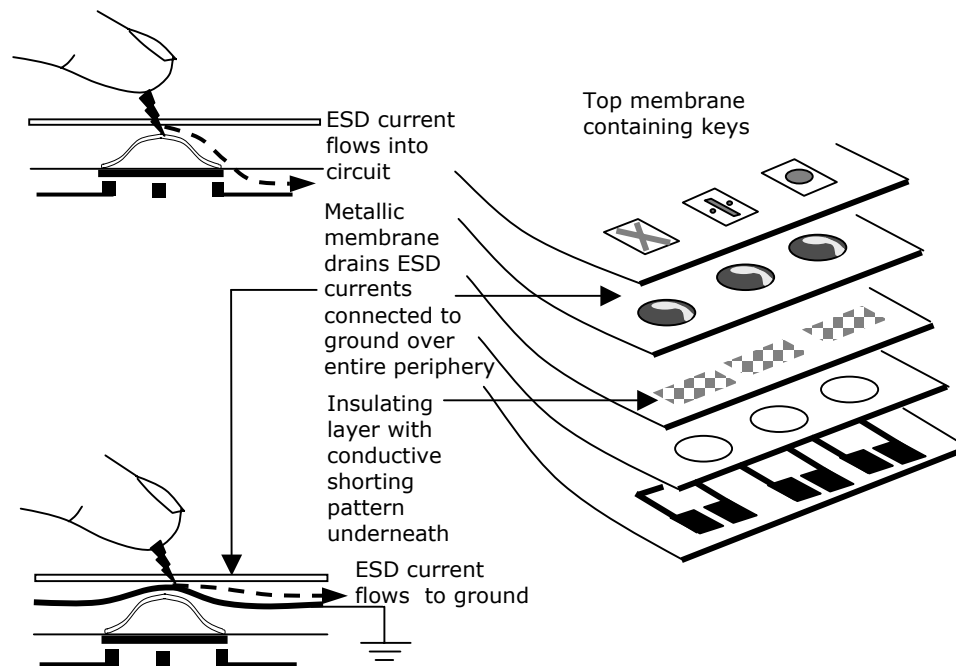
### 8.6.7 Keypad and Displays

This section deals with the methods of ensuring shielding over openings for keypads and displays. In case of metal cabinets, it is always better to use individual openings for keys instead of a large opening as shown in Fig. 8.17.



**Fig. 8.17 : Openings for keypad**

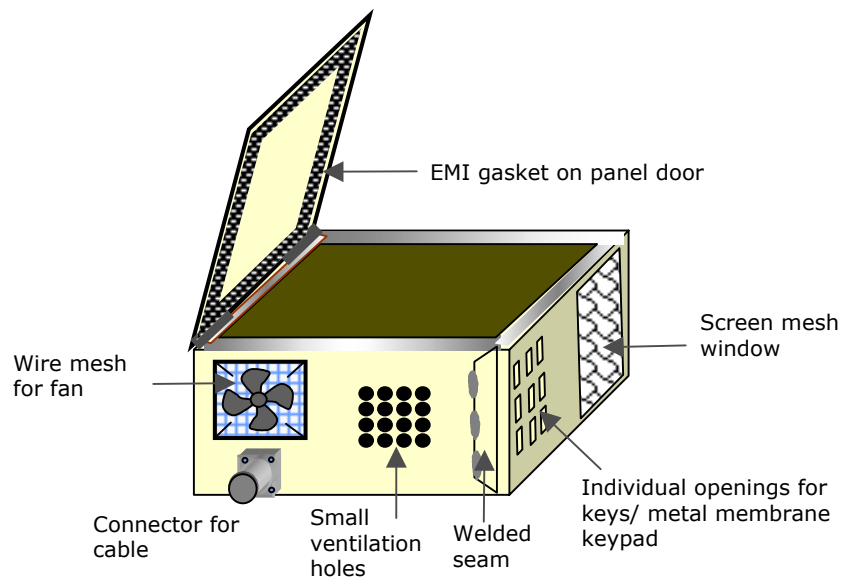
In case of non-metallic membrane type keypads, a metallic foil can be introduced between inner and outer membranes as shown in the Fig. 8.19 which not only shields against RF but also can bypass currents due ESD. This foil is brought out on all four edges of the keypad and connected to the chassis over its entire periphery which gives it a good 360 degree bonding to ground thus providing shielding integrity. Also, in the event of a static discharge, the current is diverted to ground by the foil (lower part of the Fig. 8.18) rather than going to sensitive circuit.



