EE XXX: Electromagnetic Interference and Compatibility- part-2

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    7.2 Units of radiation measurement
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References Material

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Course Syllabus:

BASIC THEORY

Introduction to **Course** EMI and EMC, Intra and inter system EMI, Elements of Interference, Sources and Victims of EMI, Conducted and Radiated EMI emission and susceptibility, Case Histories, Radiation hazards to humans, Various issues of EMC, EMC Testing categories, EMC Engineering Application.

COUPLING MECHANISM

Electromagnetic field sources and Coupling paths, Coupling via the supply network, Common mode coupling, Differential mode coupling, Impedance coupling, Inductive and Capacitive coupling, Radiative coupling, Ground loop coupling, Cable related emissions and coupling, Transient sources, Automotive transients. Categorization of the electromagnetic interference: emission, susceptibility, transients, crosstalk, shielding and compatibility, signal integrity.

EMI MITIGATION TECHNIQUES

Working principle of Shielding and Murphy‟s Law, LF Magnetic shielding, Apertures and shielding effectiveness, Choice of Materials for H, E, and free space fields, Gasketting and sealing, PCB Level shielding, Principle of Grounding, Isolated grounds, Grounding strategies for Large systems, Grounding for mixed signal systems, Filter types and operation, Surge protection devices, Transient protection.

STANDARDS AND REGULATION

Need for Standards, Generic/General Standards for Residential and Industrial environment, Basic Standards, Product Standards, National and International EMI Standardizing Organizations; IEC, ANSI, FCC, AS/NZS, CISPR, BSI, CENELEC, ACEC. Electro Magnetic Emission and susceptibility standards and specifications, MIL461E Standards.

Test Set-ups, units (e.g. dBμV$m^{-1}$$Hz^{-1}$), Antenna facture etc.

EMI TEST METHODS AND INSTRUMENTATION

Fundamental considerations, EMI Shielding effectiveness tests, Open field test, TEM cell for immunity test, Shielded chamber , Shielded anechoic chamber, EMI test receivers, Spectrum analyzer, EMI test wave simulators, EMI coupling networks, Line impedance stabilization networks, Feed through capacitors, Antennas, Current probes, MIL -STD test methods, Civilian STD test methods.

BASICS OF BIOLOGICAL EFFECTS OF EM WAVES

Mechanism of interaction of EM waves with live tissue, Ionizing and non-ionizing radiation And their effects, Measurement techniques of EM radiation.

List of Symbols and Abbreviations

Symbols

ε **:** Permittivity
θ **:** Angle of elevation, angle
λ : Wavelength
μ **:** Permeability
ν : Frequency (especially in the context of photon energy)
ϕ **:** Azimuth angle
σ : Target Cross section
τ **:** Pulse width
ω **:** Angular frequency
c : Velocity of electromagnetic waves

Abbreviations

AF **:** Antenna Factor
DUT : Device under Test (Some literature refers it as times called **EUT**: Equipment under test)
EM **:** Electromagnetic (waves, energy, radiation)
EMI : Electromagnetic interference
EMC : Electromagnetic Compatibility
EMICP **:** Electromagnetic Interference Control Procedure
EMITP **:** Electromagnetic Interference Test Procedure
EMP **:** Electromagnetic Pulse
ERP **:** Effective Radiated Power
ESD **:** Electrostatic Discharge
IF : Intermediate Frequency
FFT : Fast Fourier Transform
FM : Frequency modulation
MoSFET **:** Metal Oxide semiconductor Field Effect Transistor
IGBT : Insulated gate bipolar transistor.
NF, F_n **:** Noise Figure
PCB : Printed Circuit board(s); they are also referred as ‘printed wiring boards’
RBW : Resolution bandwidth
RF : Radio Frequency
RMS : Root Mean Squared
SNR : Signal to Noise Ratio

Chapter-3

Designing for the Compliance to CE and CS

In earlier chapters we have understood the conducted emissions. The certifications tests for conducted emission and susceptibility are presented in section 2.3. It is also clear that 'electromagnetically compliant' equipment need to clear these (or equivalent) tests. In modern days, electromagnetically compliant (to their working environment) are preferred or have commercial advantage. For strategic applications and in some market segment EMC has become mandatory. Therefore, the technology developers and electronic equipment designers should make the units/ equipment compliant to the intended working environment.

It makes sense to address the 'electromagnetic compatibility' right at the design stage. Most of the technological professionals have already included 'electromagnetic compatibility' as the key point in their "standard operating procedure (SOP). Typical electronic products are expected to operate in varied kinds of operating environment. It is not practical to study or quantify the environment in terms of electromagnetic fields and currents and 'tune' the equipment for the compatibility. Fortunately this job is done by numerous experts and they have formed the EMC test specifications!! In other words, the compliance to the EMC specifications 'automatically guarantees 'electromagnetically successful' product. In this view, a designer must provide to pass the relevant EMC tests successfully!

This chapter provides a discussion on the conducted EMI.

3.1 Generating Mechanism of Conducted Emissions

In simple terms the 'conducted EMI' is defined as fluctuations of the current in power as well as signal lines.

We have electrical/ electronic systems working on alternating currents (AC), at frequencies of 50Hs, 60 Hz, 400 Hz etc. or DC currents. On AC power lines, current (or voltage) variation at other than the supply frequencies is considered as EMI. Similarly on DC lines current (or voltage) variation of any frequency is considered as EMI. These variations are termed as 'ripple', 'harmonics' etc.

On signal lines any variation (voltage/ current) other than the signal is termed as EMI. They are referred as noise, distortions for analog signals and, dispersion, rise-time/ fall time, droop etc for the digital signals. what is EMi

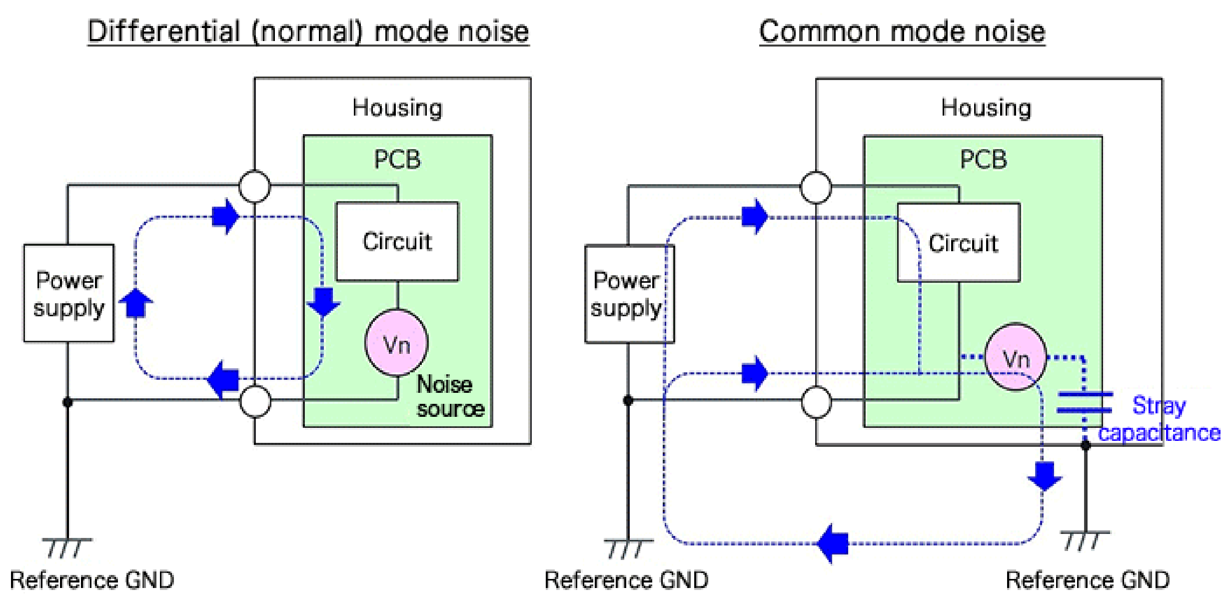
The supply as well as signal lines generally operate with two conductor-lines or a pair of lines. These lines are generally referred as 'signal or supply' and 'return'. For 3-phase supply, there are 3 or 4 line systems. In that case the supply and return is collective and distributed in time. The disturbances on the system with 'signal-return' topology can be classified in two types. Fig. 3.1 present a simple diagram explaining the common mode and differential mode noise/ disturbance.

(a) **Differential mode disturbance**: In this type, the direction of variations in signal line and the return line are in opposite direction. This means that when the current in signal flows towards the load (say) the current in the return line shall flow towards the source, see Fig.3.1 (a). It can be visualized as follows.

Consider a circuit operates with a constant load. In this situation, the current and voltage values will be steady. For both AC and DC supply, the relation could be defined by the Ohm's law➔ $V=I\ X\ Z$. Now, the load changes to a new value Z' ($Z'>Z$). The current, towards the load, in the supply path decrease increases and the current, towards the source, increases in the return path. Thus the variations of differential mode happen due to the '**change in the load impedance'** of the system or the DUT.

(b) **Common mode disturbance**: In this type, the direction of variations in signal line and the return line are in the same direction. This means that when the current in signal flows towards the load (say) the current in the return line shall also flow towards the load, see Fig.3.1 (b). It can be visualized as follows.

Consider a circuit operates with a constant load. In this situation, the current and voltage values will be steady. For both AC and DC supply, the relation could be defined by the Ohm's law $V=I\ X\ Z$. Now, external electric (or magnetic) field is induced on the supply line. That leads to increase of current to I', towards the load. The return line being placed near the supply line and has similar influence of external electric field. It also has an increase of current to I', towards the load. This change is in the same direction for the supply as well as return line. Thus the variations of common mode happen due to '**external electromagnetic influence'**. This external source could be other part of the circuitry in the same system; e.g transmitter influencing the data communication sub-system.



(a) (b)

Fig. 3.1 Concept diagram of (a) Differential mode noise and (b) common mode noise

Fig. 3.1 models this variation by introducing a voltage source. This disturbance could also be modelled using current source. It may be noted that in differential mode, the 'noise/ disturbance source, V_n' is in the circuit of the DUT. On the other hand, V_n appears between the circuit and a common reference (say, Ground). We shall identify the sources of these disturbances:

(i) Sources of differential mode disturbances:
- Oscillators
- Switched mode power supplies
- Control switching in the power electronic circuitry
- Zener, rectifying and modulating diodes
- Information transmission on the control and data bus

(ii) Sources of common mode disturbances: operating in vicinity
- Presence of power transmission lines.
- Electrical activity; e.g. start-stop of high power loads like motors, furnaces etc.
- Natural activities like lightening, weather changes etc
- Fluorescent lamps, fan regulators, ignition / cranking of the vehicles

3.2 Quantification Conducted EMI

The differential current fluctuations due the variation in load impedance can be explained by following example. Consider a simple relay driver circuit as shown in Fig. 3.2(a). This circuit shows that the relay coil is switched using BC 109 (it is not a good choice, 2N 2222is better!). However, we assume that BC 109 is an ideal switch and relay coil current is 20 mA. We assume that the relay is switched at 50 Hz with duty cycle of 10%. Neglecting other currents, it is possible to compute the current waveform on the DC supply lines and the frequency components generated by the same.

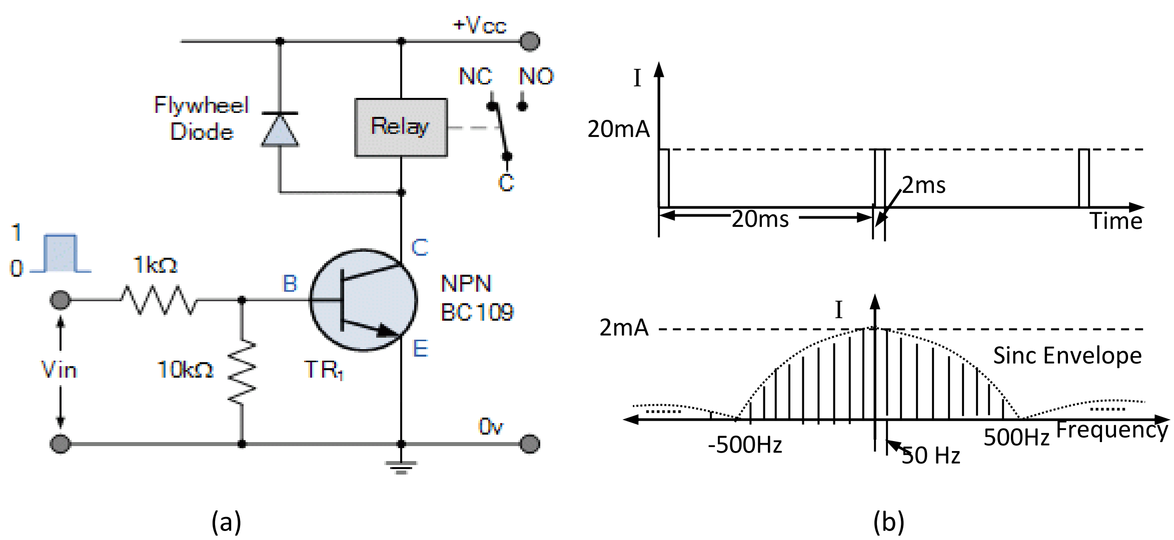


Fig. 3.2 (a) Typical Relay driver circuit (b) Current switching and frequency components

From the above exercise it is possible to relate the frequency components generated by the switching action in the DUT. A designer is expected to compare these frequency components with the allowable conducted radiation according to the applicable standards.

As an example we compare the EMI levels in this experiment with the CE 101 limits as given in Fig. 2.24. At 50 Hz, the limit is 95 dBμA= 56.234 mA. The component generated by this experiment is well below the limit. However, if the switched current was 2A, the 50 Hz component would be 200mA approximately. In that situation the a filter to supress the current variation would be required.

The current fluctuations also give rise to radiated EMI. The computation of the radiated field can be done as given in following example. Fig. 3.3 shows the electric field generated at a distance 'r' due to the communication signal through a cable of length 'L'.

