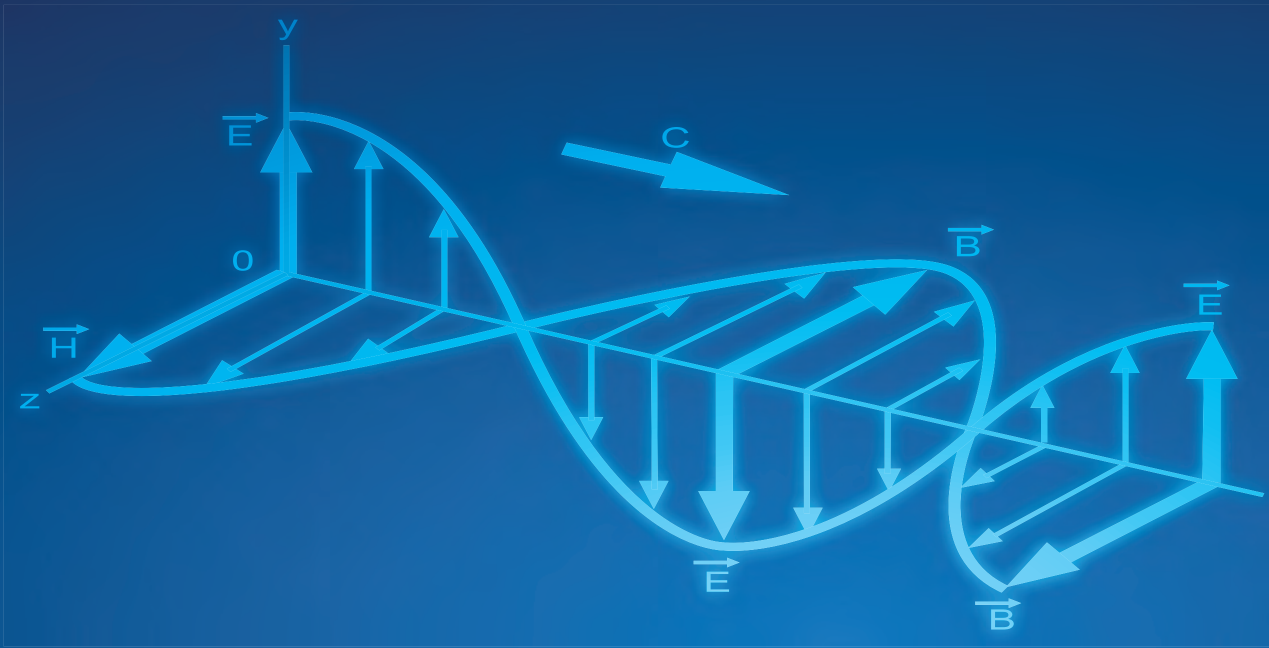

EMC BOOK OF KNOWLEDGE

Practical tips for the User

By Steve Roberts M.Sc. B.Sc.
Innovation Manager, RECOM

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RECOM

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2023 Edition

Special thanks to Simone Starlinger from SISTA Marketingwerkstatt for typesetting, getting the graphics into shape, and generally for her ability to work within impossible deadlines. Our thanks also to Schwarzbeck MESS-ELEKTRONIK OHG for permission to use their images in Chapter 10.

This book is a work in progress, so Josy and I welcome suggestions for any improvements or corrections. Please send your recommendations to **s.roberts@recom-power.com.**

Preface from the Authors

This EMC Book of Knowledge is a companion book to the RECOM AC/DC and DC/DC Books of Knowledge. They are designed to be read together, so we have deliberately avoided repeating information except where it is necessary for clarity.

Electromagnetic Compatibility (EMC) is a broad subject. A huge number of books, application notes, and technical papers are available on the topic, in print as well as online. Sometimes, it can be difficult to find practical information amidst the mass of literature available on the subject. Therefore, we decided to provide a general overview that would serve as a useful guide for an engineer or student who needs to know about EMC but is not necessarily an expert.

We appreciate that some EMC topics have had whole textbooks written about them, which we may have dismissed in just a few sentences, and other topics that are deserving of far more detail than we have had space for in this book. We have had to tread a fine line between giving concise, practical, and useful information to a majority of the readers without being overly wordy about topics that we find fascinating, but might not interest everyone. We hope that we have got the balance about right.

This book is a ‘work in progress’, so feel free to contact us if you find any errors, omissions, or inaccuracies and we will get them corrected.

Steve Roberts and Josy Lametschwandtner
Gmunden, Nov. 2022

Introduction

As mentioned in the preface, EMC is a very broad subject that covers a wide range of applications. Owing to necessity, we have focused on the basics alone, as they apply to power supplies. Compliance with EMC (electromagnetic compatibility) regulations is mandatory in almost all global markets, to be allowed to sell electronic devices in Europe as well as the important US and Asian markets.

In general, the EMC regulations can be split up into five broad areas:

1. The device should not emit excessive EM signals (electromagnetic signals)) along its power cables into the mains supply network or the load it is connected to.

2. The device should not radiate excessive EM signals into its environment, as it could cause interference with other equipment in the vicinity.

3. The device should not be susceptible to EM signals conducted into it through connection cables from external sources, as it can cause it to malfunction or fail.

4. The device should not be susceptible to EM signals radiation from external sources, as it will cause it to malfunction or fail.

5. The device should be robust against other sources of interference such as ESD (electrostatic discharge), high external magnetic or electric fields, or voltage surges and transients, the withstand limits being defined by the intended application or usage environment of the device.

In short, the device should not emit interference, nor be susceptible to external interference from other devices.

As can be inferred from these requirements, EMC is a double-edged weapon.

If the EMC regulations are ignored, then problems can swiftly occur. For example, a friend of mine works in a timber yard. He was assigned a new electric forklift truck in place of his old LPG-powered vehicle, to reduce pollution in his working environment. But he was not happy with the new machine because every time he turned on the powerful LED headlights, his radio stopped working. If the LED drivers in the headlights had been properly designed to meet the EMC regulations, then this issue would not have occurred.

Not being able to listen to the radio while working may not particularly seem to be a hardship; but if the same problem occurred between two medical devices that just happen to be placed next to each other, then the results could be life-threatening.
In today's modern world, as more and more electronic devices are being used in close proximity to each other, EMC regulations serve as an essential tool to enable electronic devices to

work as they should and not fail or cause other devices to fail simply because they are placed near each other or share the same mains outlet.

Every design engineer aims to produce products that pass the EMC testing in the first attempt. If in-house EMC testing facilities are not available, then it is not unusual having to wait for more than a month to obtain a free timeslot at an independent EMC laboratory, which typically charges testing fees that can easily exceed 1,000 Euros per day. So a first-time pass not only saves significant time but also prevents the project budget from being severely compromised.

A common complaint about products that fail to reach EMC compliance is that the product functions well, is efficient, and uses tried-and-tested topologies and components, but exceeds the limits for reasons that are not obvious. It can even seem like there is an element of 'black magic' when an experienced EMC engineer takes an existing design, makes what appears to be a trivial change, and then suddenly the power supply passes all the tests with flying colors. However, if you understand the basics of electromagnetic field theory and transmission, know how to find the sources of noise in your design and what countermeasures need to be implemented, and are aware of the limits that need to be reached, then a first-time pass can become much more likely.

This is the intention of this book. If just one engineer achieves a first-time pass because of the information we have presented here, then our efforts will have been richly rewarded.

Table of Contents

Chapter 1: EM Basics

1.1 EM Field Theory

1.1.1 E-Fields

If we take two parallel metal plates and connect a battery to them, then we create a simple capacitor, which has an electric field (E-field) between the plates:

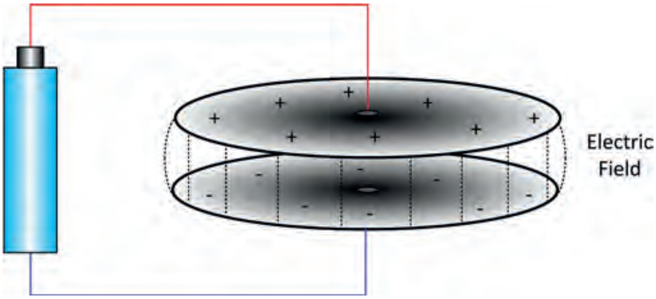


Fig. 1.1: Plate capacitor

The strength of the E-field is dependent on the voltage applied to the plates (V) and the distance between them (d):

$$E = \frac{V}{d}$$

Eq. 1.1: Plate capacitor E-field

Using a sensitive voltage probe, we can measure the electric field gradient around the plates:

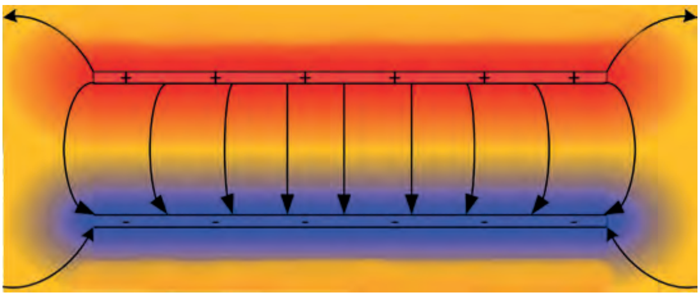


Fig. 1.2: Plate capacitor E-field gradient

What is immediately obvious is that the electric field is not limited to just between the two plates but 'bulges out' from the edges.