**Fig. 8.18 : Non-metallic keypad shielding**

**Fig. 8.19 : Layers of shielded keypad.**

mesh screen. Cable entry is via a circular bulkhead connector mounted on the chassis ensuring 360° contact. EMI gasket has been used for seams on the panel door .



**Fig. 8.33 : Shielding effectiveness over openings**

## 8.10 SHIELDING OF PLASTIC ENCLOSURES

Many electronic equipment today use plastic enclosures and to ensure shielding, these plastics must be made conductive. There are two ways of doing this either coating the plastic with a conductive material or using a conductive filler with the plastic resin prior to moulding so as to make the plastic conductive. The latter process is falling out of favour with the introduction of regulations on recycling of materials (like the WEEE regulation of the European Union) since conductive filled plastics are difficult to recycle. That leaves manufactures to use conductively-coated plastics but this has other issues, the most important one is to ensure that the coating remains firmly stuck to the plastic over at least the intended operational lifetime.

The conductive coating can be done using one of the methods like conductive paints, metal foil/ metallised fabric linings or metal deposition. Conductive paints can be applied to plastic surfaces which consists of a binder (acrylic or urethane) and a conductive pigment (silver, copper, nickel or graphite). A typical mixture may contain up to 80% pigment and 20% organic binder. This is the most inexpensive method as the paint can be applied with standard spray equipment and can provide good conductivity. A problem with some conductive paints is that they can flake off under mechanical pressure, or can rub off due to friction which can compromise reliability and increase safety risks. Accelerated lifecycle tests (temperature cycling condensation, salt spray, etc.) are often required to ensure that the conductive coatings don't crack or flake off over the anticipated life of the

# 9

## PCB DESIGN FOR EMC

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### 9.1 NEED FOR EMC DESIGN AT PCB LEVEL

In the world of electronic goods where margins are razor thin, manufacturers endeavour to keep product cost low to maintain a competitive edge. There is often a misconception amongst manufacturers that product cost can be kept low by using lowest cost components and so designers are constrained to achieve the desired function by using lowest cost PCBs and circuit components. Using EMC design techniques for PCB and selecting components with high levels of EMC is a luxury, they think, they cannot afford. Most are of the opinion that EMC measures at best can be put in place at the end of the project cycle, if at all it is found that they are really required (in case, for example, if the product fails to comply with EMC tests). Following this approach, it is not immediately obvious that the cost of these last – minute fixes (i.e. additional components for EMC protection which do not have any circuit function) incorporated without modifying original PCB design will in fact be many times the cost of EMC measures incorporated during PCB design in the initial stages of the product development cycle. So the approach of lowest BOM cost will actually result in considerable increase in product cost.

And if the problem is not solved by last minute fixes, the manufacturer is left with no choice but to go back to the drawing board and modify the PCB and product design. It can also be shown that the true cost of design modifications increases exponentially as one nears the end of the product development cycle. As shown in the Fig. 9.1, the cost of design modifications at the fag end of development cycle (say at product launch) can be 100 times higher than what it would be if the modifications were to be done at the start of the cycle (say at PCB layout).