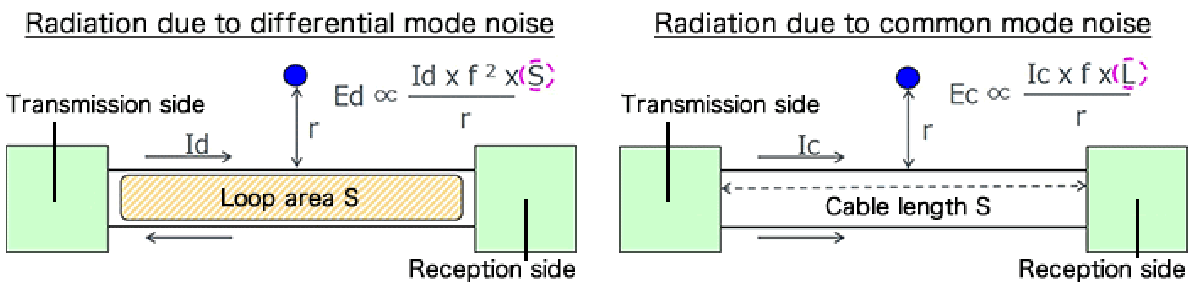
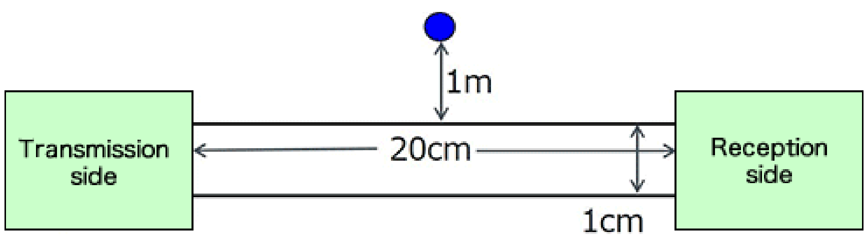


Fig. 3.3 (a) Electric field by the differential mode EMI (b) Electric field due common mode EMI

The calculations for the same can be done with reference to an example shown in Fig. 3.4. RE 102 limit as shown in Fig 2.33 at 100 MHz is 24 dBμV/m= 15.84 μV/m. It can be seen that the differential mode conducted EMI is below the limit whereas the common mode EMI is above the limit. Therefore, in order to qualify for RE 102, the common mode EMI must be supressed using appropriate filter or technique.



Differential mode noise

For a 100 MHz differential mode noise current of 1 μA flowing in a loop of area 20 cm^2

The value of the electric field intensity at a distance of 1 m (90°) is:

$$Ed = 1.316 \times 10^{-14} \times \frac{Id \times f^2 \times S}{r}$$

$$= 1.316 \times 10^{-14} \times \frac{1\mu A \times (100MHz)^2 \times (0.2 \times 0.01)}{1}$$

$$= \mathbf{0.26\mu V/m}$$

Common mode noise

For a 100 MHz common mode noise current of 1 μA flowing in a 20 m cable

The value of the electric field intensity at a distance of 1 m (90°) is:

$$Ec = 1.257 \times 10^{-6} \times \frac{Ic \times f \times L}{r}$$

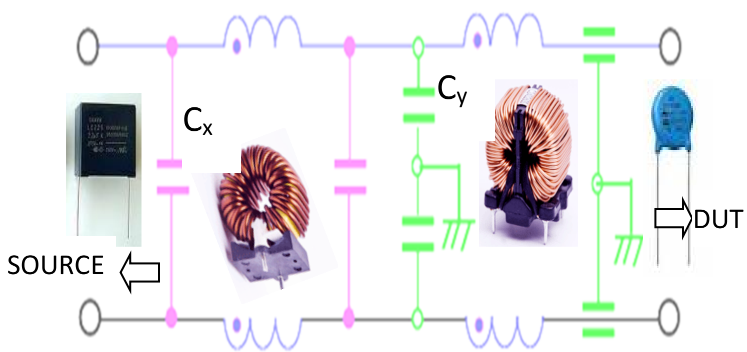
$$= 1.257 \times 10^{-6} \times \frac{1\mu A \times 100MHz \times 0.2}{1}$$

$$= \mathbf{25.1\mu V/m}$$

Fig. 3.4 Computations of the electric field generated by the conducted EMI
Source: https://micro.rohm.com/en/techweb/knowledge/emc/s-emc/01-s-emc/6899

3.3 Techniques to Reduce Conducted Emissions

Conducted EMI could be supressed by using appropriate filters. We have seen that the emissions can take place in two modes; Common mode and differential mode. We look at the classical filter topologies. Fig. 3.5 shows both the common mode and differential mode filters incorporated on a system. It is easy to appreciate that the common mode (CM) filter inductor has both the windings running together. As a result the current in power/ signal path and the return path opposes each other and attenuate the CM emissions. On the other hand the 'differential mode (DM) filter' or 'normal mode choke' can be realized as a single inductor, see 3.5 (b) lower sketch or in two winding configuration as shown in see 3.5 (b) upper sketch. In this configuration, it has one winding each in signal path and return path. Fig. 3.6 illustrates this concept.



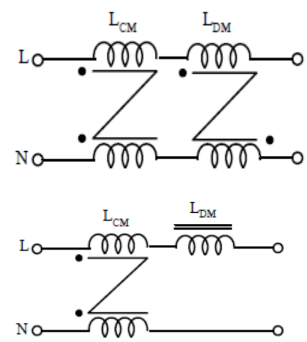


Fig. 3.5 (a) Filter schematic with picture (b) Connection schematic of CM and DM transformers

In addition to the windings, the filters consist of capacitors connected as shown in Fig. 3.5. The value of the inductors and the capacitors could be calculated by standard 'π-filter' computations.

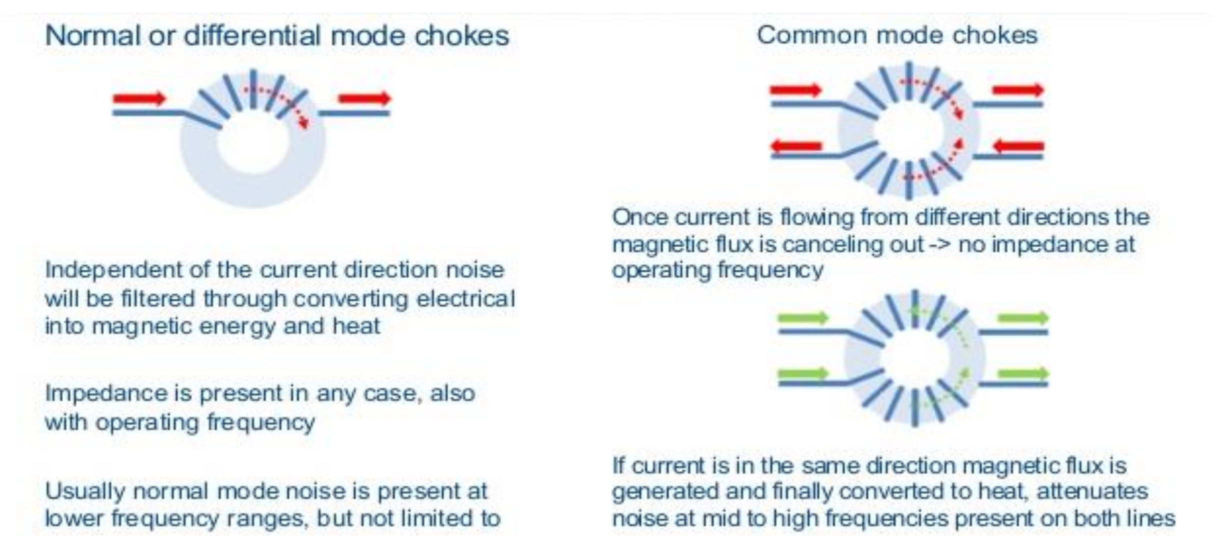


Fig. 3.6 Description of operating mechanism of DM mode and CM filters

3.3.1: Selection of correct capacitor

The capacitors of appropriate class/ safety type (X or Y) must be used for EMI filter applications. In order for these capacitors to perform their EMI/RFI filtering tasks, they are directly connected to the AC power input, that is, the AC “line” and the AC “neutral” (or DC+ve and DC-Ve) see Fig. 3.5. And because of this direct connection to the AC voltage, the capacitors may be subjected to over voltages and/or voltage transients—lightning strikes, power surges. Thus, capacitor failure is a very real possibility.

Class-X capacitor, also referred to as an "across the line capacitor". If this capacitor fails (due to overvoltage or transients, it is likely to fail-‘short’. This failure, in turn, would cause an overcurrent protective device, like a fuse or circuit breaker, to open. Therefore, a capacitor failing in this fashion would not cause any electrical shock hazards.

Class-Y capacitor, also known as the "line to ground capacitor" or "the line bypass capacitor", is placed between the line and ground. Class-Y safety capacitors are designed to fail open. A failure will cause the DUT to be subjected to the noise and interference that the capacitor would normally filter out, but there will be no fatal electric shock hazard.

There are subclasses of the X and Y-type capacitors as given in Table 3.1(a) and (b)

Table3.1(a) Sub-classes of Type Class-X and (b) Sub-classes of Class-Y capacitors

Subclass (IEC 60384-14)	Peak Voltage Pulse (while in service)	Peak impulse before endurance test
X1	>2.5kV ≤4.0kV	4kV per C ≤ 1μF 4/√C kV per C >1μF
X2	≤2.5kV	2.5kV per C ≤ 1μF 2.5/√C kV per C >1μF
X3	≤1.2kV	None

Subclass (IEC 60384-14)	Rated Voltage	Peak impulse before endurance test
Y1	≤500VAC	8kV
Y2	150VAC≤ V <300VAC	5kV
Y3	150VAC≤ V <250VAC	None
Y4	<150VAC	2.5kV

The decoupling capacitors address the issue of differential mode noise at Integrated circuit chip/ local level. This can be considered as a type of differential mode filter. These capacitors are said to ‘decouple’ one section of the circuitry from the rest of it. In other words, the current fluctuations of one part do not affect the current in rest of the circuitry.

In high speed digital circuits there is simultaneous switching of multiple devices. Depending on the operations, some devices need current to be supplied to them while others sing the current. Under normal circumstances, the power source shall supply/ sing the current giving rise to conducted emissions. The magnitude of currents is of the order of a few μA or nA. The current demand/ supply is for a very short duration depending on the clock/ data rate of the digital circuit. The long wires to the supply may offer inductance. This leads to delayed response to the current demands of the circuit. It makes sense to make the arrangement of the supply of small current by other arrangements line capacitor. The de-coupling capacitor is placed adjacent to the digital IC. Fig 3.7 shows the connection schematic of the de-coupling capacitors. The value of the decoupling capacitor is calculated based on the maximum possible demand of the circuit.

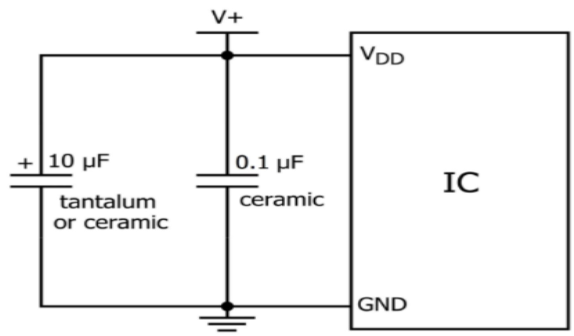


Fig. 3.7 De-coupling capacitor connections

Consider an IC with 8 switches and sink current of each switch is 25 mA. And the data rate is 10 Mbits.s^{-1}.This data indicates that the maximum demand on the supply of charge is calculated as:- current X time = 8X 25 X 10^{-3} X 10^{-7}= 2 X 10^{-8} Coulomb= 2nC. The voltage on the capacitor will remain same if it has capacity to hold at least 100 times the charge (say). Therefore, we compute for 2X 10^{-6} Coulomb. With supply voltage3.3 volts (say). We have the minimum value of the capacitor= Q/V= (2X 10^{-6})/ 3.3= 0.606 X 10^{-6}= 0.6 µF. Using higher value may make more charge available but may lead to sluggish response. Considering the Effective series resistor of the capacitor to be 0.1 Ω, we have the time constant (RXC) of 0.06µs. This will not be sufficient for the data rate of 10 Mbit.s^{-1}.

In the view of this, the decoupling capacitors are deployed in pairs. One capacitor will be ≈0.1 µF, (or laser). Other capacitor will be with value of d the other with the value of ≈10 µF, to meet the charge reservoir requirement.

3.3.2 Inductor selection and design

Generally power electronic components like DC-DC converters, inverters, rectifiers etc are the source of the conducted EMI. The conducted components are generally in the frequency band of a few 100s of kHz. These components need to be tackled by the EMI filters shown in Fig. 3.5. Current fluctuations created by digital processors are generally in the frequency bands of a few 10s of MHz. These emissions are generally handled locally by decoupling capacitor(s). In modern systems the digital electronics operates at GHz frequencies. The emissions created by the devices are generally supressed at Intra-chip level or by in Ic design. In this section we shall discuss the Classical EMI filters.

It is known that the inductors function as inductors (offer inductance as desired) in limited frequency bands. As an example, the inductors/ chokes operating in power frequencies (50Hz/60 Hz) show large power loss at kHz frequencies. It is important to select inductor with appropriate specifications. Some of the points to be noted are as follows:

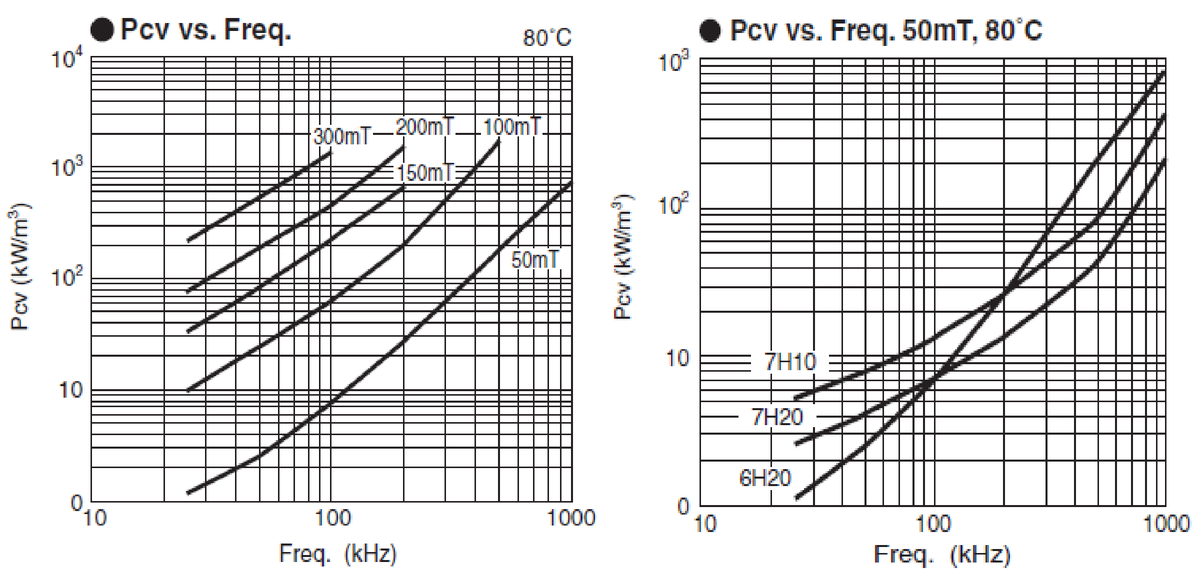
The inductor must support the line current. Lower capacity inductors offer gets saturated and offers much lower inductor. It may also be noted that DM mode filter must be rated for full line current. On the other hand the CM filter may be rated at much lower than the line current. This is because line current and the return currents induce the flux in opposite directions. However, in most practical cases, the EMI filters are not available 'off-the-shelf'. The Inductor for the EMI filter often needs to be designed. The design involves selection of appropriate core and deciding the windings to realize the inductor.