SUMMARY #1: An E-field is not restricted to just the space between two charged conductors.

1.1.2 H-Fields

If we take a coil of wire and connect a battery to it, then we create a simple solenoid that has a magnetic field (H-field), as shown below in purple:

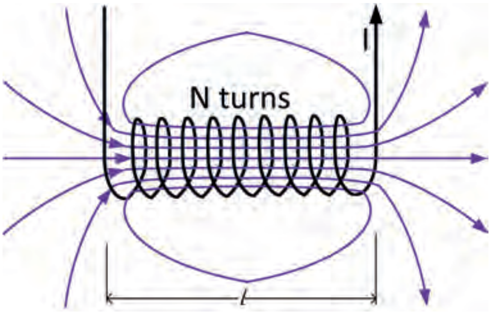


Fig. 1.3: Solenoid H-field

The strength of the H-field (also known as the magnetic flux density, B) inside the winding is dependent on the coil dimensions and the current flowing through it:

$$B = \mu_0 \mu r \frac{NI}{l}$$

Eq. 1.2: Solenoid H-field

WHERE N is the number of turns, l is the length of the winding, I is the current flowing through it, and μ_0 is a number called the magnetic constant (approximately equal to 1.26 x 10^{-6} Hm^{-1} in air, but will have other values if, for example, an iron core was inserted into the solenoid). Using a sensitive magnetic probe, we could measure the magnetic field gradient around the solenoid (or inductor, to give it a more generic name), then we would measure something like this:

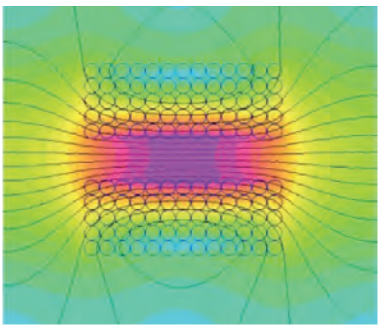


Fig. 1.4: Solenoid H-field gradient

What is immediately obvious is that the magnetic field is not limited to just inside the coil but ‘bulges out’ from the ends.

SUMMARY #2: An H-field is not restricted to just the space inside an inductor.

1.1.3 EM-Fields

So far, we considered only simple static DC (Direct Voltage/Current) situations. But if the energy supplied was AC (Alternating Current), then the situation does get more complicated. This is because every non-DC current is a wave of propagating electro-magnetic (EM) energy, which spreads out as EM-fields at right angles:

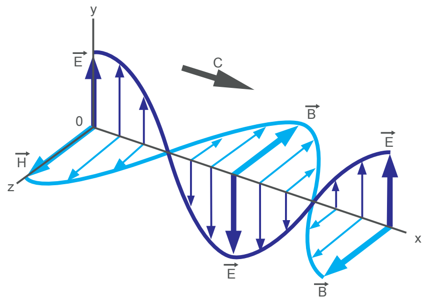


Fig. 1.5: EM wave propagation

This means that even a single straight conductor can generate both an electric E-field and a magnetic H-field as the EM wave moves along the wire (voltages create E-fields, currents create H-fields, and fluctuating currents and voltages create EM-fields).
The Maxwell-Faraday equation tells us that a varying magnetic field vector (**B**) produces a circularly moving electric field (E):

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

Eq. 1.3: Maxwell-Faraday equation

The triangle symbol is called the 'curl operator', which means that the field spreads out in three-dimensional space. **B** is written in bold because it is a vector, with both magnitude and direction. ∂t means that the result is time-dependent, so shorter time periods (higher frequencies) will generate stronger E-fields.
The Ampere-Maxwell equation tells us that a varying electric field vector (**E**) induces a changing magnetic field vector(**B**):

$$\nabla \times \boldsymbol{B} = \mu_0 (\boldsymbol{J} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t})$$

Eq. 1.4: Ampere-Maxwell equation

B, **E**, and **J** (electric current density) are all written in bold because they are vectors. μ_0, as we have already seen, is the magnetic constant (magnetic permeability of free space) and ε_0 is its equivalent electric constant (electric permittivity of free space). ∂t means that the result is time-dependent, so shorter time periods (higher frequencies) will generate stronger B-fields.

SUMMARY #3: For AC currents and voltages, electric and magnetic fields are intertwined as transverse EM-fields and spread out in three dimensions, thus becoming stronger at higher frequencies[1].

1.2 Wavelength and Frequency

As mentioned above, the strength of EM-fields increases with increasing frequency. Any EM wave propagating along a conductor will pass more easily or be restricted, depending on the ratio between the wavelength of the signal and the conductor dimensions.

In most electronic circuit layouts, EM-field losses start becoming significant above 10 MHz. EM waves also have power (Wm^{-2}), meaning that any EM energy lost in conductor impedances will be converted into heat. This power loss can be good (e.g., an EMC filter, blocking or dissipating unwanted EM energy) or bad (e.g., excessive losses in power circuits).

1.3 Propagation Velocity

The characteristic impedance of free space, Z_0, determines how EM waves travel through a vacuum. This is simply the product of the speed of light in a vacuum (C_0) and the magnetic permeability in the vacuum, μ_0. The accepted figure for Z_0 is approximately 377Ω. All materials (both conductors and insulators) will have a relative magnetic permeability (μ_R) and an electric permittivity (ε_R), which will differ depending on the type of material and alter its characteristic impedance, Z:

$$Z_{material} = 377\Omega\sqrt{\mu_R/\varepsilon_R}$$

Eq. 1.5: Characteristic impedance of a material

This impedance will also slow down the propagation velocity of the EM wave and change its wavelength, λ:

$$\lambda_{material} = \frac{c_0}{f\sqrt{\mu_R/\varepsilon_R}}$$

Eq. 1.6: EM propagation wavelength in a material

What all these equations mean in practice is that for a PCB trace, the impedance will be higher than in free space and cause the EM wave to propagate more slowly, with a wavelength of around half of what it would be in air for the same frequency.

[1]Considering a more complicated scenario, a long enough conductor cannot have the same instantaneous current and voltage along its entire length, so even switching a DC current or voltage on or off will create an EM wave and generate EM-fields along the conductor.

We usually ignore wave effects if the conductor dimensions are less than 1/100th of the wavelength, meaning for a 1GHz signal, any dimension a, smaller than 3mm in air (λ = 300mm), or 1.5mm on an FR4 PCB (λ = 150mm), will not have any significant frequency-dependent effects. However, the corollary is that track dimensions larger than 1.5mm can cause significant propagation problems at gigahertz frequencies.

1.4 Return Currents

All electronic power and signals MUST flow in a loop and have both send and return paths. So, any frequency-dependent impedances in either the send or the return legs will affect the overall signal and power integrity. This is why EM-wave propagation effects are extremely important in circuit design.

Like water flowing across a plain, electrical currents will always take the path of least resistance, in other words, for AC currents the path of least impedance. This is very often the path with the smallest possible enclosed loop area, meaning that AC return currents will flow as close as possible to the send path as they can. This means that AC return currents will appear to “choose” to flow via a different route, even if the DC resistance is lower for the intended path.

SUMMARY #4: Conductor impedances measured at DC have little or no meaning at higher frequencies.

Chapter 2: Analysis

In the previous chapter, we learned that electric fields propagate along conductors with a wavelength dependent on the material.

If the conductor dimensions are less than one-sixth of this wavelength, we can use lumped circuit analysis to describe the current flow; that is, we can use conventional resistance, inductance, and capacitance values.

If the conductor dimensions are more than one-sixth of this wavelength, we must use transmission line analysis to describe the current flow; in this case, we have to additionally consider resonances, reflections, and standing waves.

EM wave analysis can get more complex in two or three dimensions, for example, when current flows through a conducting plane or within a metal box, in which case, a full wave analysis based on Maxwell's equations mentioned previously has to be done.

2.1 Lumped Circuit Analysis

Everything has resistance, inductance, and capacitance including all materials, components, tracks, connectors and wires. These values can be intrinsic (associated with the part itself, for example, the resistance of a length of PCB track), or extrinsic (associated with its proximity to other elements, for example, the stray capacitance between the track and a ground plane on the bottom side of the PCB).

In lumped circuit analysis, these distributed resistance, inductance, and capacitance values are 'lumped' together into single equivalent values; so, we can replace all the individual intrinsic and extrinsic values with single equivalent values.