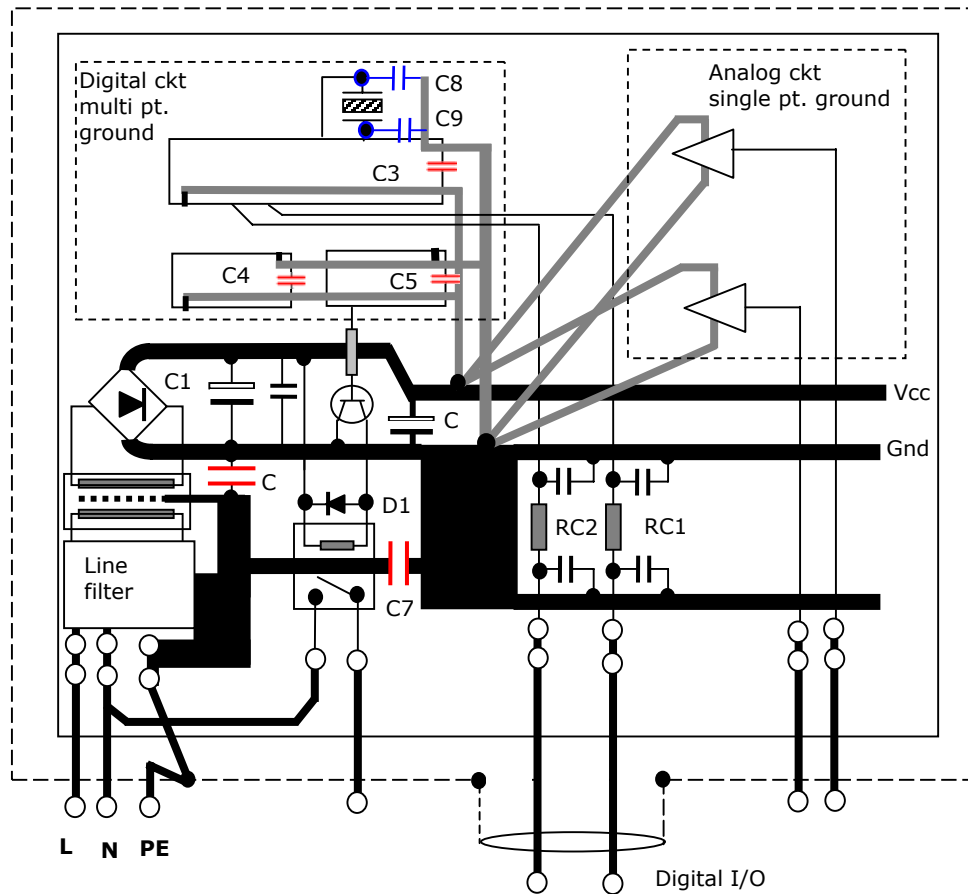
Another issue is of very short product lifetimes especially for products like mobile phone where product lifetimes may be as low as 90 days!. In such cases, if the time taken for design modifications for a particular model exceeds 90 days, there may be no market at all for that model which may result in loss of all investment for that particular project.

### 9.6.2 Entry of digital and analog inputs

RC filters (RC1 and RC2) have been used for digital input lines. LC filters like those discussed in chapter 8 can also be used for digital lines like USB, CAN or RS232. The free-wheeling diode D1 has been connected across relay coil, to short circuit the back EMF generated by the coil and to reduce subsequent emissions.