The procedure of Inductor design for the EMI filter is as follows:

1. Compute the suppression required in the filter→ Emissions (dBμA)-Allowed limit (dBμA). This value will be a ratio (in dB), computed at a specific frequency band of concern.
2. Choose a suitable filter topology and determine a value of Inductor required for the desired suppression. Pi-filter topology is very common for the EMI filters.
3. Select a core of appropriate material and dimensions. The material is selected on the basis of frequency. Ferrite materials are popular for EMI filters in the frequency range of 20 kHz to 500 kHz.
4. For a an inductance L, current I and frequency f, the energy and the power stored in the inductor is given by (3.1)

$$E_{inductor} = \frac{1}{2} L I^2 \Rightarrow P_{Inductor} = \frac{1}{2} L I^2 \times \frac{1}{2f} \quad \ldots \quad (3.1)$$

5. Most of the manufacturers provide graphs of power capacity of the cores. Fig. 3.8 gives a chart for FDK ferrites. The chart mentions the volume of the magnetic path. Select cores with appropriate volume and suitable type; e.g. E-I, Torriodal, RM, EP, PM etc. Fig. 3.8 Shows the Power density of Ferrite material from FDK Corporation, Japan. It is seen that with increase in the magnetic flux density, the power handling capacity reduces.



(a) 6H20 material (b) 7H series material

Fig. 3.8 Power densities in Ferrite material

(Source: FDK catalog: Ferrite cores for transformer and choke coils:- FE21001-1301-010)

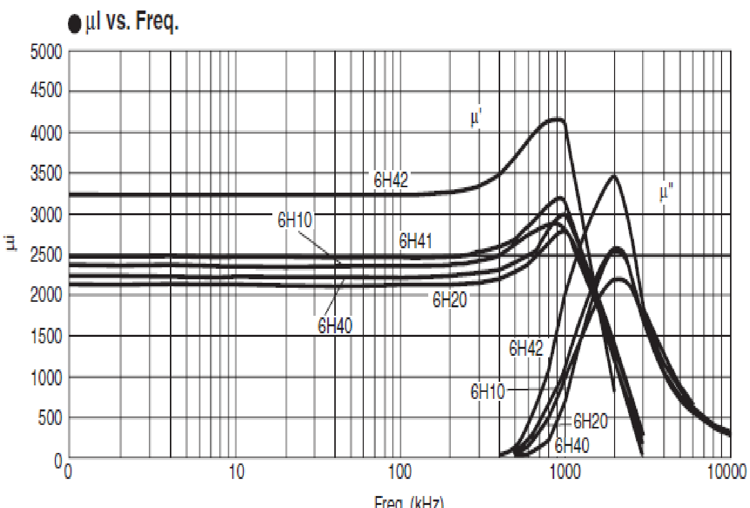
6. Determine the number of turns for realizing the inductance, see (3.2). Data sheets often mention AL values for the material. Knowing the number of turns, and the operating current (I), Compute the Magnetic field, see (3.3) and (3.4). Then compute the flux density from permeability of the material and the dimensions of the core. Ensure that the core does not saturate at the maximum current levels.

$$Inductance(L) = \frac{N^2 \mu_0 \mu_r A}{l} = N^2 (ALValue) \quad \dots \quad (3.2)$$

Where, A is cross sectional area and l are the length of the magnetic circuit, N is no of turns.

$$MMF(F) = N \times I = H \times l \quad \dots \quad (3.3)$$

$$Reluctance(R_m) = \frac{l}{\mu_0 \mu_r A} \quad \dots \quad (3.4)$$



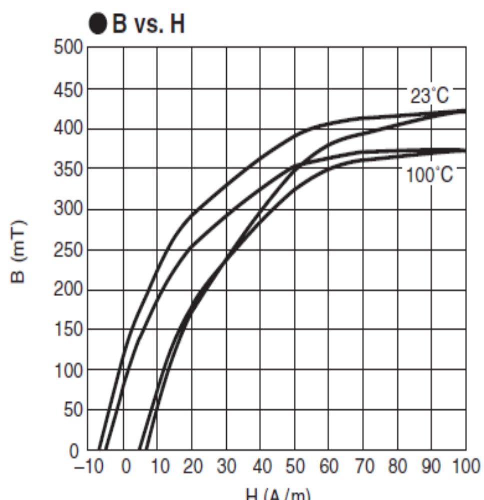


Fig. 3.9 (a) Initial (at low fields) permeability values (b) B-H Curve for6H20

(Source: FDK catalog: Ferrite cores for transformer and choke coils:- FE21001-1301-010)

Table 3.2 Inter-conversion expression for electric and magnetic fields

Magnetic			Electric		
Name	Symbol	Units	Name	Symbol	Units
Magnetomotive force (MMF)	$\mathcal{F} = \int \mathbf{H} \cdot \mathrm{d}\mathbf{l}$	ampere-turn	Electromotive force (EMF)	$\mathcal{E} = \int \mathbf{E} \cdot \mathrm{d}\mathbf{l}$	volt
Magnetic field	***H***	ampere/meter	Electric field	***E***	volt/meter = newton/coulomb
Magnetic flux	Φ	weber	Electric current	*I*	ampere
Hopkinson's law or Rowland's law	$\mathcal{F} = \Phi \mathcal{R}_m$	ampere-turn	Ohm's law	$\mathcal{E} = IR$	
Reluctance	$\mathcal{R}_m$	1/henry	Electrical resistance	*R*	ohm
Permeance	$\mathcal{P} = \frac{1}{\mathcal{R}_m}$	henry	Electric conductance	*G* = 1/*R*	1/ohm = mho = siemens
Relation between ***B*** and ***H***	$\mathbf{B} = \mu \mathbf{H}$		Microscopic Ohm's law	$\mathbf{J} = \sigma \mathbf{E}$	
Magnetic flux density ***B***	***B***	tesla	Current density	***J***	ampere/square meter
Permeability	μ	henry/meter	Electrical conductivity	σ	siemens/meter

(Source: https://en.wikipedia.org/wiki/Magnetic_circuit)

7. If the magnetic field or flux density is more than the saturation values (e.g 60 Am^{-1} and 400 mT for the material shown in Fig. 3.9(b)) the inductance may be realized in two or more modules.

This section presented the techniques to suppress conducted EMI. This and the basic design procedure above procedure

3.4 Source of Conducted EMI and Susceptibility Requirements

In earlier chapters we have seen that there are many sources of conducted EMI that could disturb the DUT. Some of the common causes are as follows.

1. In many situations, the DUT is connected on a common power grid. This means that a common bus supplies the power DUT and other equipment. In such situations, the DUT gets conducted EMI due to the operational activities on the other equipment. (e.g. Start and stop operation of a high power motor or furnace operation). If the current demands are well within the supply capacities, the current fluctuations are at moderate level. However, on a full loaded supply bus gives rise to big current fluctuations and often voltage disturbances.

In such cases, Isolation of the power supply using appropriate transformers provides a good amount of relief. It suppresses voltage disturbances substantially and moderates the current fluctuations.

2. The DUT with isolated power lines is still vulnerable to 'induced conducted EMI' through the EM field fluctuations in the environment. Though the source of disturbance is Radiated EMI, it gets manifested as conducted EMI in the DUT. This conversion of radiated EMI to conducted EMI gets limited if the power lines are shielded and routed together to have 'reduced loop area (as shown in Fig 3.3)'.

In spite of the care mentioned above, in any case, the DUT is expected to face conducted EMI as specified in MIL-STD 461 G (or other applicable standards). Therefore, DUT as a stand-alone unit must be protected to the attacks as specified in the EMC standards.

We shall continue this discussion in the context of the MIL-STD 461 G.

(a) The CS 101 thro CS106 tests are for power leads. This test involves induction of approximately 6 V (136 dBμV) signal at lower frequencies and that of lesser magnitudes at higher frequencies (see Fig. 2.28). The actual limits vary with case to case.

There are similar limits for antenna terminals and data lines.

(b) The CS 109 test is applicable for the units operating at frequencies less than 100 kHz. In this test, structured current is induced as conducted EMI. The magnitude is approximately 1 A (120 dBμA) for the frequency of 400 Hz and lower amplitudes for higher frequencies up to 100 KHz.

(c) The CS 114 test induces a common mode noise of approximately 6mA (76 dBμA) at frequencies from 4 KHz and noise lo lower magnitude for frequencies up to 100MHz.

(d) The tests which induce transients: The CS 115 test induces 5 amp 30 ns transient and CS 117 induces voltage strokes of fast rising pulses (to imitate lightning).

(e) The CS 116 introduces damped sinusoids on the power lines.

(f)The CS 117 injects 'lightening inducted transients' on cables and power leads.

(g) The CS 118 test executes personnel borne electrostatic discharge with 6ns ±2kV pulse

3.5 Techniques to Reduce Conducted Susceptibility

In section 3.4 we have presented the requirements of various CS tests. The DUT is accepted or said to comply the EMC tests if it does not show any degradation for the CS test conditions. In other words, the unit is not susceptible to the conducted attacks. Normal electronic designs are generally susceptible to such conducted attacks. Systematic efforts must be done to reduce the susceptibility of the DUT.

CS 101, CS 109, CS 114 and CS116 tests introduce continuous/ sinusoidal wave disturbance, such disturbance must be tackled by appropriate filter as discussed in section 3.3. The procedure is as follows.

1. Find out inherent tolerance of the system: This process involves determining the tolerance of the system based on circuit component, e.g acceptable ripple on the power supply or the Maximum voltage of an IC. In most of the cases, the system is capable of surviving overstressing (in voltage as well as current) by about 20%. In this view, in absence of accurate data, it is practical to assume approximately 20% over stressing at lower frequencies (upto 1kHz) and about 1 % overstressing at frequencies in MHz. In other words, a system operating at 24Vdc can be assumed to tolerate 28.5 Vdc. Similarly a system with rated current of 10 A can tolerate 12 A current.
2. Derive the conducted emission suppression of conducted disturbance required in the system so that the DUT survives. As an example, consider a 2 A system to undergo CS 109. Acceptable input current is 2.4 A. However, the test induces 1 A current at 400 Hz. Therefore, the system needs to be protected by a filter which suppresses 400 Hz signal by more than 8dB. Similarly, the required suppression can be calculated at all frequency bands under test.

   If there are multiple tests to be conducted, the suppression required for each test with respect to the frequency band need to be computed. Amongst all suppression values for the test, the highest suppression values should be computed for each frequency band. This exercise determines the suppression profile with frequency or the desired specifications of the filter.
3. Using any of the standard methods, a filter for desired performance may be designed. Filters for wide range of specifications are available 'of-the-shelf'. If required the inductors could be fabricated using the procedure described in section 3.3.

It may be noted that the filter need to be introduced for the CE as well as CS. In case of the filters for CE compliance, specific frequencies (which are generated by the DUT) need to be suppressed to meet the limits. These filters can be deployed locally at the subsystem levels, internal to the DUT, at the location where the EMI is generated. On the other hand, the filter required for the CS tests must cover the complete band specified in the tests and the filters need to be deployed at the power leads, antenna terminals and the data lines as required.

CS 115, CS 117 and CS 118 inject transient signals or high overstress signals for short time duration. The design strategy from such 'attacks' involve safety and divert of absorb the transient energy out of the DUT.

Components like Zener diodes, transient absorbers, Metal Oxide Varisters (MoV) and spark gaps are used for the protection of the DUT. These devices operate as 'Voltage clamping devices' by offering variable Impedances across the terminals, see Fig. 3.10 (a). Zener diode is the simplest example. It offers much lower impedance for voltages higher than V_z. For high current applications, early popular design known as 'crow-bar circuit' (see Fig 3.10) was used.

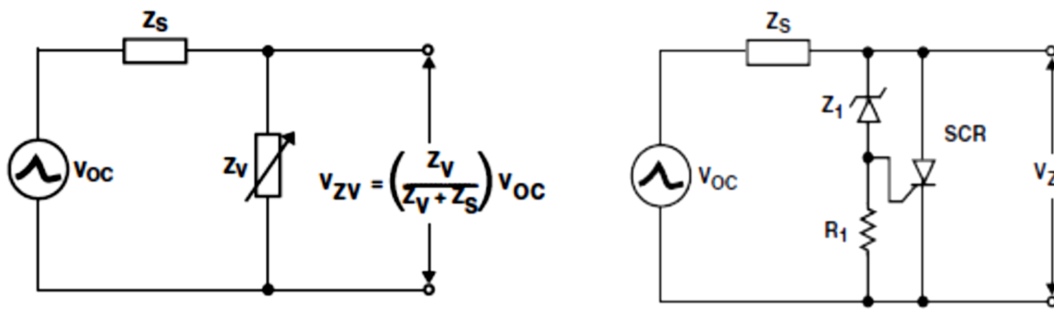


Fig. 3.10 (a) Protection by a variable impedance device (b) Crow-bar circuit

The induced voltage is taken as the open circuit voltage (V_{OC}). Knowing the impedance offered by protection device, it is possible to calculate the extent of suppression of the voltage across the terminals. The choice of the protection device must be such that the voltage V_{ZV} (as in Fig. 3.10(a)) must be safe for the DUT. It may be appreciated that a nonlinear impedance, with V-I characteristics given by $I=KV^{\alpha}$ (see Fig. 3.11) gives protection up to higher voltages. This is because the non linear device offers much lower impedance. Other critical parameter for selecting the transient suppressors is the total energy absorption capacity. The total energy absorbed is simply $= I_{\max}^2 Z_v t$. More devices may be used in parallel if the power absorption capacity of single device is not adequate.