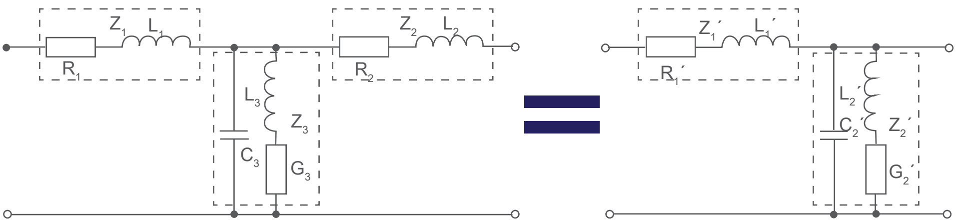


Fig. 2.1: Distributed circuit vs. lumped circuit equivalent for a PCB track

A similar analysis can be carried out on a single component, such as an inductor:

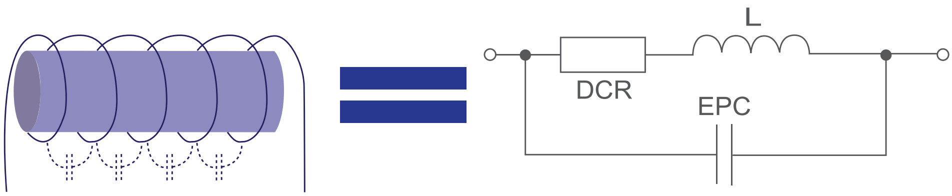


Fig. 2.2: Distributed circuit vs. lumped circuit equivalent for a wire-wound inductor.

DCR is the DC resistance of the wire, L is the inductance, and EPC is the Equivalent Parallel Capacitance, which is the sum of all the individual turn-to-turn capacitances.
The analysis of lumped circuits follows the familiar V-I equations:

$$V = IR$$
$$I = C\frac{dV}{dt}$$
$$V = L\frac{dI}{dt}$$

Eq. 2.1: Standard lumped circuit analysis relationships

Any inductances and capacitances (both intrinsic and extrinsic) will store energy in their own E and H fields, which will cause resonance effects at certain frequencies:

$$f_{resonance} = \frac{1}{2\pi\sqrt{LC}}$$

Eq. 2.2: Resonance frequency

In practice, this means that at frequencies above the resonance frequency, the capacitive elements will start becoming more prominent in inductors and the inductive elements will start becoming more prominent in capacitors, often leading to unexpected results:

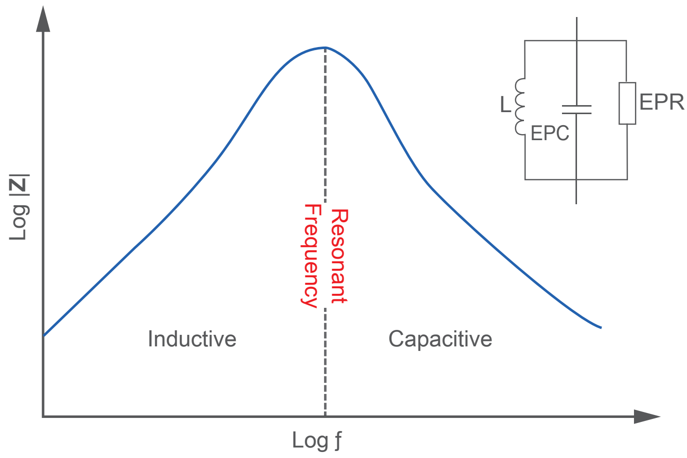


Fig. 2.3: Frequency response of an inductor

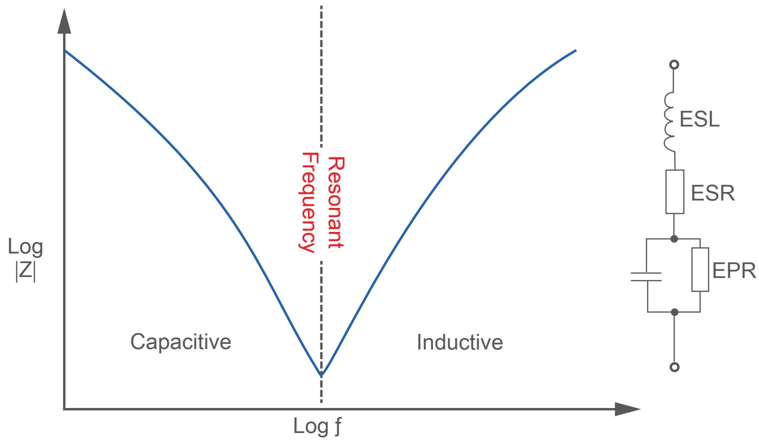


Fig. 2.4: Frequency response of a capacitor

SUMMARY #5: Inductors can behave like capacitors and capacitors can behave like inductors!

The effects of these component resonances are damped by the resistances in the circuit, so can be ignored if well-damped or if the component is used at frequencies well below the resonance frequency; but they can cause serious consequences if they get out of hand.

The self-resonant frequency is dependent on the construction parameters of the component in question (its intrinsic R, L, and C values); but the extrinsic or parasitic elements are mostly

dependent on its proximity to other parts, conductors, or materials. Stray inductance will increase if ferromagnetic materials are in the vicinity, but decrease if non-ferrous conductors are nearby. Stray capacitance will increase in proximity to both high permittivity dielectrics such as insulation materials and other conductors. The effect of these stray or parasitic elements will increase with frequency or rate-of-change of voltage or current (slew rates) and will add other peaks and troughs to the simplistic frequency response shown above.
A short-hand way of indicating that a circuit element has a frequency-dependent reactance as well as a DC resistance is to use Z (impedance):

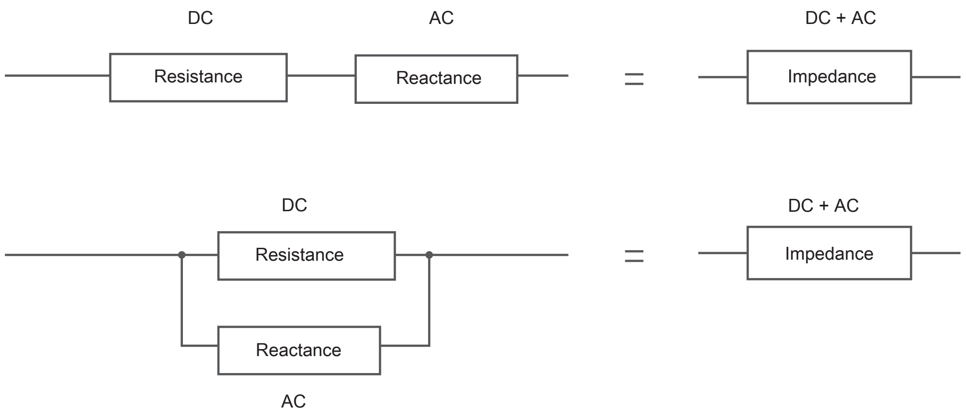


Fig. 2.5: DC resistance + reactance for an inductive (top) and a capacitive (bottom) element

The above diagram is a simple one. When active components are considered, parasitics further complicate the AC impedance response:

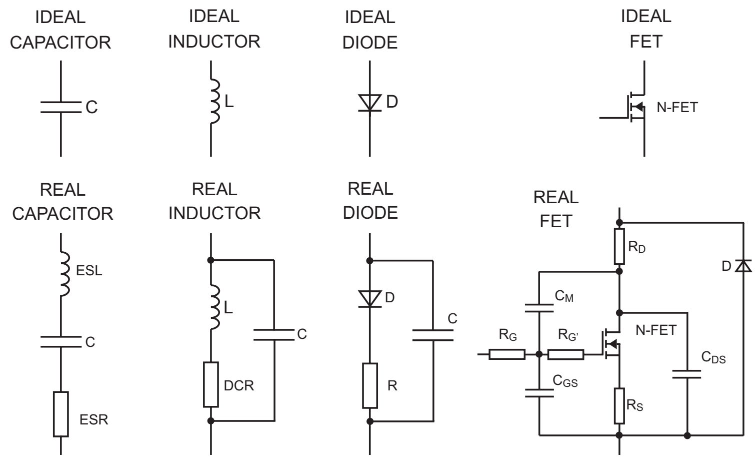


Fig. 2.6: Typical component parasitic elements (Source: DC/DC Book of Knowledge, Fig. 1.33)

2.2 Skin Effect

A complication that further influences the lumped circuit analysis is the skin effect. When an AC current flows through a conductor, it tends to travel along the surfaces rather than through the bulk of the material. Thus, the effective resistance of a conductor is frequency-dependent. This effect is caused by eddy currents within a conductor acting to cancel out the current flow in the middle and reinforce the current flow outside the conductor. The highest current flows along the skin of the conductor and sometimes little or no current flows through the core.

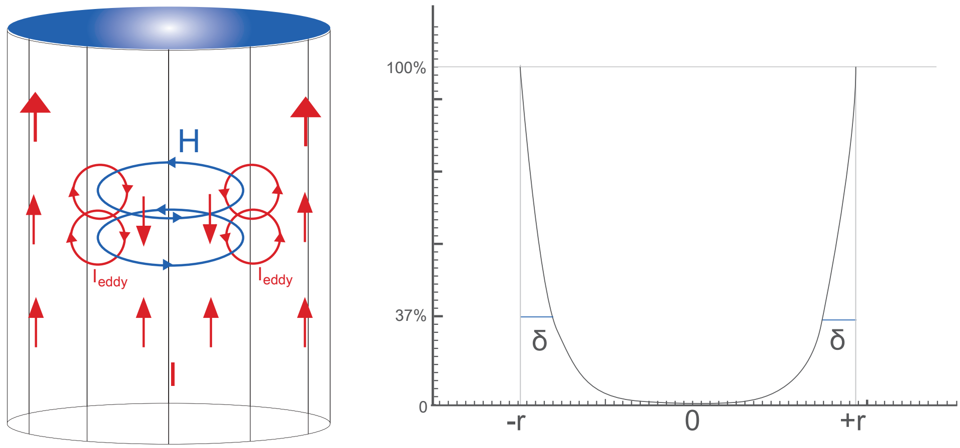


Fig. 2.7: Skin effect (Source: DC/DC Book of Knowledge, Fig. 10.23)

The effective penetration depth of the surface current (when the current has dropped to 1/e or 37% of the total) can be determined using the formula:

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu_r}}$$

Eq. 2.3: Skin effect penetration depth

where skin depth (δ) is the penetration of current flowing in a round conductor, ρ is the bulk resistivity of the conductor, f is the frequency, and μ_0 and μ_r are the permeability of the free space and conductor material respectively.