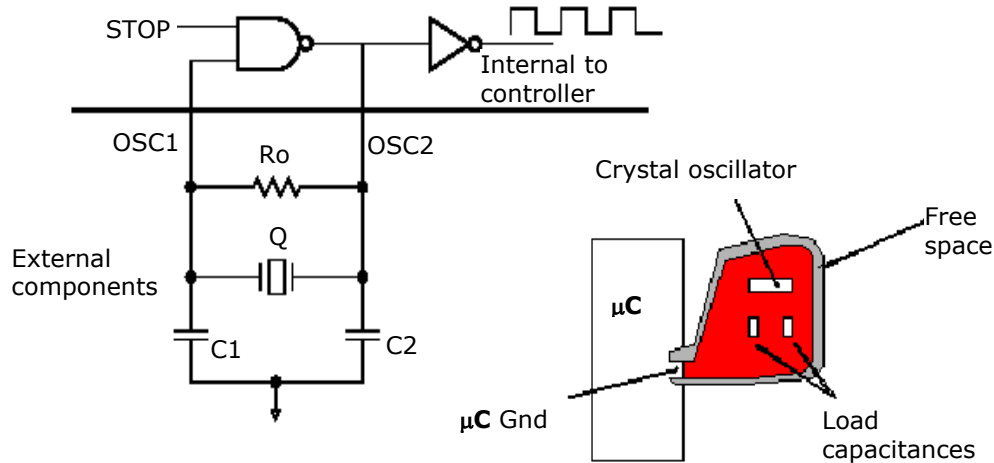
### 9.6.3 Bypass capacitors

Conducted RF disturbances such as burst pulses are generated during switching operations which couple to the signal and mains lines mostly in the common mode. If the ground is left floating, the supply lines spread the disturbances inside the device. To remove the disturbances, bypass capacitors (1 to 100 nF) C6 and C7 have been connected near the rectifier between the ground and earth which provides a low resistance path for ground referenced bursts to earth.



**Fig. 9.18 : PCB general considerations**

oscillator is designed as a bubble with free space between this bubble and rest of the tracks. The crystal is thus embedded in a ground moat. The load capacitance of the oscillator is directly connected to the GND pin of the processor. Using this method, the quartz oscillations are not spread unnecessarily in the circuit. In the Fig. 9.18, this idea is incorporated for crystal and its load capacitors i.e. C8 and C9 which are connected to IC ground first and then to circuit ground.



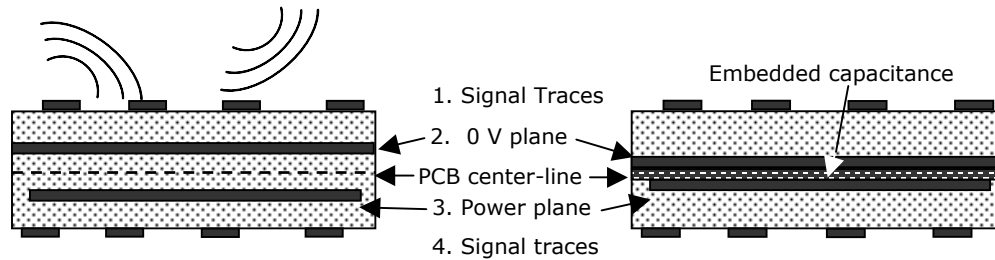
**Fig. 9.20 : Oscillator crystal mounting**

## 9.7 MULTILAYER BOARD AND HIGH SPEED PCB DESIGN

Up till now we have seen PCB design issues related to single and double layer boards. We have also discussed how ground track impedance can be reduced by judicious design of ground system and PCB layout. The reader may have realized by now that by having ground planes, the ground impedance can be reduced drastically solving many EMI and signal integrity issues. Now, for having an entire layer as ground, we have no option but to use a multilayer board where we could have a separate plane for power as well and separate layers for signal tracks. Multilayer board helps the PCB designer to push the envelope further and to overcome such design challenges (especially in case of high speed design) which he could only dream of using a normal single or two layer board.

Multilayer board is a PCB having separate layers for power, ground and circuit tracks. It facilitates use of entire copper layers for power and ground connections called power planes and ground planes respectively. This decreases their inductance and impedance allowing the use of high clock and signal frequencies and reducing ground noise. Integral ground and power planes also reduce the number of signal returns and all but eliminate power conductors, enabling the designer to reduce the size of various circuits on the board as well as its overall size. This is especially important in reducing propagation delay, keeping loop areas small, and minimizing the size of PCB – mounted shields. The ground plane also makes it possible to route signals in transmission line configuration either as microstrip or stripline with much less radiation than random traces used in two layer

traditional stacking in a four layer board where the layers are spaced equally. The ground and power planes (layer 2 and 3) are sandwiched between signal layers (layer 1 and 2).