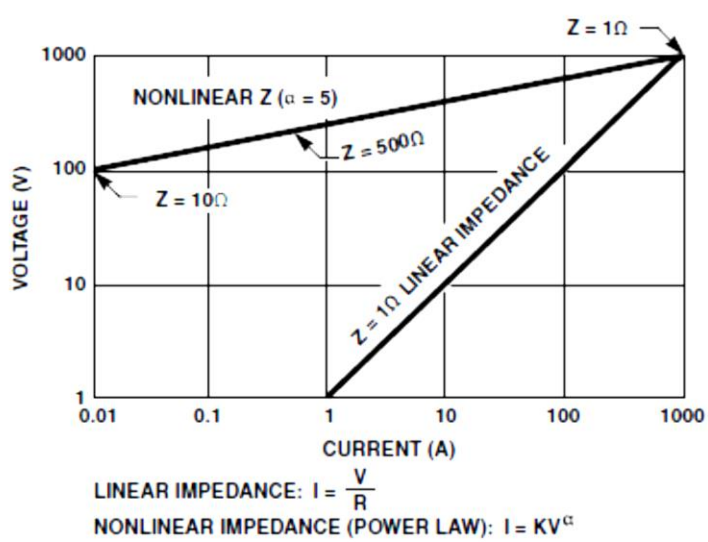


Fig. 3.11 Voltage –Current (V-I) characteristics for linear device and non-linear devices (Zeners, varisters etc.)

3.6 Numerical Problems

All the sections in this chapter present different concepts in simplistic manner. The mathematical expressions are generally and consider only one aspect/ phenomenon for a limited range of parameters. However, in practical situation, multiple aspects of EMI become significant. Accurate electromagnetic analysis of the system is only possible by solving differential equations with certain boundary conditions. These equations can be solved by numerical methods of with fine discretization; ‘finite element analysis’, finite difference methods. Advanced software tools are available. Leading tools are as follows.

1. Altair FEKO
2. ANSYS
3. National Instruments- AWR
4. Computer Simulations Technology (CST)
5. Keysight Technology Solutions (separate tool for circuits, antennas etc.)

Chapter-4

Designing for the Compliance to RE and RS

In this chapter we shall have discussion on the Radiated EMI and protection from those emissions, their quantifications and related aspects. For the reasons mentioned earlier, the issues of radiated EMI and EMC must be addressed as design stage.

Electromagnetic waves are generated whenever an electrically charged particle moves. Hence they can be generated in nature as well in man-made systems. In modern times, electronics is being used in almost every gadget. There has been a large technology development in communications, Industrial control and monitoring, and the Internet of things. Due to this, there has been presence of EM radiation everywhere!! We have seen that this indiscriminate flooding of EM radiation has forced the authorities to come up with EMC standards and implementing mechanism. We shall begin with understanding the mechanism of the EM radiation.

4.1 Generating mechanism of radiated emissions

Radiation from all celestial bodies is always in form of EM waves. The EM wave spectrum extends from extremely low frequencies (ELF≈ 3 Hz) to Gamma rays (≈ 10^{20} Hz)and beyond. In this context we will discuss the EM waves with frequencies used by various electronic devices; a few KHz to 40 GHz (say). The EM energy at these frequencies is generated by electronic systems with oscillators/ resonators. The EM energy thus generated is used for the following purpose:

1. As a signal/message for communication
2. As a command for remote Industrial control operation
3. As a power source for heating or enhancement of chemical process
4. As facilitator/ process triggering input for sensing

While performing the above functionalities, the EM energy is

1. Transported from one location to other with the help of transmission lines.
2. Frequency converted to other frequencies, using mixers
3. Radiated using antennas.

In practical situations, the transmission lines are leaky. This means some part of the energy is radiated in the space. Fig. 1.6 shows pictures of some of the transmission lines. The electric field in micro-strip line or parallel plate lines extends beyond its physical boundaries. Similarly in co-axial lines the outer conductor has a limited ‘shield effectiveness’ and allows some energy to be radiated out of its physical boundaries. We shall learn this concept later in the course. The communication/ radar antennas have radiation pattern extending beyond the region of interest. This may be due to broader beam of the side-lobes of the antenna.

In the above description we have seen that the EM energy 'leaks', 'spills-over' or 'escapes' to the regions where the presence of these EM wave is undesirable. This is called electromagnetic interference (EMI). In short we could say that the EM energy, present in undesirable regions due to non-ideal properties of electronic components like transmission lines, antennas and so on. The electromagnetic energy present due to natural phenomenon, though often undesirable is not called EMI. As an example the stellar radian reaching earth is referred as 'sky-noise' or 'background radiation', but not EMI.

The unwanted RE is capable causing disruption/ malfunctioning in sensitive electronic gadgets. We shall understand with the help of following example.

Mobile phones operate in the frequency range of 800 MHz, 900MHz and 1800 MHz. It has high emission levels of ≈ 10 Vm^{-1}. This radiation can easily create the disruption in sensitive equipment functioning and long term biological effects on living beings. Fig 4.1(a) shows waveform specifications for cell phones.

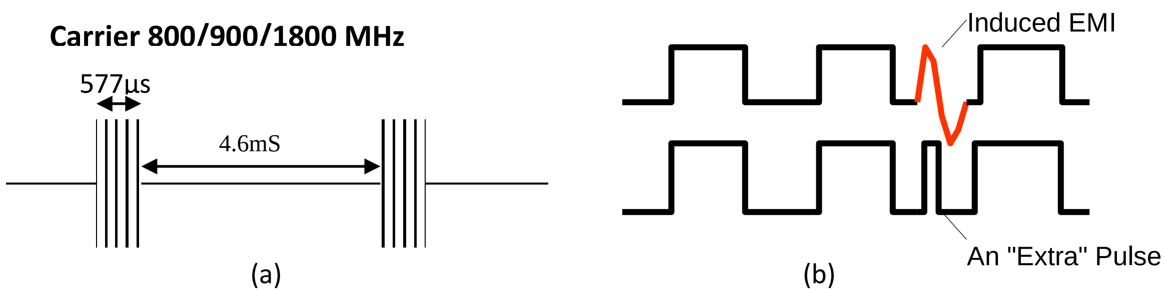


Fig 4.1 (a) A sketch of Cell phone radiation timings (b) Corruption in data due to induced EMI

The erroneous performance in any electronic system is generally caused by seemingly legitimate signals into the sensor/ communication circuits. Modern high speed circuits are more susceptible to EM field/ ESD which induce transients. Such signals are extremely difficult as they appear legitimate. Fig. 4.1(b) shows an example. The quantification of the EMI effect can be done by the process described below.

4.2 Quantification radiated EMI

We have seen that the radiated EMI is actually in the form of electric (or magnetic) field. The unit for electric field is Vm^{-1} and that for magnetic field is Tesla (T: kg $s^{-2}.A^{-1}$). In this section we shall discuss the radiated emissions from the DUT. The emissions can take place from following sources.

1. If the DUT has transmitter and the power amplifier, being non-linear generates radiations in harmonic frequencies or frequencies other than the intended frequencies (known as Spurious). The quantification of this type of emission is done in following steps. The harmonic level of the transmitter (P_t) is measured at the antenna terminals. The radiated power (P)and hence the field) outside the DUT is computed by (4.1)

$$P(r) = \frac{P_t}{4\pi R^2} = \frac{E^2}{377} \quad \ldots \quad (4.1)$$

2. Power switching or PWM type of waveforms for supply inter-conversions. The power electronics subsystems Switched mode power supplies (SMPS) and the DC-DC converters in the DUT shall have components producing current fluctuations. The isolated voltage sources often have accumulated static charge on their surfaces. Knowing the magnitude of current fluctuations or charge accumulation, it is possible to compute the electric and magnetic field using the expressions in Fig. 1.5.

   Most of the units mentioned above usually have a metal cover surface or enclosure. The current switching in those subsystems induces 'eddy currents'. It is difficult to compute the exact path of the eddy current in the metal mass. However, a reasonable estimate of power dissipated (P) can be calculated empirical formula given in (4.2). In this expression, the skin effect, and spatial variation in magnetic field is neglected. In absence of exact geometrical and material details, in most practical cases, the EMC engineers use empirical expressions. These expressions avoid complex computations; acceptably approximate values. Knowing the resistivity and approximate path of the eddy current the magnitude of the current on any metal surface in the vicinity can be computed. This part of the current can re-radiate.

$$P(W \cdot kg^{-1}) = \frac{\pi^2 B_p^2 d^2 f^2}{6\kappa\rho D}$$ (Source: https://en.wikipedia.org/wiki/Eddy_current … (4.2)

Where, B_p is magnetic field, d is the sheet thickness, ρ resistivity, D is density and κ is 1 for thin sheet and 2 for thin wire. (Ref: F.Fiorillo, Measureement and characterization of magnetic materials, Elsevier Academic Press, 2004 ISBN 0-12-257251-3, p 31)

3. High speed data / communication lines: Modern communication equipment has data transfer rates in Gbits.s^{-1}. The data communication lines or clock lines in the modern processor boards are not well-designed microwave transmission lines. (The strong demand of miniaturization does not allow it. We shall discuss this in more details in Chapter 6). As a result. The data lines function as leaky transmission lines. It may be noted that at lower frequencies or data rates the problem of leakage is much less. Therefore, it was not an issue when the data rates (and clock speeds) were low.

The RF leakage from all these components can either be measured with sniffer probes or pointer probes as shown in Fig 2.17. Alternatively, we can calculate the electric field as well as magnetic field at a distance either from (4.2) and expressions shown in Fig 1.5. The fields computed in such manner are approximate and computed with simplistic assumptions and adequate for engineering decisions. Accurate computations require complex computerized analysis with powerful software tools.

While considering the RE, the computed values must be compared with the allowable levels according to the EMC standards. If the DUT field values are higher, the radiated field must be reduced by one of the techniques mentioned in section 4.3; the next section.

For radiated susceptibility (RS), one must analyse using reverse procedure. In this procedure, one needs to compute induced currents/ voltages due the presence of disturbing fields at the level allowable by the EMC standard. If these induced currents and voltages are harmful to the critical paths/ sections of the DUT and could lead to degraded performance, the techniques presented in 4.5 must be incorporated.

4.3 Techniques to reduce radiated emissions

The radiated emissions can be reduced by one of the following methods.

(a) Reducing the RE by design changes:

In the last section, we have seen that the radiated emissions are caused by the Fluctuating currents in the power electronics units and high speed control and computing units. The magnitude current/ voltage fluctuations at various frequencies can be computed with the help of the Fourier transform computations. Fourier transforms of some of the functions are given below:

(a) Sinusoid: $x(t) = \cos(\omega_0 t) \Rightarrow \frac{1}{2}\left(e^{j\omega_0 t} + e^{-j\omega_0 t}\right)$ ➔Symmetrically placed components

(b) Exponential Decay: $x(t) = \mathrm{e}^{-\alpha t}\mathrm{u(t)} \Rightarrow \dfrac{1}{\alpha + j\omega}$ ➔Decaying in frequency domain

(c) Comb function: $x(t) = \sum_{n=-\infty}^{\infty} \delta\left(t - nT\right) \Rightarrow \frac{1}{T}\sum_{k=-\infty}^{\infty} \delta\left(f - \frac{k}{T}\right)$ ➔Impulse train

(d) Square wave: $x(t) = u\left(t+\alpha\right) - u\left(t-\alpha\right) \Rightarrow \frac{2}{\omega}\sin\left(\alpha\omega\right)$ ➔Sinc Function

(e) Triangle function: $x(t) = \begin{cases} 1-|t|, |t| < 1 \\ 0, |t| \ge 1 \end{cases} \Rightarrow \left(\dfrac{\sin^2\left(\pi f\right)}{\left(\pi f\right)^2}\right)$ ➔Sinc squared

(f) Gaussian function: $x(t) = e^{-\pi t^2} \Rightarrow e^{-\pi f^2}$ ➔ Gaussian

We see that the abrupt functions lead to significant frequency components up to higher frequencies (e.g. Comb function). On the other hand, the Fourier transform of smoother functions have low magnitude components at higher frequencies

Considering the fact, that RE limits are reducing lower up to 100 MHz, it makes sense to reduce the magnitudes of the high frequency components. This strategy is the best as it reduces the high frequency RE at generating point. However, may not be always possible.

(b) Supressing the RE by shielding:

If the reduction in RE generation is not possible, the magnitude of RE outside DUT can be reduced by using appropriate shielding material. Shielding is done using an enclosure of suitable metal surface. Such metal surface offers suppression of the EM field. The EM field induces current on metals. The surface current density 'J_s' gets reduced exponentially, at depth 'd' inside the body of the metal, according to the relation (4.3).

$$J(d) = J_s e^{-(1+j)d/\delta} \text{ Where } \delta = \sqrt{\frac{2\rho}{\omega\mu}} \sqrt{\sqrt{1+(\rho\omega\varepsilon)^2} + \rho\omega\varepsilon} \quad \ldots \quad (4.3)$$

(Ref: Jordan, Edward Conrad (1968), Electromagnetic Waves and Radiating Systems, Prentice Hall, ISBN 978-0-13-249995-8)

Also, $\mu=\mu_0 \times \mu_r$, μ_r is relative permeability and $\varepsilon=\varepsilon_0 \times \varepsilon_r$, ε_r is relative permittivity

Now it is seen that most of the frequencies in electronic systems, are <<(1/ $\rho\omega\varepsilon$). This is because, $\rho < 10^{-7}$ for all the metals and ε_0= 8.87 x 10^{-12}. Therefore, the skin depth is

$$\delta \approx \sqrt{\frac{2\rho}{\omega\mu}} \quad \ldots \quad (4.4)$$

It can be seen from (4.3) that the skin depth is the depth at which the current density falls to 1/e times the surface value. Or the suppression of ≈8.68 dB ≈ 20 log (1/e).