When using a copper wire at room temperature, the equation reduces to:

$$\delta_{copper} = \frac{66}{\sqrt{f}} mm$$

Eq. 2.4: Skin effect penetration depth in copper

This relationship indicates that skin depth is dependent on the frequency of the current, but not on the amount of current. Therefore, even low current circuits can suffer from skin effect. In copper, at 60Hz, the skin depth is >8.5mm, so it is important only for very massive bus bars; but it reduces to 0.66mm at 10kHz, and further reduces to only 0.21mm at 100kHz. Thus, the skin effect can become an important factor in circuit design at just moderately high frequencies.

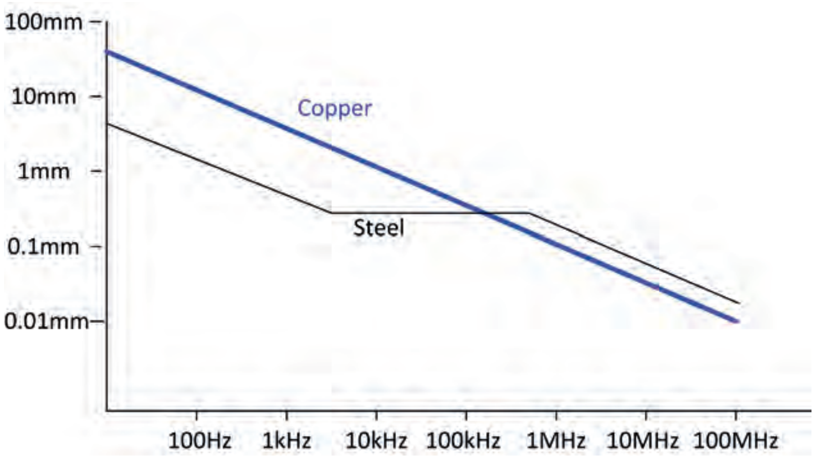


Fig. 2.8: Skin depth vs. frequency for copper and steel (typical values)

The skin effect can be significant in two ways—firstly, for high-current inductors, increasing the gauge of the wire or width of the track to reduce I^2R copper losses may not be as effective as Ohm's law would lead you to believe, as the skin effect will prevent the whole cross-section of the conductor from carrying the current; Secondly, high-frequency signals and switching spikes are strongly attenuated by the skin effect.

Therefore, it is critical to filter any high-frequency noise at the source and keep track and connector lengths very short. This advice is often quoted in many textbooks and guides on EMC design practice. However, it would be much easier to comprehend how a relatively wide copper track or copper plane can fail to conduct high-frequency noise when you have an understanding of the skin effect.

SUMMARY #6: A conductor may have a low DC-resistance, but significantly higher impedance at high frequencies, due to the skin effect.

Chapter 3: Transmission Lines

As mentioned earlier, if the conductor dimensions are more than one-sixth of the wavelength, we must additionally consider resonances, reflections, and standing waves in the conductor. The EM wavefront will travel along the conductor with a velocity, v:

$$v = \frac{1}{\sqrt{LC}}$$

Eq. 3.1: EM wavefront velocity

where √LC is the characteristic impedance of the conductor when written using lumped circuit analysis.

If the characteristic impedance is the same as the impedance of the source and sink at each end of the transmission line, then 100% of the wave will be communicated and the connection will be called a matched transmission line.

However, if the source or sink of the signal has a different characteristic impedance, then some of the wave will be reflected or fail to propagate from the source into the conductor, causing a mismatch or a reflection. This can be a good effect if we want to stop EM noise from being transmitted from one part of the circuit to another, but often less helpful in high-frequency circuits if unwanted resonances or standing waves occur. Standing wave resonances in cables can be avoided by having matched impedances (e.g., a 50 Ohm cable driven from a source with 50 Ohm impedance into a 50 Ohm load).

Resonance in a transmission line arises due to standing waves, much like a vibrating string:

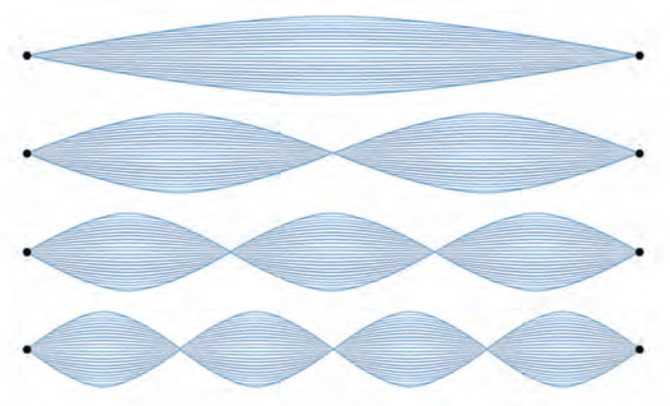


Fig. 3.1: Standing waves (integer number of half-wavelengths) in a vibrating string.

As the two ends of the string are fixed, only an integer number of half-wavelengths can exist.

Such standing wave patterns can only occur with whole numbers of half-wavelengths (N = 1,2,3, etc.), the resonant frequencies of which are:

$$f_{RES(1/2)} = \frac{aN}{L}$$

Eq. 3.2: Half-wavelength resonant frequencies

where a is the air dielectric factor (when f is measured in MHz and L in meters, then a = 150), N is the number of half-wavelengths, and L is the length of the conductor.

Half-wavelength resonance in a transmission line occurs when the impedance of both the source and the load are mismatched to the characteristic impedance of the conductor; in other words, both Zsource and Zload are much higher or lower than Z_0, for example, when both the source and load are having low impedance. When half-wavelength resonance occurs, the E-field at the ends of the transmission line will be at a minimum but the H-fields will be at a maximum.

It is also possible to get quarter-wavelength resonance waves. This effect can occur when the source and load impedances are opposing; for example, a low-impedance source and a high-impedance load. An equivalent mechanical model would be a spinning hanging string with one end left free to move:

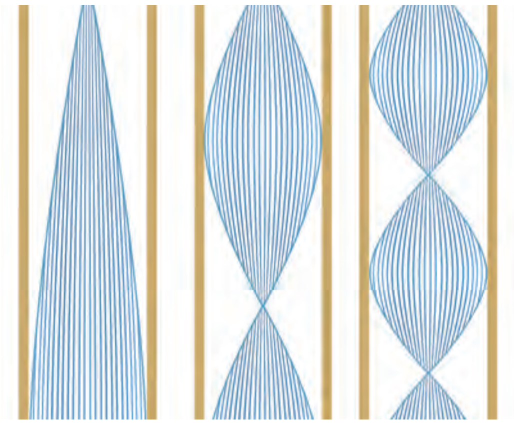


Fig. 3.2: Standing waves (odd number of quarter-wavelengths) in a suspended, rotating string

The quarter wave resonant frequencies are:

$$f_{RES(1/4)} = \frac{aN}{L}$$

Eq. 3.3: Quarter-wavelength resonant frequencies

where a is the air dielectric factor (when f is measured in MHz and L in meters, then a = 75), N is the odd number of quarter wavelengths (N = 1,3,5, etc.), and L is the length of the conductor.

When quarter-wavelength resonance occurs, the E-field and H-field strengths at the source and the load will be opposite (maximum H-field and minimum E-field or minimum H-field and maximum E-field) at each end of the transmission line.

The representations shown below are the transmission line equivalents to the vibrating string (both ends fixed), which only allows whole numbers of half-wavelengths to exist, and the spinning string (only the top fixed and the bottom allowed to move freely), which only allows odd numbers of quarter-wavelengths to exist.

If neither of these conditions exist, then the transmission line must be mismatched, which can cause reflections to occur.