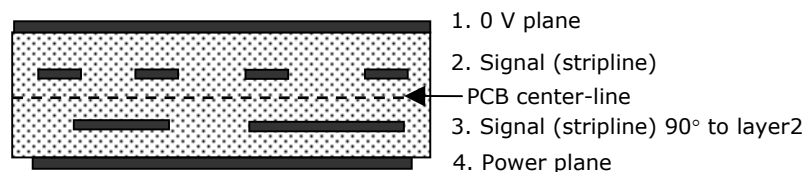


**Fig. 9.43 : Micro-strip configuration**

This type of distribution is called as a microstrip distribution and provides excellent decoupling capacitance between power and ground planes since they are located close together. This along with reduced inductance provides a 20 – 30 dB improvement for emission and susceptibility over the two layer board. However since the traces are on the outside of the board, there exists potential emission and susceptibility problems which may require, in some cases, the use of shielding cans (see section 9.24). Some variations of this stacking exist, one being unequal spacing (Fig. 9.43 'b') where the power and 0V planes are placed right at the center line of the PCB separated by an embedded capacitance which gives far better power supply decoupling and decaps may not be required at all. But now the tracks are located far away from the planes increasing the loop area between forward and return currents and degrading their EMC characteristics.

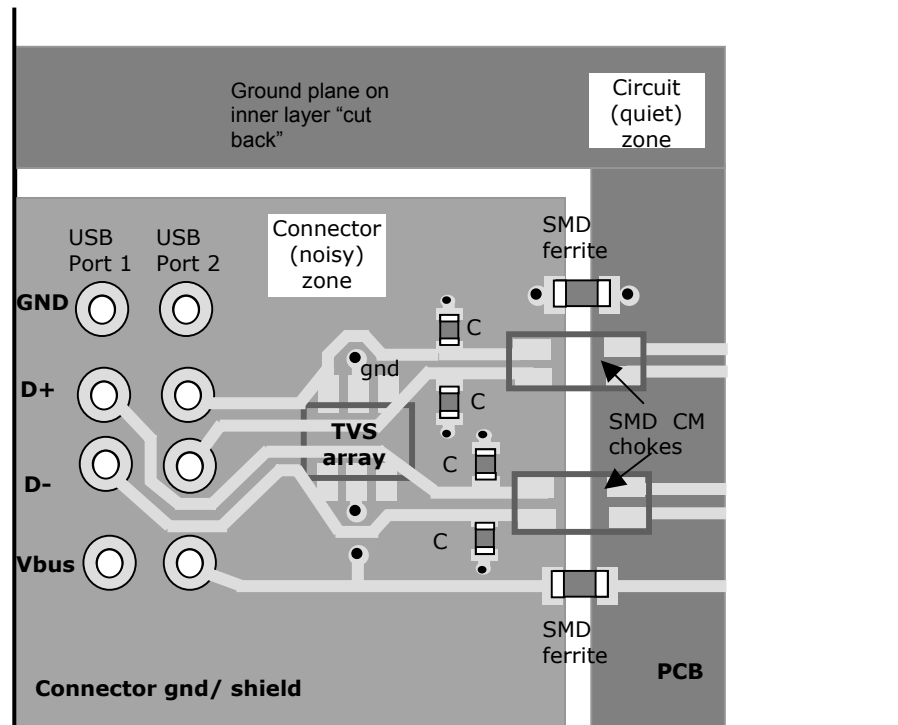
In another variation using unequal spacing, the power and 0V planes are located closer to the surface of the PCB away from center line. Now the loop area between forward and return currents is drastically reduced, giving better EMC performance but poor power supply decoupling. This method can be used in severe EMC environments and decoupling problems are taken care by other means (like larger decaps).

To reduce potential emission and susceptibility problems of microstrip distribution power and ground planes can be placed on the outside, while the signal traces are sandwiched between the two, the layers being equally spaced. Such type of distribution is called as stripline distribution. As shown in Fig. 9.44, the signal traces on layer 2 and 3 are very close and are oriented perpendicular to each other (for reducing cross talk).



**Fig. 9.44 : Stripline configuration**

capacitor is common to the current loops on the connector side and on the circuit side and the associated magnetic field coupling will degrade filter performance. To reduce this coupling, the capacitor is split into two half value capacitors (shown in the Fig. 9.54 'b' as C1 and C2), providing some isolation between the two loops. Tee filters are also available as single component as a three terminal device where the two ferrites and the capacitor is integrated into a single component with a central terminal. When these are used they should be mounted as shown in the Fig. 9.53 'c' where the center terminal has been soldered directly on a guard trace connected to ground plane by equally spaced vias with two vias on either side of the center terminal. The Fig. 9.55 shows layout implementation of a USB filter for a double USB connector as described in section 7.12 chapter 7.