It can be seen that the thickness of 5δ will give suppression of 43.42 dB

It may also be appreciated that magnetic materials due to high values of μ_r, offer much lesser values of δ; thereby giving shielding with much thinner enclosures compared normal metals. Table 4.1 gives relative permeability values for some of the common shielding materials.

Table 4.1 Permeability of common materials
(Source: http://info.ee.surrey.ac.uk/Workshop/advice/coils/mu/#mu)

Material	Ferrite T38	Ferrite M33	Nickel (99%)	Ferrite N41	Iron (99.8%)	Silicon GO steel	Supermalloy
μ_r	10000	750	600	3000	5000	40000	1000000

The suppression offered by shielding is often referred as 'Shield(ing) Effectiveness (SE)'; it is simply the value of total EM field suppression. Fig. 4.2 shows a sketch showing general situation when an EM wave passes through an enclosure of certain thickness. The detailed analysis is as follows (Source: https://www.sciencedirect.com/topics/engineering/shielding-effectiveness):

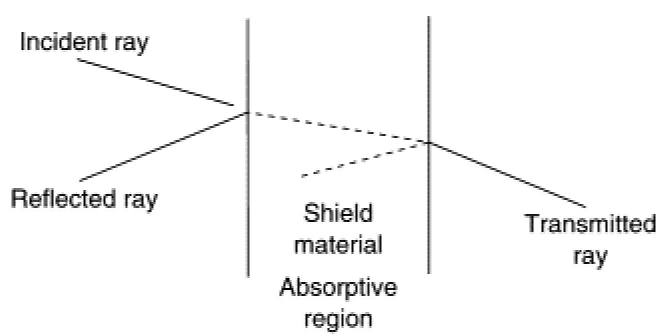


Fig 4.2 Ray diagram explaining the passage of EM waves through shield material

It is seen from Fig.4.2 that an EM wave undergoes loss due to three factors, namely, Reflection (R_1), Absorption (A), and Re-reflection (R_2). Therefore, the SE is the sum (in dB scale) of all the three losses.

$$SE\ (dB) = R_1(dB) + A(dB) + R_2(dB) \quad \text{... (4.5)}$$

We evaluate each of these terms.

Reflection loss at the interface between two media depends on the difference in the characteristic impedances. When electric field is considered, the expression for the reflection loss is given by (4.6). For magnetic fields, the loss depends also on the shielding material and the frequency. The expression of the loss is given in (4.7). Same expressions are valid for R_2 with appropriate substitution of values of the parameters.

$$R_{1E}(dB) = 322 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r \cdot f^3 \cdot r^2}\right) \quad \text{... (4.6)}$$

Where, σ_r is the relative conductivity (Sm^{-1}), μ_r is the relative permeability (Hm^{-1}) of the shielding material, f is the frequency and r is the distance (m) from source

$$R_{1M}(dB) = 14.6 + 10\log_{10}\left(\frac{f \cdot r^2 \cdot \sigma_r}{\mu_r}\right) \quad \text{... (4.7)}$$

When incidence of a plane EM wave at a distance r > λ/2π, is considered, the loss is given by expression (4.8).

$$R_{1PW}(dB) = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r \cdot f}\right) \quad \text{... (4.8)}$$

It may be appreciated while considering RE from a DUT (for most of the packaged electronic units), the condition, 'r > λ/2π' is not valid. Therefore, the expressions (4.6) and (4.7) must be used. On the other hand, while considering the compliance to the RS tests, the distance of the DUT from source is 1m, 3 m or 10m (depending on tests). The condition 'r > λ/2π' is valid for frequencies in VHF and higher bands. In such situations, (4.8) can be used.

Second factor is the absorption loss. This loss in the shielding material of thickness t (inches) is given by (4.9). If 't' is expressed in meters, the constant will be 131.496.

$$A(dB) = 3.34t + \sqrt{\sigma_r \cdot \mu_r \cdot f} \quad \text{... (4.9)}$$

If the enclosure has any holes or the openings, they act as a slot. The longest dimension of the opening must be considered while considering its shielding capability. The shield effectiveness of a slot of maximum dimension 'L' is given by (4.10)

$$SE_{hole}(dB) = 20\log\left(\frac{\lambda}{2L}\right) \qquad \text{... (4.10)}$$

The shield effectiveness of the slot is generally lesser than the solid metal part of the enclosure. Therefore, the value given by (4.10) should be used while computing the shield effectiveness of a perforated enclosure.

The DUT generates only a few specific frequencies that are unwanted. Therefore, for RE compliance, only these frequencies need to be supressed. In such cases, the the direction of the leakage path is known. Such leakage radiations can be effectively supressed using periodic structures. These structures are known as 'electromagnetic band–gap (EBG). EBG structures are extensively used to reduce the mutual coupling in multi-antenna systems (e.g MIMO) and to supress the surface wave propagation in multi module microwave systems.

Many electronic systems have movable/flexible parts. There portions are shielded by polymeric composites. In modern systems composites with nano-particles are also used. Theie shielding ability is termed as shielding efficiency (SE). This is conceptually equivalent to shield effectiveness. The shielding material is used as closely fitting cover, sleeve or cladding. There is no gap between the EM source and the shielding material. The computation of the SE is done by modelling these systems as cascaded RF systems. The classical calculations for such arrangements are using the S-parameters. Therefore, the S parameters of the shielding material are measured with a vector network analyser/ impedance analyser set-up as shown in Fig. 4.3.

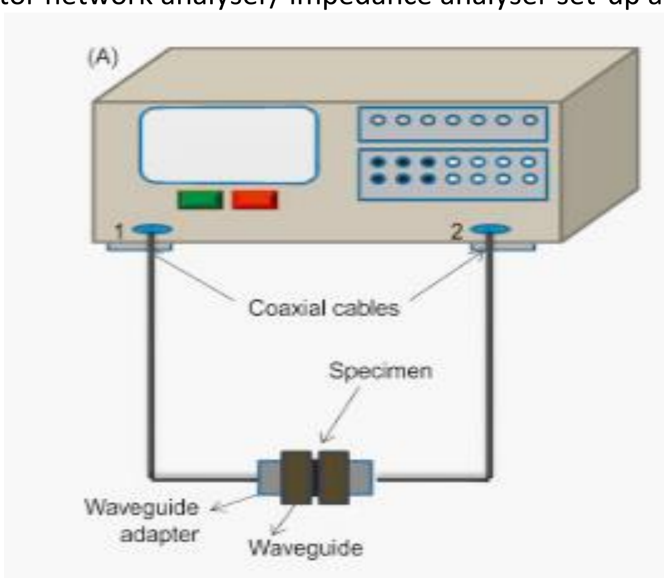


Fig 4.3 S parameter measurement of flexible shielding material

Knowing the S parameters, the computations of SE are done as follows: The total SE is the sum of the values due to one-time absorption and two reflections, as in (4.5).

$$R_1(dB) = 10\log_{10}\left(\frac{1}{1-R}\right) \text{ and } A(dB) = 10\log\left(\frac{1-R}{T}\right) \qquad \text{... (4.11)}$$

Where, Transmittance (T) = $|S_{12}|^2 = |S_{12}|^2$ and Reflectance (R) = $|S_{12}|^2 = |S_{12}|^2$

These materials are passive and therefore show reciprocity.

(c) Shielding signal cables

The cables carrying signals or control signals are often shielded by conductive cladding. This shield is in form of braiding of thin conducting wires or cylindrical cover of conducting foil. Electrical modelling of this shield is shown in Fig. 4.3. This shield must be grounded. For frequencies up to HF band, we have $(R+1/j\omega C_{cable}) >> (R_s+j\omega L)$. The electric field attenuation due to shielded cable or the shield effectiveness of the cable is given by (4.12).

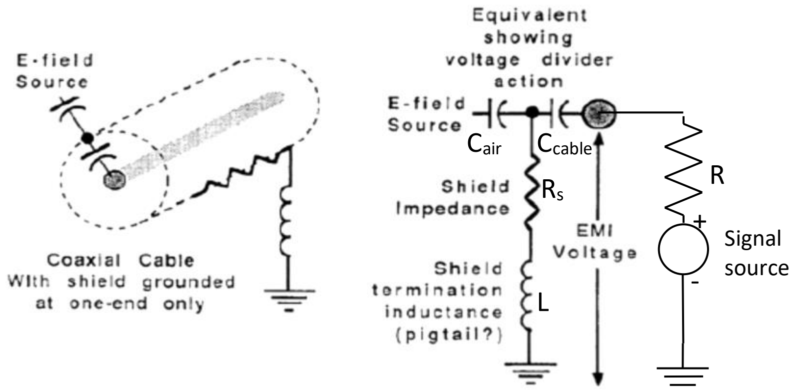


Fig 4.4 Cable shielding and the associated electrical model

$$SE_{cable}\left(dB\right)=20\log\left(\left(\frac{R_s+j\omega L}{(R_s+j\omega L)+1/j\omega C_{air}}\right)\left(\frac{R}{R+1/j\omega C_{cable}}\right)\right) \quad \dots \quad (4.12)$$

4.4 Source of radiated EMI and susceptibility requirements

We have seen in earlier chapters that the EM waves are generated by natural sources as well as man-made electrical/electronic components. The DUT is expected to function as desired in the intended environment, in-spite of the presence of the other systems. These systems may create EMI which could disturb the DUT function. Various EMC standards are designed considering a reasonable amount of disturbance. In this view, the DUT is considered rugged/ acceptable to operate in the intended environment if it complies with the relevant EMC standards. Therefore, a system designer must design the DUT to meet the compliance requirements.

4.5 Techniques to reduce radiated susceptibility

We have discussed all the techniques of reducing the Radiated emissions in section 4.3. Exactly same techniques are used for reducing radiated susceptibility. This means that the system is able to function in the presence of radiation defined in various applicable tests.

The specifications are defined in terms of frequency profile electrical (or magnetic) field strength. In order to face the radiation attack of EMC tests, the DUT designer must find out the sensitivity of the DUT. This includes identifying the failure modes DUT and the situations when the DUT malfunctions.

The failure conditions can be found out from the absolute maximum ratings (Voltage, currents, EM fields) of the components. These ratings can directly be converted into the 'tolerable external EM field strength'.

Similarly, the minimum EM field strength that causes malfunctioning needs to be computed. The malfunctioning can be due to the corruption in data or in sensor values. Knowing the line impedance and the data threshold voltage, it is possible to compute the induced current/ voltage levels. As an example, the TTL threshold of 1.8 volts indicates that the induced voltage must be less than 1.8 volts. Also, on 50 Ω line can be achieved by induced current of 36 mA. Therefore, the induced current on the data lines must be less than 36 mA. As another example, consider a sensor giving output on a 4-20 mA line. This sensor is expected to function with 0.1% accuracy on full scale reading (full scale is 16 mA➔ 16 µA is 0.1 %). Consider that the sensor impedance is 100 kΩ. This means that induced voltage must be less than 1.6 volts so as to have disturbance less than 0.1% of the sensor readings.

After computing the requirements of induced voltage/currents, we know the difference between the EMC test field levels and the tolerable field strength. The system should be given adequate shielding so that the induced disturbance is acceptable for performance. The techniques for the same are already discussed in Section 4.4.

4.6 Numerical Problems

Chapter-5

Grounding and Shielding

In earlier chapters we have developed some understanding about the effect of electromagnetic interference (EMI), the Electromagnetic compatibility (EMC) tests. We have also got introduced to some design techniques to mitigate the effect of EMI towards the compliance with the EMC tests. There is another very important aspect in electronic system design; is grounding. The word 'ground' or 'grounding' is used with a wide range of meanings. It is also referred as 'earthing'. Following discussion is intended to remove confusion and offer clarification to a reasonable level.

In the context of electrical and electronics systems, grounding or earthing, is expected to perform following function.

1. **Lightening protection**: This arrangement offers protection to the system from 'high energy discharge attacks' like lightening.
2. **Protective earth /grounding**: This offers protection to the human (birds, animals and so on) from possible malfunctioning of the system like electric shocks.
3. **Shielding:** This attenuates external EMI and also restricts the system interference to the external environment.
4. **System reference:** This is 'equipotential plane' for all the system signals and power supplies.
5. **Signal return or signal ground:** This is a return path for the various signals. In large systems, there could be multiple signal return paths, isolated from each other.
6. **Supply ground:** This is the return for the power supply. Though neutral line is not considered as ground/ earth, 'neutral line' performs this function for AC power supply.

In system schematic and circuit diagrams these 'grounds (?)' are shown with different symbols, as shown in Fig 5.1.

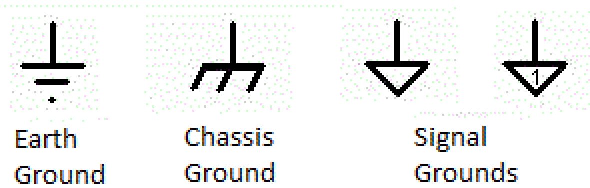


Fig 5.1 Use of different symbols for grounding

5.1 Significance of the earth-ground: faults and protection

Every electrical or electronics system is designed by considering one earth ground. The Earth ground is expected to be an entity which serves as an arrangement to absorb 'external charge-transfer attacks', divert the current away from critical objects and provide a voltage reference to complete system. On our planet, the obvious choice for this functionality is the 'Earth' itself! That explains the origin of the terms 'earth' and 'ground'.

This 'earth-ground' is indicated by the 'earth ground' symbol in Fig.5.1. This ground performs functions 1 and 2 in the list mentioned above. Metal enclosures of various subsystems, are electrically connected together and perform function 3 and 4, aptly called the 'chassis ground' indicated by the symbol shown in Fig.5.1. In a large system, multiple sub-systems operate at multiple power supply levels and often isolated with respect to each other. The 'signal return' or the '0 Volt of DC power supplies' is referred as 'signal ground' and indicated by the symbol shown in Fig. 5.1. As mentioned earlier, there could be multiple signal returns. They are identified by the number written in the triangle, as shown in Fig.5.1. Following sections present more elaborate discussion on each aspect of the grounding.

Contrary to the belief, the earth need not be an object with a very high capacity/ capacitance. The earth or ground is a part of the system that ensures that any charge movement, injected or released from it is equally distributed all over it in the fastest manner. This quality automatically ensures the protection, safety and voltage referencing. It may be appreciated that the 'earth' for satellite electronics is the body of the satellite. Similarly the earth for a cellular phone is organized in metallic portion of the body.