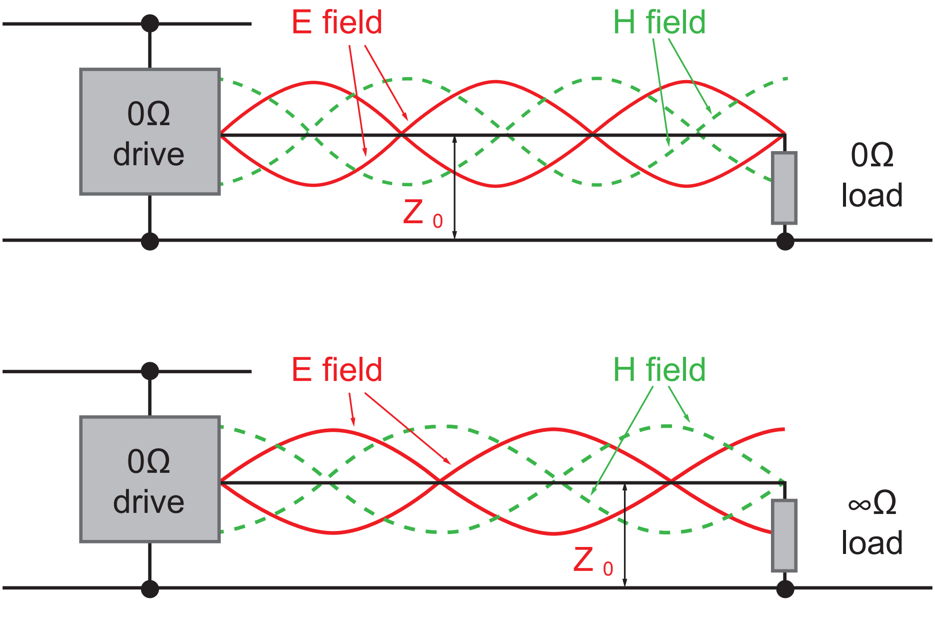


Fig. 3.3: Half-wavelength and quarter-wavelength transmission line resonances

SUMMARY #7: All non-matched conductors and circuits will have high-frequency resonance modes in which the E-field or H-field at the ends of the transmission line will be at their maxima, which could either generate emissions or be most susceptible to outside disturbing signals.

Whether these fluctuating fields will create interference emissions or susceptibilities depends largely on whether the interfering external signal is near-field or far-field.

PCB Antennas

A patch or microstrip PCB antenna can be used at microwave frequencies (> 1 GHz) and consists simply of a square or circular area of copper one half-wavelength in size backed by a ground plane.
Patch antennas are inefficient with low radiation power, but they are cheap, low profile and easy to implement. The radiation pattern is very broad (which can be useful, for example as a WLAN antenna).
Impedance matching is critical for best performance:

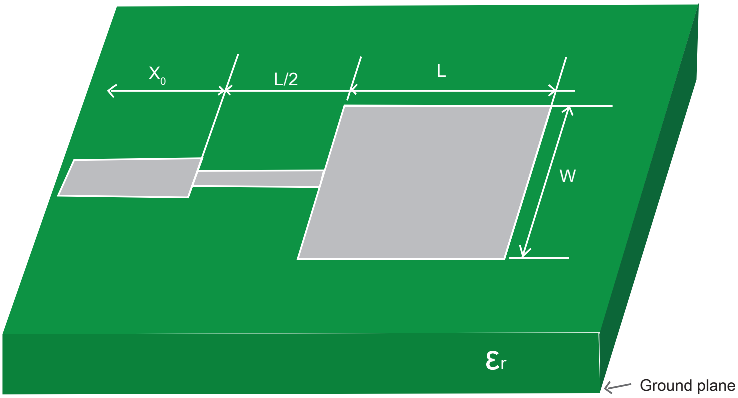


Fig. 3.4: Patch antenna

The impedance of a square patch is…

$$Z_{patch} = 90\,\frac{\varepsilon_r^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2$$

Eq. 3.4: Impedance of a square patch

…and the transmission line interface section between the 50 Ohm microstrip feed line and the patch should be a quarter wavelength long with a characteristic impedance, ZT of:

$$Z_T = \sqrt{50 + Z_{patch}}$$

Eq. 3.5: Characteristic impedance of a patch antenna feed line

The required width of the 50 Ohm microstrip and transmission line interface can be found from Equation 6.2.

There are several variations on the basic patch antenna such as the inverted-F, meander and slot which can be used depending on the space available or the required application (the inverted-F is commonly used as a low-cost WiFi antenna, for example)

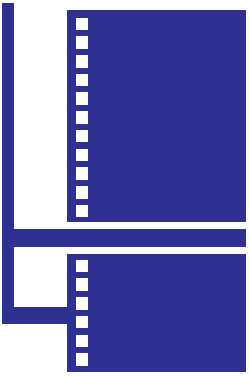


Fig. 3.5: Inverted-F PCB antenna

Another popular PCB antenna is the loop antenna - the larger the circumference the better (the more efficient). The loop antenna can also be created with several turns to increase the beam power and range. It is typically used with a capacitor in parallel to create a resonant tank which can operate well at lower (VHF) frequencies than the patch antenna. Loop antennas are used in many low range applications such as smart cards, garage door openers and keyless entry systems.

A loop antenna also has the advantage that it can pick up sufficient power from a local transmitter to energise a battery-less chip module to transmit a code back to the transmitter/receiver. The RFID (Radio Frequency Identification) chip module usually has a further integrated loop antenna for the data transmission.

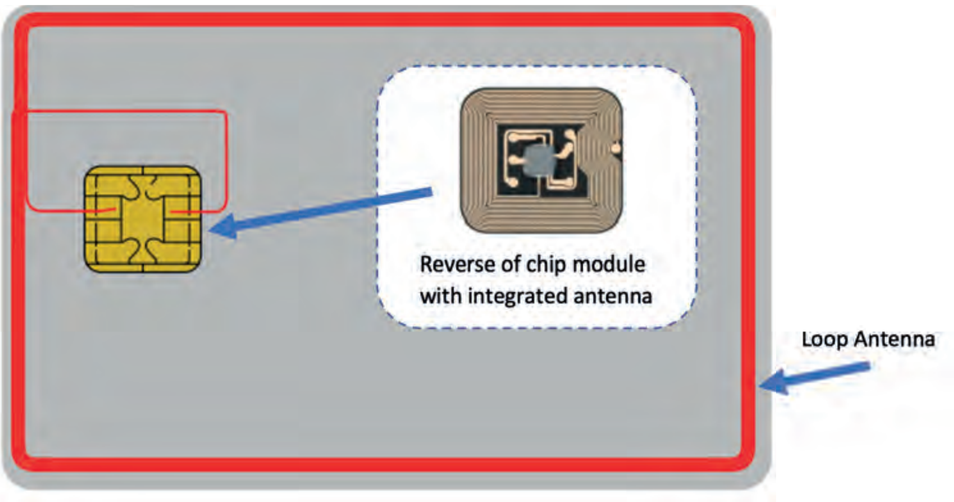


Fig. 3.6: loop antennas in a typical smart card

dielectric chip antennas or ceramic resonators are very compact PCB antennas. The ceramic core has a high dielectric constant which allows the length of the antenna to be reduced proportionally to $\lambda/\sqrt{\varepsilon r}$, where λ is the resonant wavelength and εr is the dielectric constant of the ceramic.
When used as a transmitter, RF excitation causes a resonant oscillation in the ceramic core cavity creating an E-field standing wave between the ends. The H-field is at a maximum at each end of the cavity causing a strong radiated field:

Fig. 3.7: Resonance standing wave diagram (left) of a chip antenna (right)

Chip antennas behave similarly to classic dipole antennas with almost identical beam patterns, but different geometries and metallisation patterns can be used to create different beam patterns or even dual band antennas (e.g., 2.4GHz and 5GHz Wi-Fi with the same cylindrically-shaped antenna.)

Chip Antennas are very sensitive to their surroundings. So, when placing an antenna on the PCB, it is important not to place any other components in the near field immediately around the antenna, as they will interfere with its performance - the antenna specification will state the size of the keep-out area required. This will apply to every layer in the PCB, as well as any other passive or active components and conductors - even mounting screws. If these rules are not followed, then even low energy near field radiation from adjacent components or signal tracks can be picked up by the sensitive antenna resulting in a higher background noise floor and a lower overall antenna sensitivity. This effect of a self-induced reduction in antenna performance is called ‘de-sense’ and is particularly difficult to control in very dense circuit board designs such as smartphones.

The corner of the PCB is generally the best place to position an omnidirectional antenna because it allows the antenna to have clearance in five spatial directions (up, down, left, right and forward) with the feed to the antenna in the sixth direction (behind). For multiple antenna designs, such as MIMO, then the antennas should be placed on separate corners.

If a more directional beam pattern is required, then placing a copper ground plane benea
th the antenna will give it a reflector to radiate against. The size of the ground plane should be related to the resonant frequency for optimal results. Again, the antenna specification will indicate whether a ground plane is required or must be avoided.

Chapter 4: EM Coupling

4.1 Near-Field and Far-Field

Any near-field fluctuating E-field or H-field will spread out in a complex manner, depending on the effects of local parasitic capacitances and inductances. However, far-field interferences will spread out according to plane wave characteristics, eventually approaching the 377 Ohm impedance characteristic of free space.

So, while far-field (radiation) field strengths will decay at a rate that is inversely proportional to the radius of the EM plane wave (1/r), near-field (induction) field strengths will decay more rapidly, as they are inversely proportional to the square or cube of the radius ($1/r^2$ or $1/r^3$). The boundary between near-field and far-field decay rates depends on the physical size of the source with respect to the EM wave wavelength:

For source dimensions << λ, $r = \frac{\lambda}{2\pi}$

For source dimensions > λ, $r = \frac{2D^2}{\lambda}$, where D is the dimension of the source.