**Fig. 9.55 : Double USB filter layout**

The circuit or quiet ground plane on layer 2 has been cut back and segregated from the noisy USB connector ground plane on which the USB shield has been terminated. The noisy shield ground is bonded to the PCB chassis. If the circuit ground needs to be connected to the shield ground it should be done only at one point either directly or through a suitable inductor which maintains high frequency isolation. The two grounds have been bridged by the CM choke for D+ and D - lines and chip ferrite beads for Vbus and USB gnd. It should be ensured that no track crosses the segregated grounds on layer 1. The situation still be improved by shielding the connector zone by suitable shielding can, - a method described in next section.



# **10**

## **GROUNDING AND BONDING**

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### **10.1 INTRODUCTION**

Most of the EMI suppression methods, in one way or the other, use two basic techniques –filtering for conducted EMI and shielding against radiated EMI. The common mode interference currents in a typical power line filter are bypassed by the Y-capacitors, the effectiveness of which depends on a low resistance connection to earth. Similarly the radiated electromagnetic noise impinging on a shield induces currents in the shield. The shielding is effective only if these currents are siphoned off to earth effectively. A low resistance connection to earth is therefore required if any of the interference suppression methods are to work properly.

Now grounding can be defined as "a connection, whether intentional or accidental, between an electrical circuit or equipment and the earth or to some conducting body that serves in place of the earth".

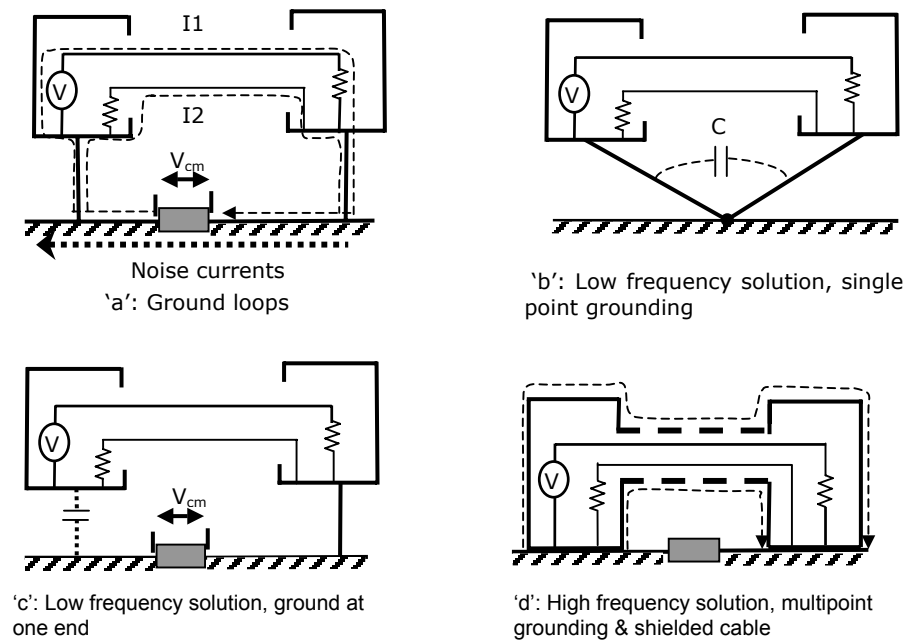
Hence one can conclude that grounding is nothing but connection to earth or to a conductor that serves as earth. Going by this definition, a connection between a circuit and its zero volt reference can also be considered as grounding while earthing can be considered as a case of grounding where the ground is essentially the planet Earth. On the other hand, bonding is defined as "a permanent joining of metallic parts to form an electrically conductive path that not only ensures electrical continuity but also has the capacity to conduct safely any current imposed on the joint". Thus bonding is that means which serves to give a "low resistance connection to earth" which is an essential part of a good ground.

### **10.2 PURPOSE OF GROUNDING**

The primary aim of grounding, as we all know, is to prevent shock hazard that exists in a high voltage distribution system. Other functions include power fault clear-out, protection against lightning and electrostatic discharge hazards and protection against EMI. Lets us take a look at all these one by one.