Equation (5.2) gives the capacitance of a conducting sphere of radius '*a*'; is given in (5.2).

$$C_{sphere} = 4\pi\varepsilon a \qquad \text{... (5.2)}$$

The derivation of this expression is as follows:

Consider a sphere with radius '*a*' with a charge '*Q*' on it. Since the similarly charged particles repel each other and the sphere being conductive, the charge will be on the distributed on the surface of the sphere. (See Fig. 5.2(a)). The electric field at a distance '*r*' is $E=Q/4\pi\varepsilon r^2$. Now, we consider a larger sphere with radius '*b*' around it with charge '$-Q$' on it. This will maintain the 'conservation of charge' over the system. Now the expression for the voltage '*V*' developed between the spheres and the capacitance of the system is given in (5.3).

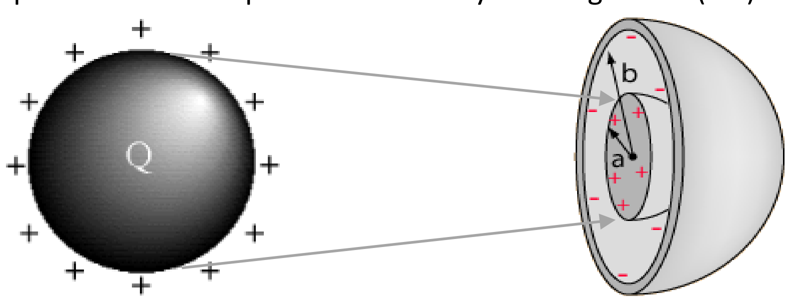


Fig 5.1 (a) Charged Conducting Sphere (b) Sphere enclosed in larger sphere with opposite charge

$$V_{a-b} = \frac{Q}{4\pi\varepsilon}\left[\frac{1}{a}-\frac{1}{b}\right] \text{ and hence the capacitance } C_{a-b} = 4\pi\varepsilon\left[\frac{1}{a}-\frac{1}{b}\right]^{-1} \qquad \text{... (5.3)}$$

For an isolated conduction sphere, $b \to \infty$. The capacitance is '$4\pi\varepsilon a$'. Considering the earth as conduction sphere, we have the capacitance of the earth is approximately = 711.11μF! Since earth is not a perfect conductor, the capacitance will be even lesser!

This re-iterates that the earth is not the system that has high capacitance. However, the 'earth or ground' must have the ability to conduct and distribute the charge over its spread. In the view of this the conductivity of the earth must be as high as possible, at least over the region covering the system span.

5.1.1 Earth System for lightening protection

Lightening is a natural process where friction of storm clouds results in the cloud getting polarised with static charge. Generally the top of the storm-cloud gets +vely charged and the portion facing the earth gets negatively charged. This induces +ve charge on the earth surface near the cloud. In this process generates a large voltage, 1 00V to even up to 100s of million volts, between the earth and the cloud. The process of lightening stroke is illustrated in Fig. 5.3. The currents of discharge could from 10000 A to 20,000 A. The duration is generally from a few microseconds to one second. The protection from such attacks is provided by creating a 'bypass path, that avoiding the system components for the high currents.

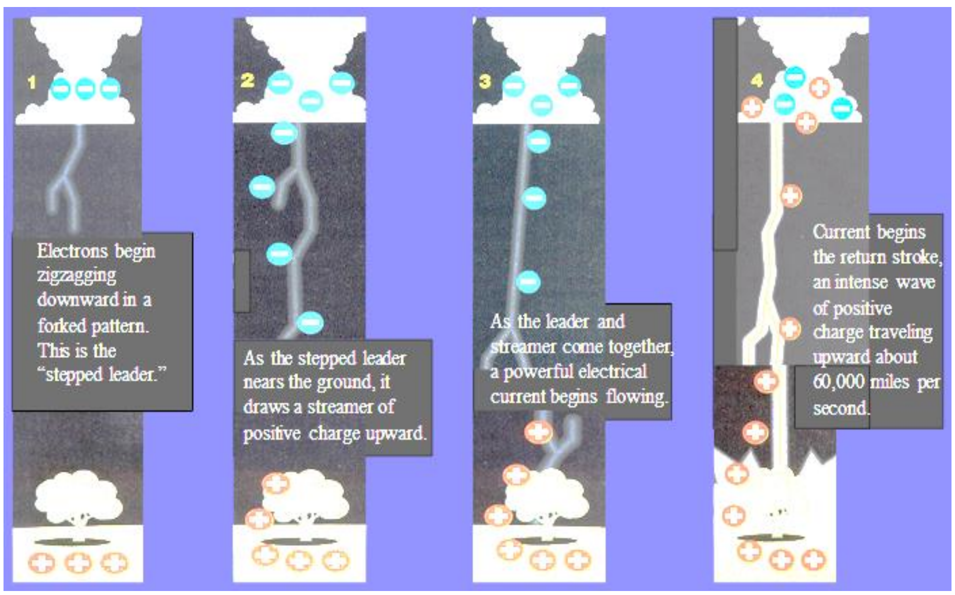


Fig 5.2 Static charge generation and movement in a lightning stroke

Source: *https://www.usps.org/national/eddept/me/files/ch_6_lightning_slides%20042509.ppt*

This is done by creating artificial lead for diverting such currents to the earth. Fig. 5.3 shows the positioning of the 'lightening arrestors' and zone of protection.

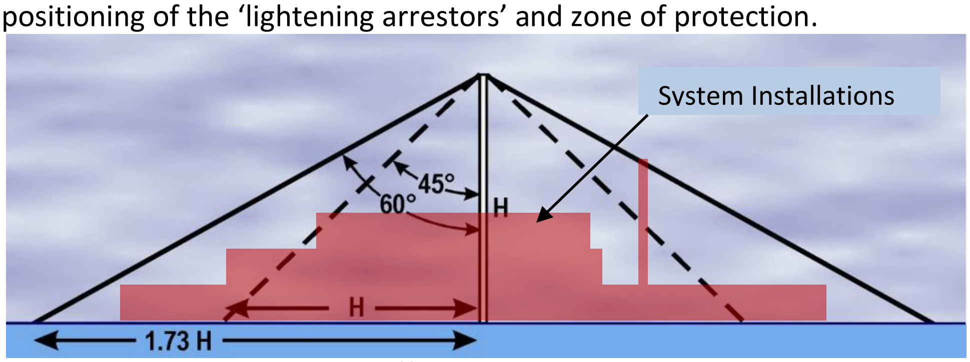


Fig 5.3 Protection offered by the lightening arresters

(Objects in 60^0 are protected 99% while those in 45^0 are 99.9% of times)

The main ground or system earth is the reference point of earth/ ground functionality. This is realized by installing an 'earth-electrode' in the ground. A typical earth pit construction is as shown in Fig. 5.4. The underlying principle of earth protection system is to maintain very low impedance and high current capacity path to 'main ground' or 'system earth'. This is ensured by using thick copper conductor from the lightening arrester installed above to the earth electrode. For small installations, the copper conductor cross section should be more than 14 mm^2, thicker than AWG 6. Any type of joints, painting and any activity that may increase impedance, introduces capacitances or inductances. Generally earth systems have at most one bolting joint in the path. This joint ensures a large surface contact and is protected from environmental degradation using gels like silicone grease.

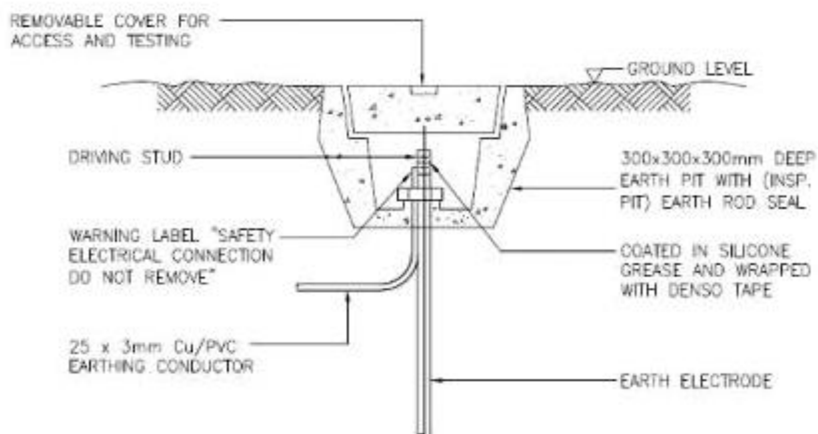


Fig 5.4 Typical structure of the electrical earth

Source: https://www.electricveda.com/building-services/electrodes-for-earthing-or-grounding-system-in-building-construction

Apart from lightening, the electrical current discharge attacks are also possible due to accidental situations like short circuiting to power supply line to some of system parts or floor on which the system is installed, see Fig. 5.5. The unwanted current is diverted from the system components by providing metal enclosures to the system components. These protective metallic enclosures and structural components (chassis) are interconnected and finally connected to the system 'earth'.

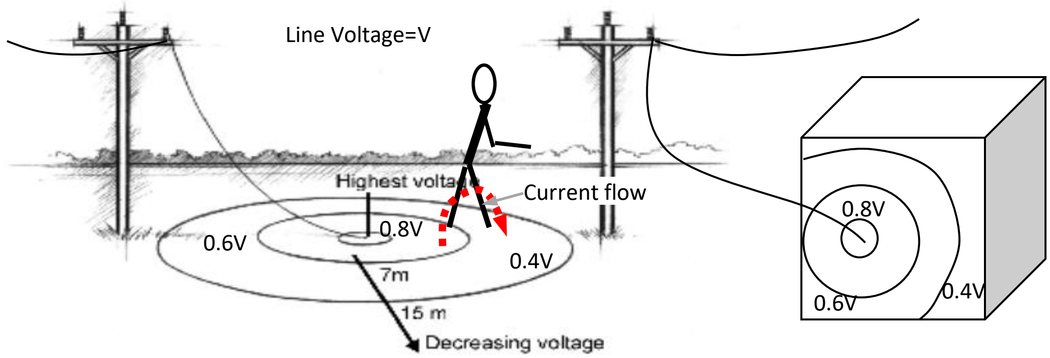


Fig 5.3 Broken transmission line: Sketch showing voltage gradient on land & on system enclosure

Simultaneously touching two points in the gradient area results in current discharge through the body

5.2 Equipotential plane and grounding

In addition to the protection, metallic enclosures perform the function of shielding the system from high EM fields in the exterior of the system. The shielding aspect of the enclosures is discussed in Section 4.3. In a distributed systems the metallic enclosures also functions as a reference plane. It is also known as 'equipotential plane'. The connection schemes for power installations, Low frequency circuits and high frequency circuits are different. However, the rationale behind these differences is the same. We shall have discussion on this point in this section.

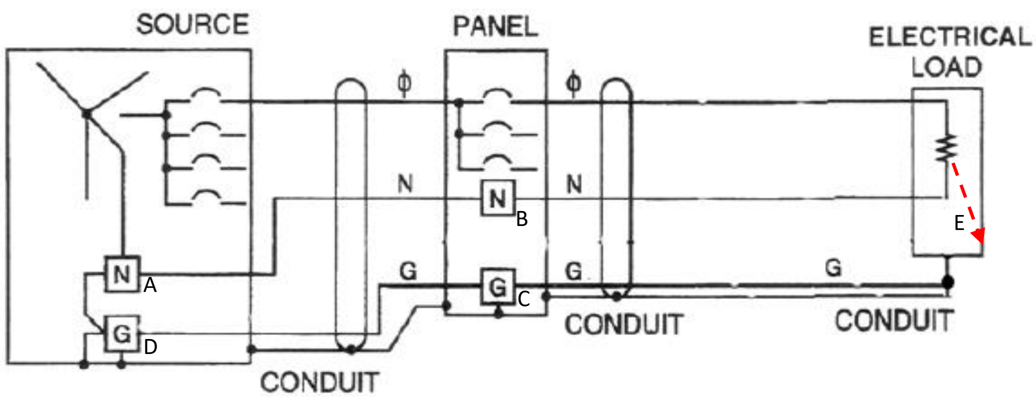


Fig 5.4 Standard ground connections for a typical electrical installation.
(Source: qtwork.tudelft.nl/~schouten/linkload/grounding.pdf). Fault Occurrence is shown by dashed red line

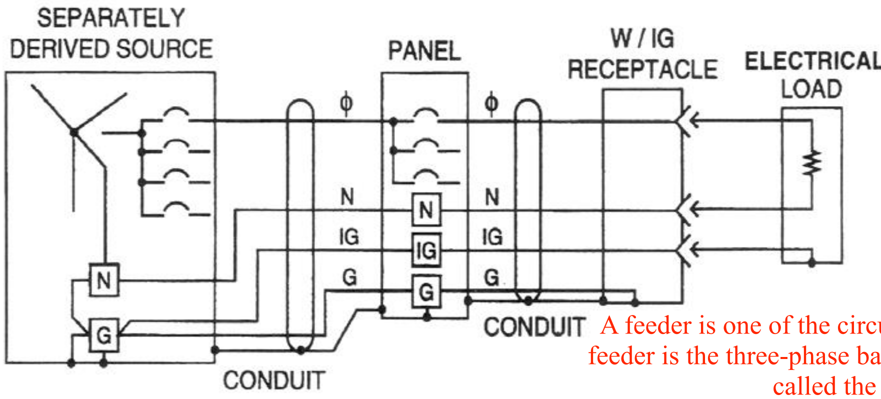
In normal electrical installations, the grounding connections are continued done as shown in Fig. 5.4. It may be noted that at every location, The enclosure (chassis) ground is locally connected to the 'main ground/ system earth' locally. This is because; functionally independent units must maintain individual earth connections. In this context, any unit/ system having all electrical activities (except power supply lines) confined within itself is referred 'functionally independent' unit.

cable conduit : separate line

It may also be noted that the classical/ standard ground maintains the chassis and earth connectivity to the main distribution transformer through cable conduit. This system requires mechanical integrity (all connections make excellent 'Ohmic contact (a contact that offers only resistance and no inductance or capacitances)' with a very low resistance so as not to disturb the other installations. The concept of 'non-disturbance' is vague and it changes with context. This can be explained by following example.