Eq. 4.1: Boundary between near-field and far-field

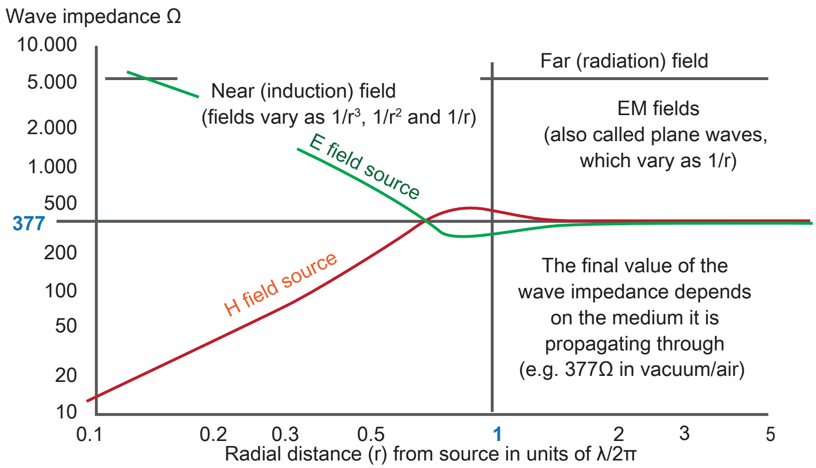
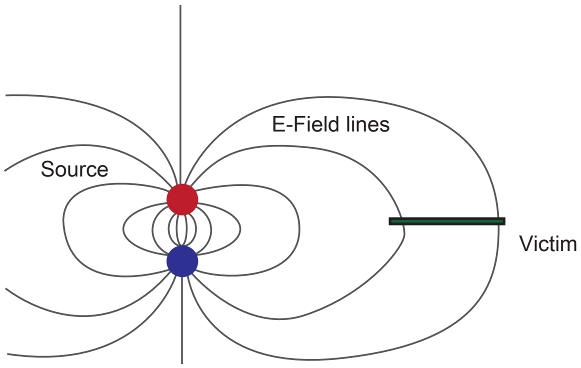


Fig. 4.1: Boundary between near-field and far-field

SUMMARY #8: The physical size of an EM-signal source or sink plays an important role in determining the coupling characteristics and rates of decay of those fields.

4.2 Near-Field and Far-Field Interference Coupling

Near-field dV/dt (E-field) interference can cause noise currents to be injected into victim circuits through stray capacitance coupling:



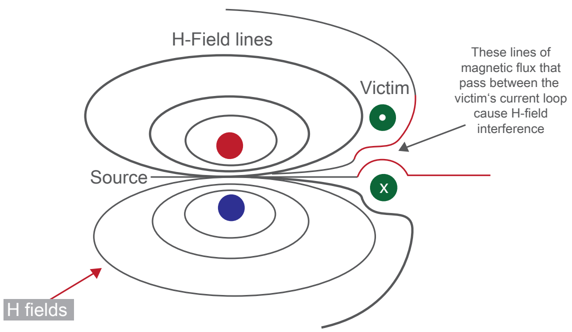
$$\text{Coupling current, IC} = C_{stray} \frac{dV_{signal}}{dt}$$

$$\text{assuming near field and victim impedance C} << \frac{1}{2\pi f C_{stray}}$$

Fig. 4.2: E-field near-field coupling

Near-field dI/dt (H-field) interference can cause noise voltages to be injected into victim circuits through mutual inductance coupling:

Coupling voltage,V_c= -M_(stray) (dI_signal)/dt



$$\text{Coupling current, IC} = C_{stray} \frac{dI_{signal}}{dt}$$

$$\text{assuming near field and victim impedanceIC} << \frac{1}{2\pi \imath f M_{stray}}$$

Fig. 4.3: H-field near-field coupling

In far-field separations (distances >> λ/6), the interference will be through EM-field radiation with both E and H field elements, which can couple into victim circuits through unintentional antenna coupling (see section 7.4.4).

4.3 Near-Field Coupling Noise Interference

Near-field E-field and H-field coupling is one of the most common sources of noise interference in circuits.
A stray capacitance of just 1pF (0.000 000 000 001 Farads) with a 5V, 10MHz source will couple around 300μA of noise into a victim circuit.

$$I_c = \frac{1}{2\pi f C} \cdot \frac{dV}{dt} = \frac{5}{2\pi.\ 10x10^6 .1x10^{-12}} = 314\mu A$$

Eq. 4.2: Noise current due to stray capacitance

A stray inductance of just 1nH (0.000 000 001 Henries) with a 100mA, 10MHz source will couple around 6mV of noise into a victim circuit.

$$V_c = -\ 2\pi f L.\frac{dI}{dt} = \ 2\pi .10x10^6 .1x10^{-9} x\ 0.1 = \ -6.3mV$$

Eq. 4.3: Noise voltage due to stray inductance

To put these numbers into context—a stray current of just 10μA may be sufficient to cause an EMC compliance fail.

4.4 Near-Field Coupling Countermeasures

Near-field coupling mechanisms often cause unwanted behavior and problems with EMC compliance. Due to these coupling effects, HF signals can appear in other parts of the circuit or affect other components even when there is no direct connection between them, traveling through 'invisible' stray inductances and capacitances.
The origin of the interference is called the 'noise source' and the part of the circuit that the unwanted interference is coupled into is called the 'victim'.
Several techniques can be used to reduce such near-field coupling:

4.4.1 Stray Capacitance Coupling Reduction

1. As stray capacitance is inversely proportional to the distance—doubling the separation will halve the capacitance value. If it is not possible to route noisy tracks away from victim tracks on a PCB layout, then make the tracks thinner to increase the physical distance between them.

2. If the noise source send and return paths are very close together, they will have high mutual capacitance between them, which will reduce the stray electric field strength. In the drawing below, noise Source A couples more E-field energy into the victim circuit than noise Source B, even though Source B is physically closer to the victim.

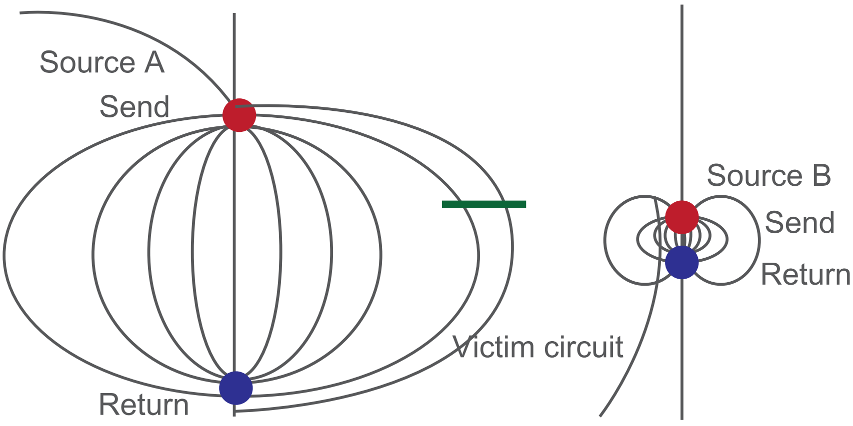


Fig. 4.4: E-field noise coupling into a 'victim' circuit

3. On multi-layer boards, it is common to use the inner layers for ground and power planes. In some cases, the physical closeness of these planes to the noise source can allow the noise to couple back into them, especially if the ground or power planes do not have very low impedance paths back to the noise source reference voltages. PCB interconnection vias can pose a big problem—at DC, they may appear to have a low resistance, but at high frequencies, they will have high impedances, which will allow the noise to reappear in another part of the circuit that shares the same ground or power plane. Multiple parallel vias can be used to reduce the overall impedance path as shown in the image below. But in some situations, it may be better to remove the inner ground or power plane from beneath the noise source altogether.

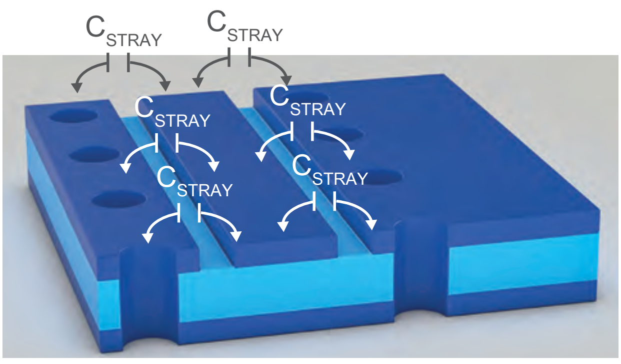


Fig. 4.5: Stray capacitances in a multilayer PCB

4. Add shielding such as a guard rail or track between the noise source and the victim. It is important that the shield connection is is a clean ground. No other elements in the circuit should use the shield ground as power ground reference. And it must have a low impedance connection. Unlike point 2, the idea of a shield connection is to deliberately act as a noise sink to ‘short circuit’ the interference away from other components or tracks.

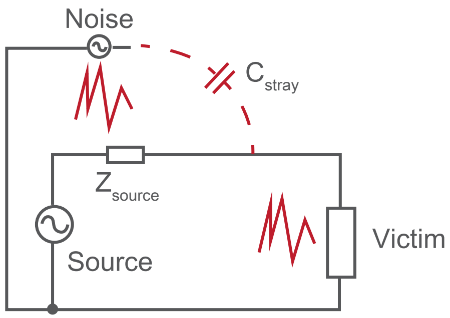


Fig. 4.6: Noise is coupled by the stray capacitance Cstray into a victim circuit.
The coupled noise current flows through the high circuit impedance ZVictim to the ground, generating interference.