## 10.6 REDUCING GROUND IMPEDANCE COUPLING

As we have seen earlier, due to improper grounding and bonding or due to improper grounding practices, the ground impedance tends to increase. This has been shown as a lumped impedance in the Fig. 10.5'a'.



**Fig. 10.5 : Reducing ground impedance coupling**

EMI currents flowing through this impedance cause a voltage drop ' $V_{cm}$ ' across it, which forces common mode EMI currents  $I_1$  and  $I_2$  through the circuit. The first way is to eliminate this common impedance completely by grounding the modules at a single point as shown in Fig. 10.5 'b'. The second option is, opening the ground loop by grounding only one of the modules (Fig. 10.5 'c'). But these hold good only at low frequencies up to a few tens of kilohertz, where this impedance behaves only as a resistance. At higher frequencies, stray capacitance ' $C$ ' (shown dotted) begins to appear between grounding cables or between the module and the ground, causing common mode currents to circulate again. Also, at higher frequencies the ground wires themselves start offering high impedance since their inductive reactance and resistance due to skin effect start to increase, causing potential gradients along the wire. At high frequencies therefore, efforts should be directed towards reducing ground impedance which in turn can be reduced first by reducing the inductance i.e. replacing the wires by a metal sheet (a mounting plate) and then to reduce the value of ground resistance by proper grounding and bonding practices. Also interconnecting cables should be shielded so that the common mode EMI currents now flow (see Fig. 10.5d) on the outside of the shield reducing common mode coupling.

# **11**

## **CABLE SELECTION AND ROUTING**

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### **11.1 INTRODUCTION**

An electronic equipment manufacturer may take all measures for EMC discussed until now. He may select modules and components that are fully compliant to EMC norms. He may also employ such EMI fixes as filters, transient protection devices, EMI gaskets etc. He may also mount devices and fixes correctly by employing proper grounding and bonding. But if he does not pay attention to the cables that feed these modules especially as regards to their selection, segregation and routing, he may miss the plot altogether. His system may be rendered non-compliant despite his sincere efforts.

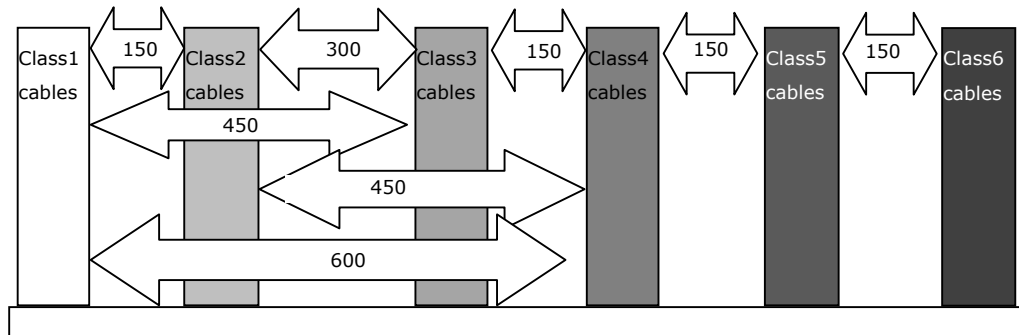
It is frequently observed, and more so with those who design and manufacture electronic control panels, that the overall system often fails to pass EMC tests (particularly emissions) even though the manufacturer has meticulously taken all precautions to ensure product compliance, just because he forgot one crucial aspect of EMC design that of cable routing and selection. And as the old saying goes "all is well...that ends well" so proper cable selection and routing is the last major design consideration to make a system complaint to EMC norms. To complete the EMC design process therefore, one has to select the correct cable type i.e shielded or unshielded, armoured or un-protected, balance or unbalanced, single core or multi-core, twisted or un-twisted etc depending upon the frequency of operation, voltage and current levels, type of loads and length of cable runs. After identifying the cable type, attention has to be given to the grouping or segregation of cables to avoid interference between various type of circuits. Thirdly, various cables and cable groups have to be properly routed to so as to minimize cable-to-cable and cable-to-component coupling.