Consider a fault (or current leakage) happens at the load side resulting in establishing connection from one of the power lines (or neutral line) and the ground with an impedance of 'E'. Impedances of the contacts are A, B, C and D, as shown. The fault situation at load will disturb the voltages at panel as well as the source. The effect will be minimal if A,B,C,D << E. In such situations, it is said that the contact resistances are appropriate (does not create disturbance to other installations). In normal circumstances the "earth leakage circuit breaker (ELCB) would open at the load and the supply will be disconnected.

In power supply grids, with multiple connections, it is difficult to ensure, good contact resistances at all the locations. It is a good practice to maintain every independent installation, at least the critical ones, to maintain 'isolated ground' for electrical loads (typically a machine shop). The isolated ground connection is carries to the main ground (or system earth without connecting to the other grounds in the path, see Fig. 5.5.



A feeder is one of the circuits out of the substation. The main feeder is the three-phase backbone of the circuit, which is often called the mains or mainline.

Fig 5.5 Connecting ground with 'ground-isolation' to the load

(Source: qtwork.tudelft.nl/~schouten/linkload/grounding.pdf)

Bulk power distribution is always done with 3-phase line supply feeders. These feeders operate at line voltages of 11kV, 22kV, 33 kV ... 132kV. These feeders almost always have long distance (a few km o 100 km) 'supply hop'. Underground feeder lines have conduits and the overhead lines do not conduits. Therefore, it is impractical, inappropriate and sometimes impossible to maintain 'main-ground'/ 'system earth' connection to the other end. due to such a large distance it is not practical to have one more line

On the load distribution side, there is a mix of single-phase and three-phase loads. Therefore on the load side, there is 4-wire (RYB & N) system. The voltage level on the consumer side is also low; 415 Vac. There is a step down transformer, which also provides isolation between the feeder and the load side. The ground connections for the isolation transformer are shown in Fig 5.6.

feeder is just the line coming from

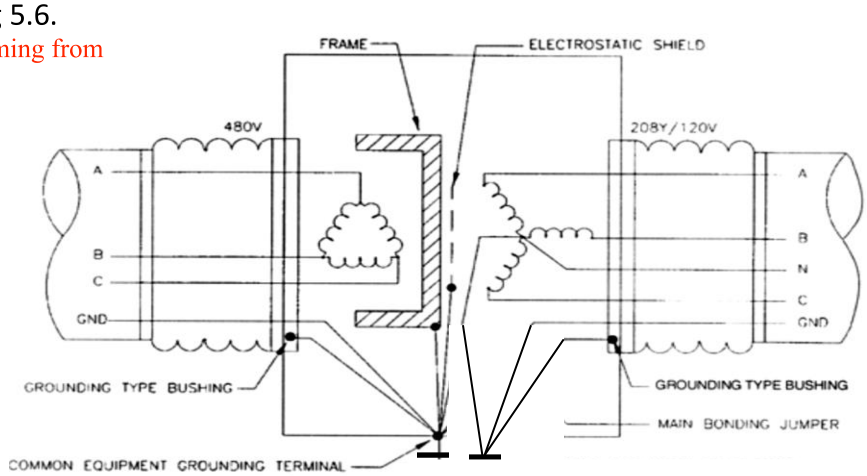


Fig 5.6 Ground connections for isolation transformer Connecting ground with 'ground-isolation' to the load (Source: qtwork.tudelft.nl/~schouten/linkload/grounding.pdf)

In all the above grounding schemes it may be noted the neutral connection is maintained as isolated connection and connected to the 'main-ground' or 'system-earth' through directly (at the transformer location). This automatically means that at the user end, the neutral MUST not be connected to ground. This is because; neutral is the 'supply return' path. In the next section we shall discuss the grounding requirements of supply return and the signal return.

Main reason of connecting neutral line to ground is to take care of the unbalanced (different loads in different phases) load.

Fig. 5.6 shows that the ground connections performing different functions are connected directly to the earth; namely, shield, conduits, structural members, feeder ground and utility ground. This connection topology is called 'star connection' or 'single point ground (SPG)'. This topology ensures that current flowing in one connection does not introduce voltage in other. We have already seen that the daisy chain connection of ground leads to introduction of voltage in the ground circuit of other installations (4th paragraph, of section 5.2 with reference of Fig. 5.4). The ground connections are ideally expected to have zero impedance. However, in practice it has finite impedance as shown in Fig 5.7. The maximum expected current through each ground current is estimated. The impedance of each link is kept low so as to limit the voltage drop in ground connection to acceptable level. Knowing the length, the conductor cross section is decided to keep the resistance of the ground link.

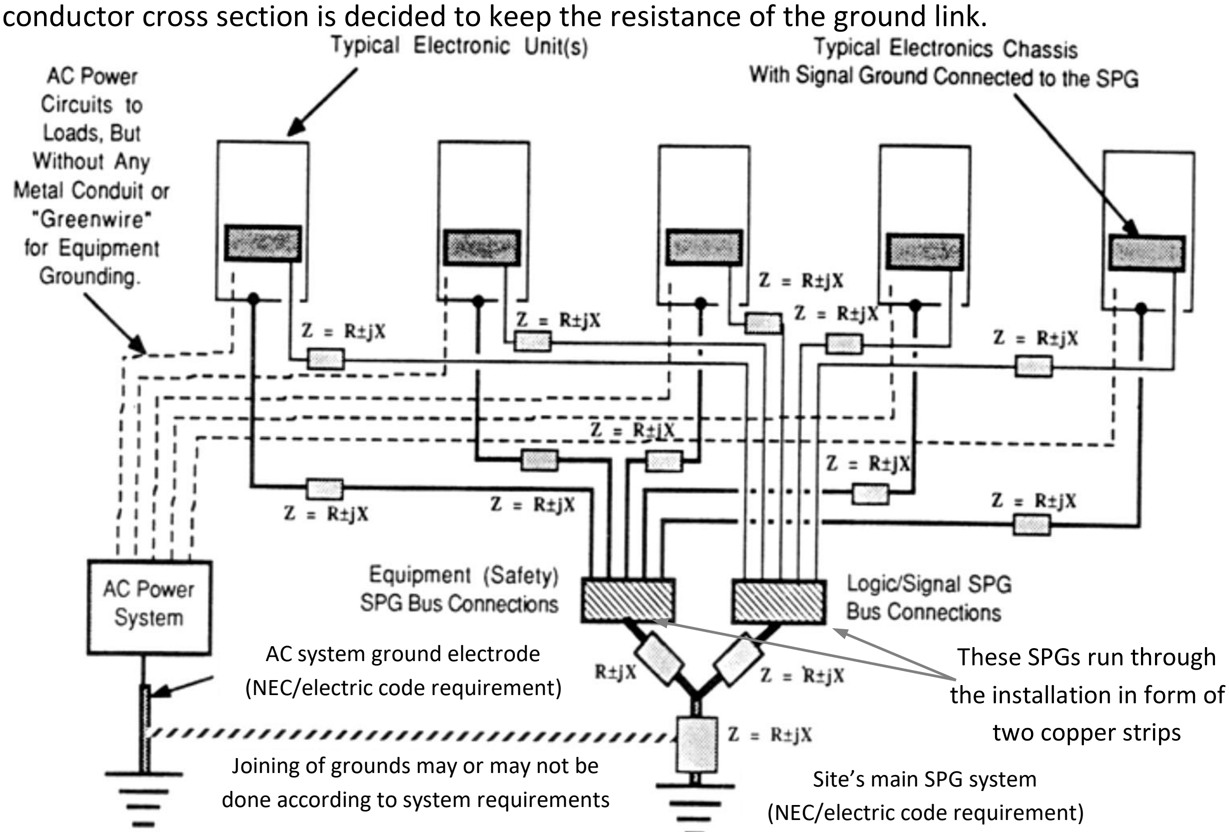


Fig 5.7 Connection impedances in single point grounding system
(Source: qtwork.tudelft.nl/~schouten/linkload/grounding.pdf)

The resistance is calculated using (5.4).

$$Resistance(R) = \frac{\rho(resistivity) \times l(length)}{A(cross\,sectional)} \qquad \ldots \quad (5.4)$$

The resistivity of Cu= 1.68 X 10^{-8} Ω.m (for annealed, 1.72 X 10^{-8}); and for Al= 2.65 X 10^{-8}.
The inductance of the circular conductor is given by (5.5)

$$L(\mu H) = 0.002 \times l(cm)\left(\ln\left(\frac{4 \times l(cm)}{d(cm)}\right) - 0.75\right) \quad \text{... (5.5)}$$

Where, d is the diameter of the conductor. The inductance for a strip is given by (5.6)

$$L(\mu H) = 0.002 \times l(cm)\left(\left(\ln\left(\frac{2 \times l(cm)}{b(cm) + c(cm)}\right)\right) + 0.5 + \left(0.2235 \times \frac{b+c}{l}\right)\right) \quad \text{... (5.6)}$$

Where, b is the strip-width and c is the thickness.
If a conductor is kept as coil, approximate inductance is given by (5.7);

$$L(coil, \mu\text{H}) = \frac{r^2 \times N(coillength, inches)^2}{9r(inches) + 10d(inches)} \quad \text{... (5.7)}$$

(Source: Vladimir Kraz, https://www.slideserve.com/vernon/emc-for-semiconductor-manufacturing-facility-equipment-electromagnetic-compatibility-and-e33-directions)

Both these expressions are empirical and practically valid for frequencies of a few hundred kHz. (Ref: qtwork.tudelft.nl/~schouten/linkload/grounding.pdf). At frequencies higher than HF band, these expressions give erroneous results.

For the above discussion, it is seen that looped and daisy-chained ground connections introduce unwanted voltage in other ground circuit. Therefore, star connection or single point ground (SPG) topology is the best for effective grounding functionality. However, in distributed system SPG connections become complex/ impractical. In this view, the low current ground circuits may be connected in loop on the high current ones, se Fig. 5.8.

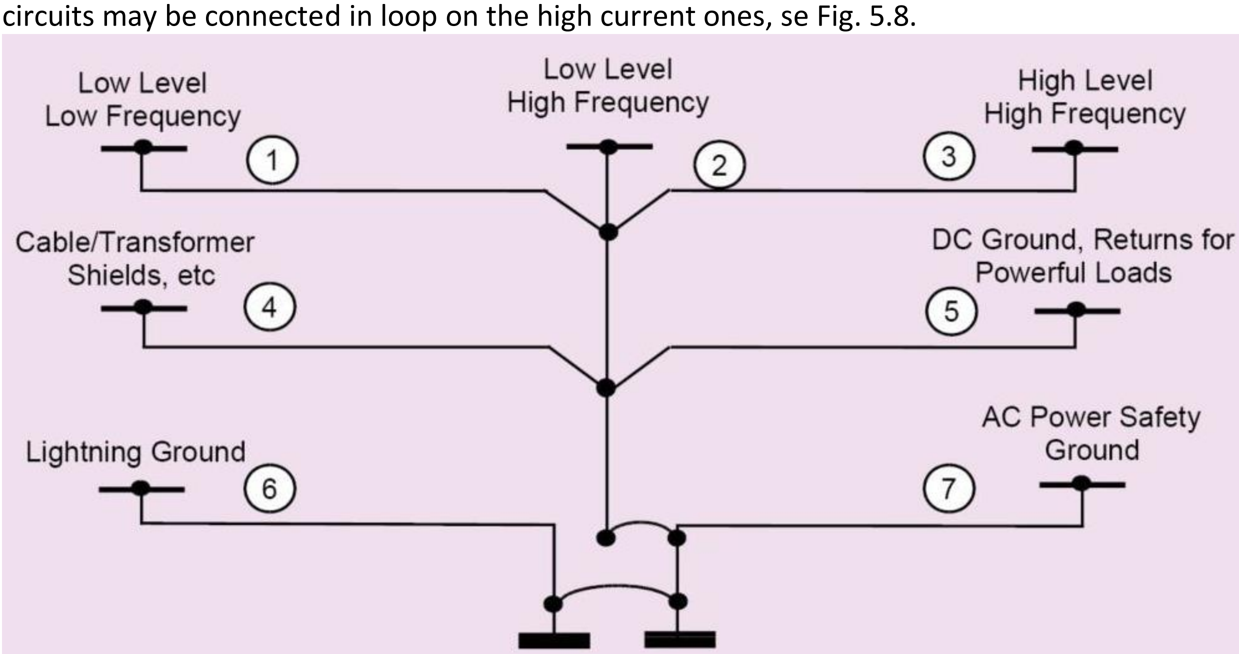
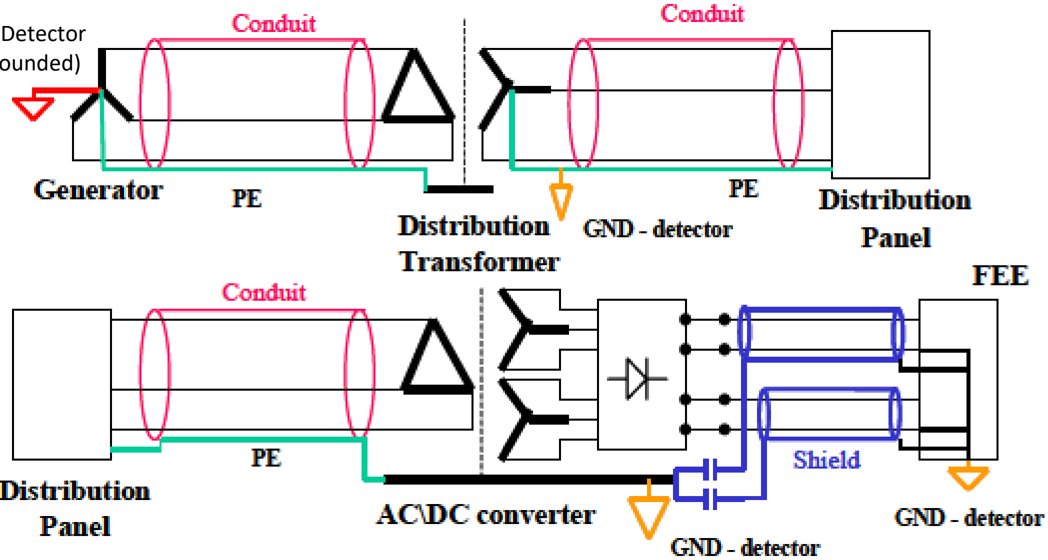


Fig 5.8 Allowable looping for minimal ground interference

External electromagnetic pick-ups and faults in the system lead to currents in ground connections. These currents are detected by putting ground detectors at appropriate locations. If this current is more than safety/ allowable limit, corresponding part of the circuit is isolated by switching off the power. This 'sensor-switch' is known as 'Earth Leakage Circuit Breaker (ELCB). The recommended location of ground detectors is shown in Fig 5.9.