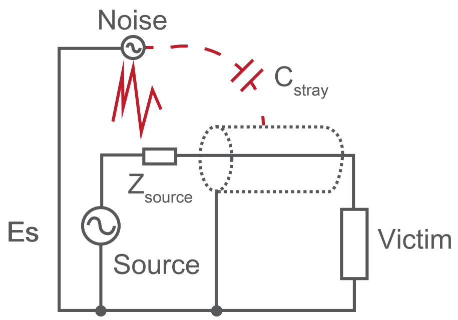


Fig. 4.7: Noise is coupled by the stray capacitance Cstray into the shield. Best to always connect the shield on both ends. Otherwise the shield can work as antenna.

The coupled noise current flows through the low-impedance shield connection back to the ground and does not generate interference in the victim.

4.4.2 Stray Inductance Coupling Reduction

As stated in section 1.4, all electronic power and signals must flow in a loop. All current loops will have a self-inductance, L, that is dependent on the loop area and create a magnetic flux that is dependent on the current flowing around it :

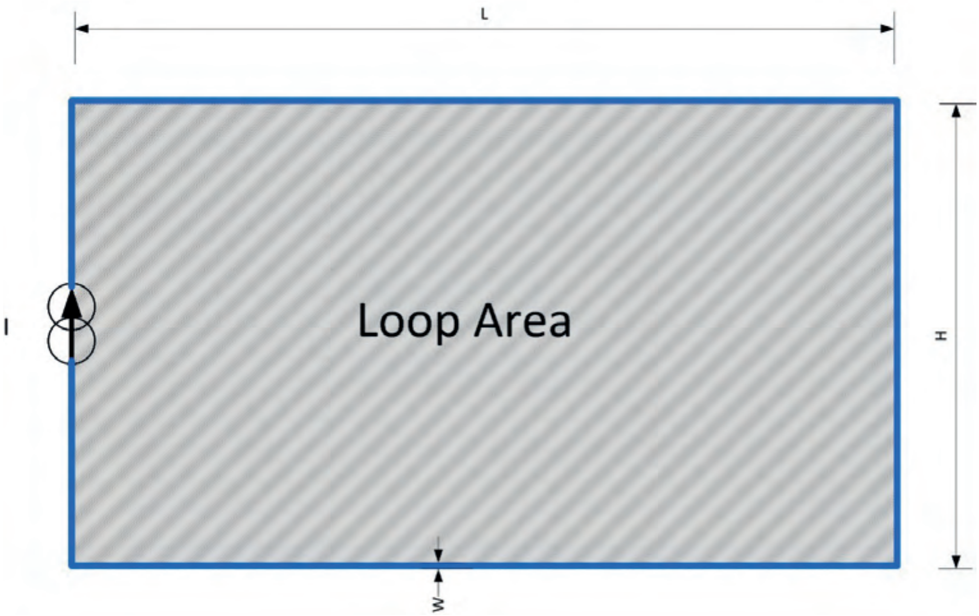


Fig. 4.9: Rectangular current loop

$$L_{loop} \approx \frac{\mu_0 \mu_r L}{\pi} \ln\left(\frac{H}{0.5W}\right)$$

Eq. 4.4: Rectangular current loop Inductance

Self-inductance of a current loop with track width W, length L and height H (assuming W<<H and L>>H)

The resulting magnetic flux is the loop inductance times the current flowing around it:

$$Loop\ Magnetic\ Flux, \Phi_M = I\ L_{loop}$$

Eq. 4.5: Rectangular current loop magnetic flux

So to reduce the loop magnetic flux, either reduce the current or reduce the loop area in order to reduce its self-inductance (for example, by making H as small as possible or increasing the track width, W)

1. As the inductively coupled voltage is dependent on the rate of change of the noise current, make the noise current loop area as small as possible. This will reduce the strength of the stray magnetic field by increasing the source's own mutual impedance.
2. In the drawing below, noise Source A couples more H-field energy into the victim circuit than noise Source B, although Source B is physically closer to the victim.

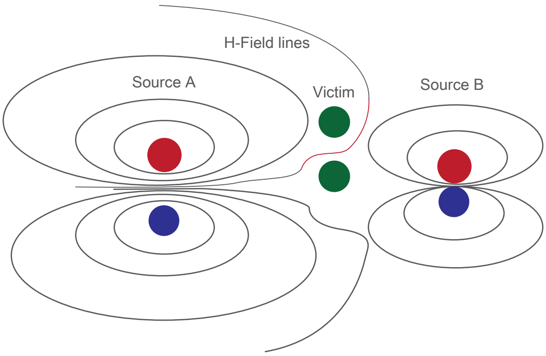


Fig. 4.9: H-field coupling into a 'victim' circuit

Orient noisy components and victim components at 90° to each other. Making component orientation perpendicular rather than parallel can reduce the mutual inductance between them.

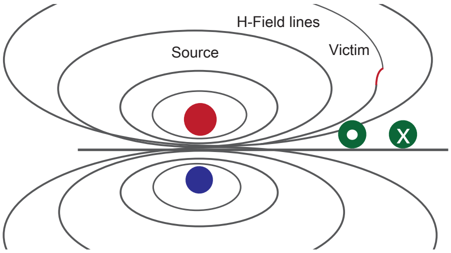


Fig. 4.10: H-field coupling

H-field coupling increases if the source and victim have the same orientation (high mutual inductance), and decreases when they are oriented perpendicular to each other, as shown in the figure above. Add a shielding material around a source or victim that has a high permeability. This will concentrate the magnetic flux lines inside the shield and reduce the strength of any residual field leakage to the victim.

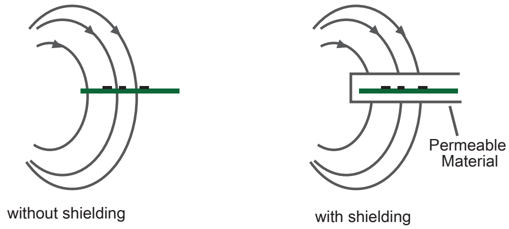


Fig. 4.11: Magnetic field shielding

There is an informative technical article from MPS („When is it beneficial to place a copper layer beneath DC/DC power supplies") discussing the advantages and disadvantages of adding a copper ground plane below inductors for magnetic screening purposes.

A grounded copper plane below an unshielded inductor will effectively screen the radiated magnetic field below the inductor. The magnetic field generates eddy currents in the copper layer which counteracts the field, weakening it considerably. Additionally, a large copper plane on the bottom side of the PCB will help dissipate heat.

The downside is that the eddy currents flowing in the ground plane could cause secondary interference in other nearby components and that the "short-circuiting" of the radiated magnetic field increases the peak current flowing through the inductor.

4.5 Galvanic Coupling

Besides interference coupling through near-field mechanisms, noise interference can also be galvanically coupled through the electrical connections in a circuit.

In the following examples, the load represents a sensitive circuit path or victim, which could be, for instance, an analog amplifier, and the noise source with its associated noise impedance is part of the circuit creating high-frequency disturbances.

In the image shown below, the return path of the noisy signal partly uses the same return path as the victim circuit. In other words, they share a common current return path. The resistance R_{GND} is the resistive element of the part of the PCB trace or wire used by both circuits. Due to the noise current flowing through this resistance, the resulting noise voltage will be superimposed on top of the ground connection seen by the victim circuit.

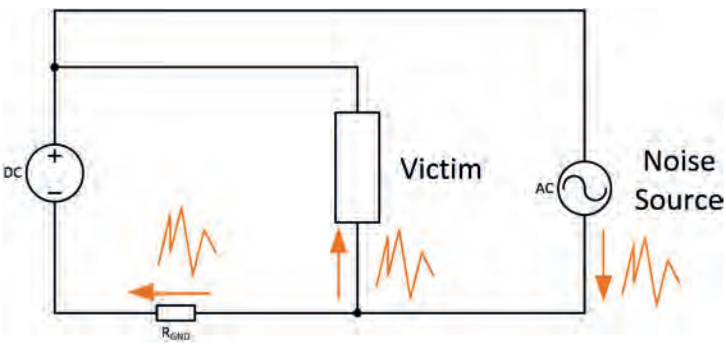


Fig. 4.12: Galvanic noise coupling

As this kind of noise interference coupling is galvanic, it occurs at low as well as at high frequencies (where R_{GND} can be replaced with Z_{GND} in the diagram).

Sudden changes in the noise source current can also generate the so-called 'ground bounce' effect, wherein the ground reference voltage seen by the victim will change as the noise current switches on or off.

The effects of galvanic coupling can be mitigated in several ways.

One way would be to reduce the noise disturbance itself, for example, by placing a capacitor across the noise source, as when this is done, the coupled energy will also be reduced. These capacitors are commonly called decoupling capacitors and should be placed as close to the noise source terminals as physically possible:

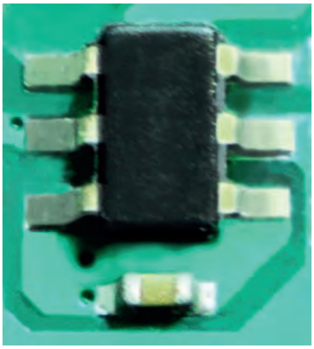


Fig. 4.13: A switching regulator IC with a decoupling capacitor placed close to the supply terminals

Another approach would be to separate the ground return paths so that the noise is not seen by the victim circuit.