### **11.2 CABLE COUPLING MECHANISMS**

In chapter one we had seen three different cable coupling mechanisms. Firstly , field-to-cable common mode coupling (section 1.9.2.5) which occurs when wires or traces

should be 150mm. Now these distances are for a cable run of less than 30 metres. For longer cables, the separation distance is multiplied by the length and divided by 30.

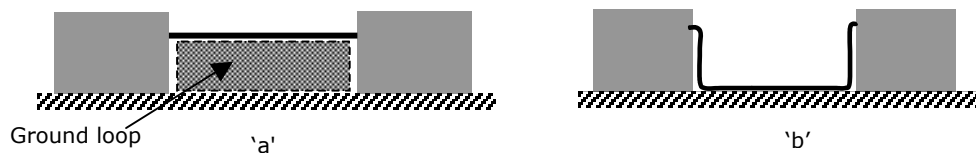
When cables run within a product, they must be physically segregated depending upon their class at all times, long parallel runs should be avoided and if it is not possible they should be more than 150mm apart, cable classes as far as possible must not cross or if at all they have to, they should do so at right angles and the cables should run as close as possible to their local RF reference or to cables carrying return signals. Cables of the same class when routed through the same tray or duct should not be twisted around one another.



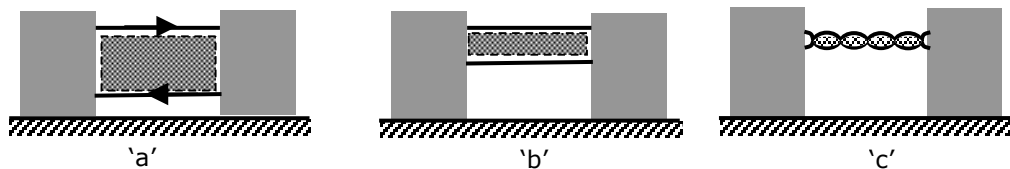
**Fig. 11.1: Cable classes (dimensions in mm)**

## 11.6 REDUCING COMMON MODE (CM) COUPLING

When cables are routed away from the ground plane or earth, a ground loop is formed as shown in Fig. 11.2. This loop acts as an antenna for stray fields causing common mode EMI to be coupled into the system and by the same token, the loop can also cause radiated emission. The coupling or radiation is directly proportional to the area of the loop and in order to reduce this, the area of the loop must be reduced. This is done by routing the cable as close as possible to the ground reference which, in case of control panels, is the mounting plate.



**Fig. 11.2 : Reducing CM coupling**



**Fig. 11.3: Reducing DM coupling**

# 12

## CE MARKING

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### 12.1 INTRODUCTION

"CE" is the French acronym of "Conformite Europeenne". In English it stands for "European Conformity" i.e. conformity of a product to European laws / standards / norms. It is a mandatory compliance marking printed on all products intended to be placed in the European Union (EU). It consists of the label "CE" printed on the product (or its nameplate) as a visible proof indicating that the product meets all health and safety requirements by conforming to applicable EU directives (read laws). Once a product bears the CE marking, it is free to enter and move freely within the EU and hence many people consider CE marking as a "visa" to the EU.

### 12.2 THE EUROPEAN UNION BACKGROUND

The EU treaty or the Maastricht treaty was signed in 1991 between fifteen nations of the European region. The objective was to establish a common internal market without boundaries which will ensure the four freedoms i.e. free movement of goods, persons, services and capital. During the formation of the EU, it was realized that differing national laws will lead to barriers in trade which can be removed if only one law is applicable over the EU. This process of harmonisation (i.e. the same law for all member states) is one of the basic foundations of the EU.

In the year 1994, three members of the erstwhile EFTA (European free trade agreement) namely Iceland, Liechtenstein and Norway joined the EU to form the European Economic Area (EEA) often referred to as the "community market". Starting from fifteen nations, the EU membership has now grown to twenty-eight (at the time of writing this book) and the number is expected to rise. The CE marking is not only mandatory over twenty-eight EU nations but also over Iceland, Liechtenstein and Norway. Switzerland and Turkey are presently not a part of the EU, but have implemented the EU directives and as such the CE marking is required by these countries as well.