5.3 Signal return

From the foregone sections of this chapter, it is clear that the ground connections like safety earth, chassis ground etc. are not required for the correct operations of the system. Under normal circumstances, no current should flow through safety and reference grounds. These connections are incorporated to divert the electromagnetic pick-ups and hazards.

On the other hand, the 'signal return' connection is necessary for the system functioning. All the electrical and electronic circuits need signal return. In order to interpret the signals, they must be 'referenced' to some voltage level. Hence they have to be ultimately connected to the ground. It may also be noted that the neutral line is also 'signal return' for the AC power supply. The grounding schemes need to be planned depending on the nature of the signal and required sensitivities. There is no strategy which works for all cases.

We shall discuss grounding issues in the context of following cases.

1. **Sensor and data communication signal:** These signals are generally low current signals. Small EMI also leads to error. Balanced lines (lines with no 'reference potential' levels) are generally used for these signals. Fig 5.10 shows the circuit schematic.

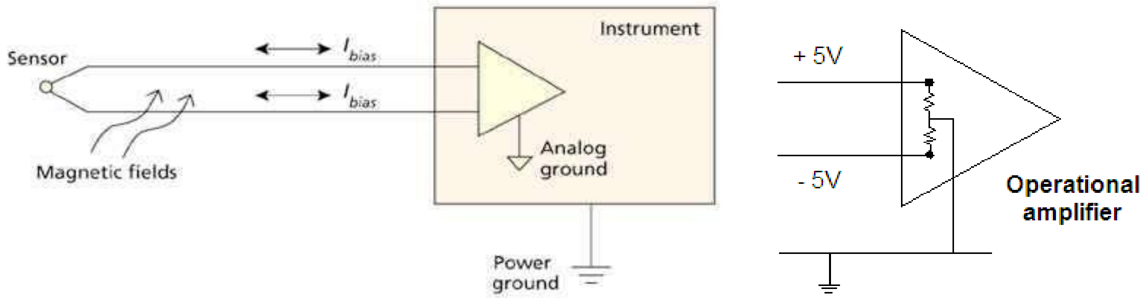


Fig 5.10 Balanced line arrangement for receiving sensor signals
(Source: Martin Rowe, “Grounding and shielding: No size fits all” Electronics Design Center, Aug 2001)

The common mode noise gets induced almost identically on both the signal lines. Thus, this arrangement is immune to common mode noise. These lines do not share any voltage reference with external sources. Therefore, the differential mode noise cannot enter. The signal lines are further processed with either isolated or balanced circuitry. It is important to have separate (not directly/ solidly connected) ground points see Fig 5.11. These two grounds maintain induced common voltage between them. The two grounds MUST NOT be connected.

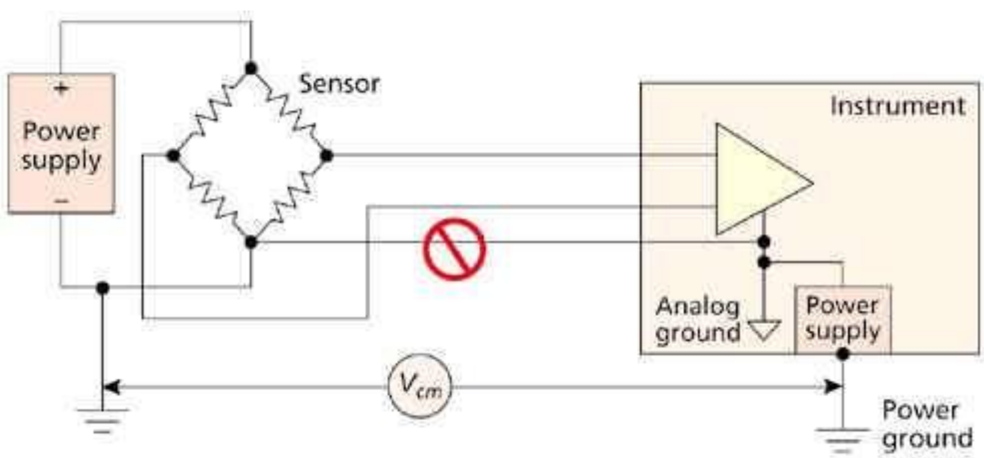


Fig 5.11 Balanced line arrangement for receiving sensor signals
(Source: Martin Rowe, “Grounding and shielding: No size fits all” Electronics Design Center, Aug 2001)

For the same reason the shield needs to be grounded at one end only See Fig 5.12
The V_{cm} will make some current flow through the shield. On the other hand, we know that a conductor grounded at one end may function like a ‘monopole-antenna’! In case of sensors, the signal is DC or near DC. However, fast data transfer signals have the bit-rates in VHF-UHB bands. The length of the cable shields being comparable to the wavelength of the EM waves at these frequencies. Knowing the frequencies and the inductance of the shield it is possible to choose the capacitor values to supress the radiation. Modelling this arrangement as series resonant circuit, maximum attenuation at frequency ‘f’is achieved when, $f = \frac{1}{2\sqrt{L_{shield} C}}$.

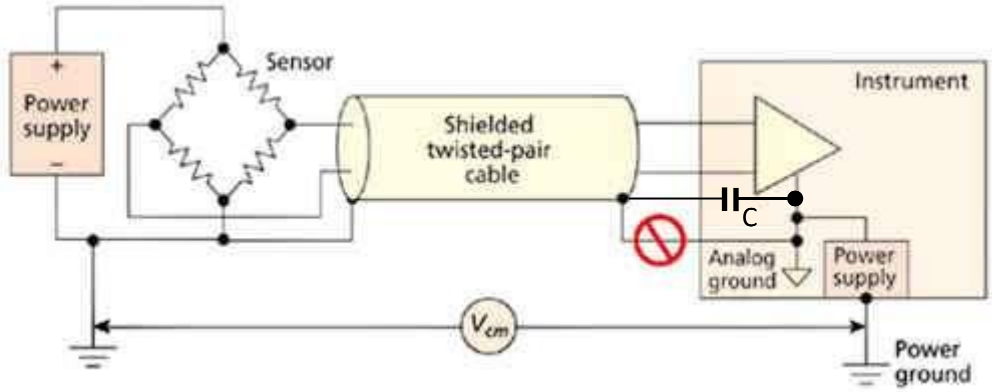


Fig 5.11 Balanced line arrangement for receiving sensor signals
(Source: Martin Rowe, "Grounding and shielding: No size fits all" Electronics Design Center, Aug 2001)

2. **Analog and digital ground (signal return):** Modern electronic circuitry often has to deal with analog as well as digital signals. Generally the digital ground (signal return for digital circuitry, GND_{dig}) has considerable amount of noise. This is due to the fact that the digital signals have transition between two voltage levels (e.g. 3.3 Volts) with abrupt transients. This signal induces differential mode noise on the GND_{dig}. On the other hand anolog signal's integrity mainly depends on the correctness of voltage on the signal line. Due to this fact, analog and digital grounds are never connected on circuit boards. They meet on the single point ground point (SPG). Detailed address to this issue is discussed in Chapter 6.

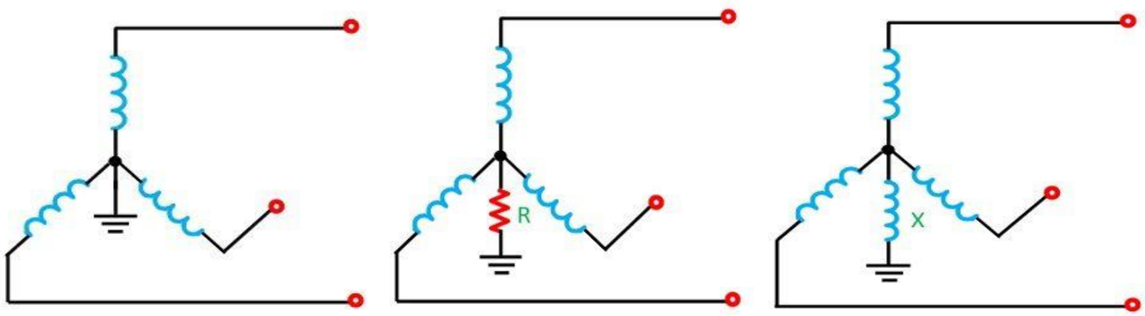
3. **Neutral Grounding:** Neutral being signal return for the AC power system need to be grounded except for perfectly balanced load and power transmission lines, where there is no neutral line.
   Some of the advantages of the neutral grounding are as follows:
   - Voltages of phases are limited to the line-to-ground voltages.
   - Surge voltage due to arcing grounds is eliminated.
   - The over voltages due to lightning discharged to ground.
   - It provides greater safety to personnel and equipment.
   - It provides improved service reliability.

Neutral is grounded in one of the following methods. See Fig. 5.12.

(a) Solid grounding (or effective grounding): In this method, the neutral is connected to the ground with a conductor with negligible resistance and high current capacity (commensurate with the power handling capacity of the power system.

However, this method has a disadvantage in fault conditions where one of the phases short. Fig 5.13(a), shows the fault at phase a, making its voltage zero. The remaining two phases, b and c will still have the same voltages as before. In addition to the charging current the power source also feeds the fault current. This may increase more than the safe limit. Such high currents damage other equipment in the vicinity due to the EMI.

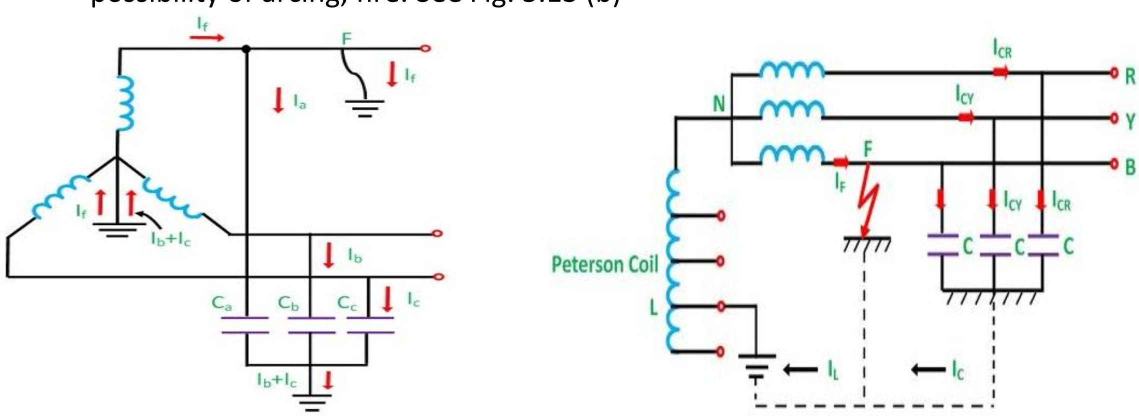
Other methods, attempt to limit the current by introducing some impedance.



5.12 Basic types of neutral grounding (a) Solid (b) Using resistance (c) Using reactance
(Source: https://circuitglobe.com/neutral-grounding.html)

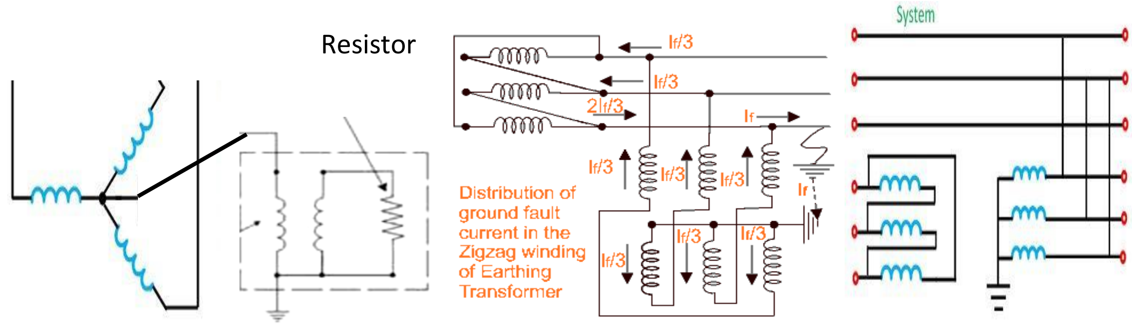
(b) Resistance grounding: In this type of neutral grounding, the neutral of the system is connected to ground through one or more resistance. Resistance grounding limits the fault currents. It protects the system from transient over-voltages. Resistance grounding decreases the arcing grounding risk and permits ground-fault protection.

(c) Reactance grounding: Very low resistance makes the system equivalent to solidity grounded, whereas a very high resistance makes it ungrounded. However, it is necessary to limit the ground current to 5% to 20% of that which occur with a three-phase line. This is better achieved by reactive (inductive) grounding. It also achieves suppression of transients. Peterson coil grounding is a special case of reactive grounding where the inductance is tuned to match the fault current to the current through inductor. This makes the ground current zero and eliminates the possibility of arcing, fire. See Fig. 5.13 (b)



(a) Grounding using capacitors) (b) Peterson Coil Grounding
Fig 5.13 Reactance grounding

(d)Transformer grounding: Modern trends in providing a current limit in case of earth fault on one or more) of the phases is the use of transformers. Neutral grounding transformer connections are shown in 5.14(a). This connection offers advantages of resistance as well as reactive grounding of the neutral line. Current limit on short current transients can be achieved by grounding transformers even on 3 line system. In this systems, neutral line is absent. Two types of connections are used; zig-zag transformer, shown in Fig 5.14(b) and using star-delta transformer shown in Fig 5.14(c)



(a)Neutral grounding (single phase)   (b)Zig-Zag transformer   (c)Star-Delta Transformer

Fig 5.14 Use of grounding transformers for limiting the fault current

The guidelines discussed above are for handling the ‘signal return’ lines for lower loop currents, and lower amplitude fault currents. These precautions ensure that unwanted currents will be eliminated or minimized. This limits in the event of fault. It also reduces the EMI in normal operation conditions.

5.4 Numerical problems