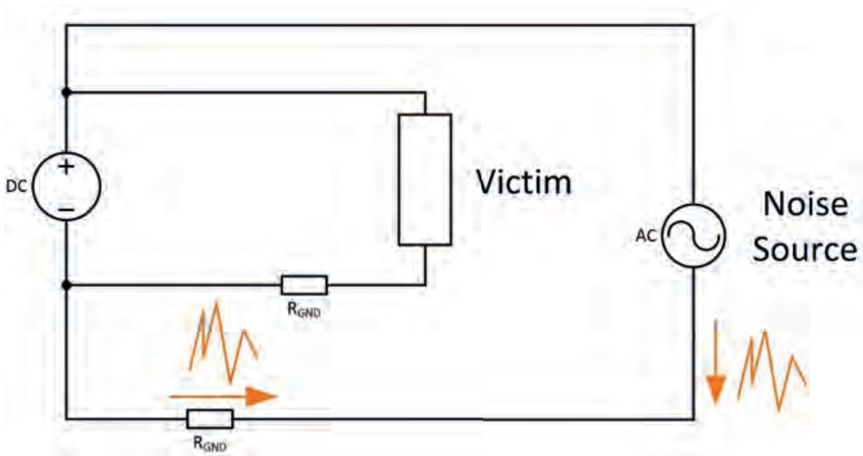


Fig. 4.14: Using separate supply and ground return paths to reduce galvanic coupling

4.6 Capacitive Coupling

The principle of capacitive coupling was already described in the section on E-Field Coupling 4.4.1 Stray Capacitance Coupling Reduction. In a physical circuit, this means that traces or conductive parts with different potentials nearby influence each other, so the signal that is higher in amplitude or higher in frequency couples into other lines nearby. This effect is sometimes also called electrostatic coupling.

Capacitive coupling can cause crosstalk or unwanted coupling between signal or power paths, even if they are galvanically separated from each other.

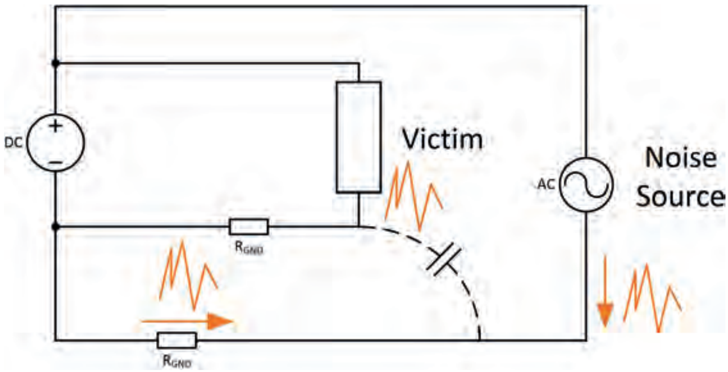


Fig. 4.15: Capacitive noise coupling

The effects of capacitive coupling can be mitigated in several ways.

The most obvious way is to avoid parallel routing of high-current or high-frequency signal tracks close to sensitive or high-impedance tracks. As a rule of thumb, all tracks containing high-frequency signals should have a separation from sensitive tracks of at least 2W, where W is the track width.

However, this may not be easy in a densely-routed board. If you use more than one layer, you can separate the traces by routing them at 90° to each other, as the capacitive coupling mechanism is strongest for parallel-routed traces but has very low coupling between orthogonal

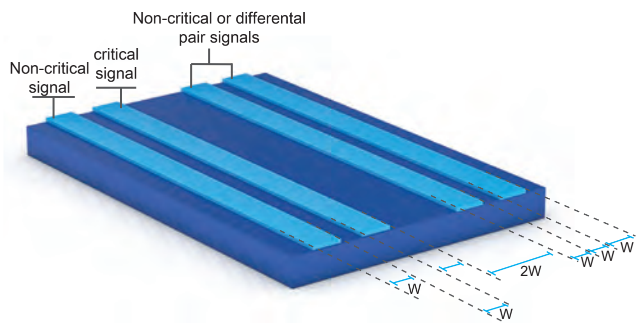


Fig. 4.16: Recommended minimum separation between sensitive and non-sensitive parallel tracks

Differential signal parallel tracks generate less stray capacitive coupling if they are laid out close to each other with a small separation of 1W. This increases their mutual capacitance and reduces stray fields. For the same reason, twisted pair cables are often used in high-speed data network cabling.

When a trace encounters a 90° bend, the characteristic impedance changes, causing increased capacitive coupling. This can be avoided by replacing sharp bends with 45° or rounded turns. If a 45° bend is used, it should have a chamfer length of at least 3W:

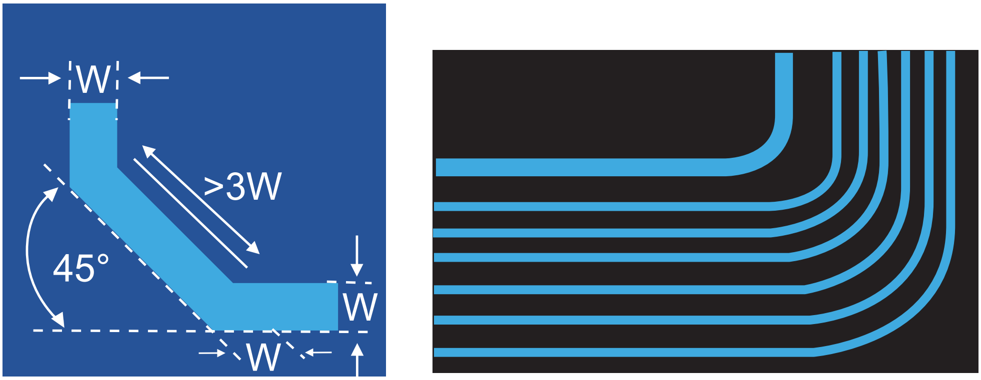


Fig. 4.17: Use 45° or rounded track corners to reduce capacitive coupling interference

Capacitive coupling can also be reduced by using guard rails tied to a low-impedance potential to shield the noisy part or the sensitive part. Depending on the layout, the guard rail or rails can be most effectively tied to the ground or to one of the supply voltages. The recommended separation between signal/power and guard tracks is one track width (W).

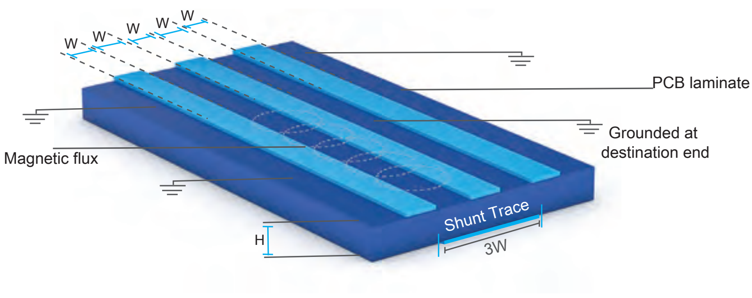


Fig. 4.18: Recommended guard rail dimensions (track width = W)

Capacitive coupling mechanism is not only dependent on the impedance but also on frequency. So, the lower the frequency, the lesser the capacitive coupling will be. Therefore, make the switching frequency as fast as necessary, but as low as possible.

4.7 Inductive Coupling

Inductive coupling occurs when high-frequency current flowing in a loop generates an H-field that couples into another loop and induces a voltage. This induced voltage will cause current to flow into the victim and generate a disturbance. The strength of the inductive coupling depends on the relative orientation and the loop areas, meaning the larger the loops, the more the noise coupling, which we want to avoid.

The difference between capacitive and inductive coupling is that inductive coupling can occur through both non-conductive and conductive materials, including non-magnetic metals; so, it is more difficult to block or shield.

If we consider the example circuit shown below, although the positive supply rails are not shared, the supply current loop of the noisy source is inductively coupled by the mutual inductance of the parallel PCB tracks into the supply rail of the victim:

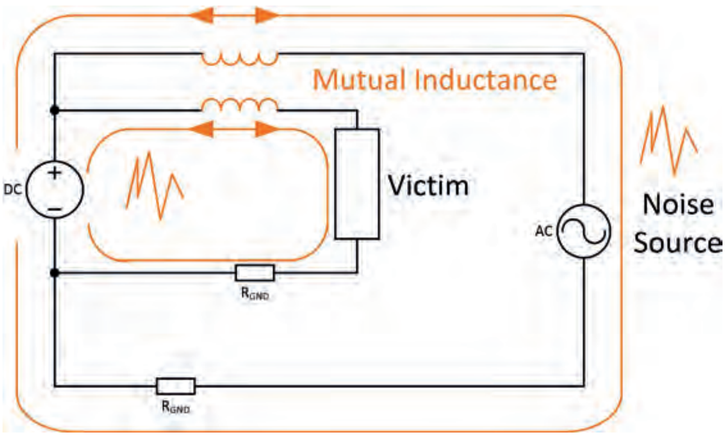


Fig. 4.19: Mutual inductance interference paths

The mutual inductance of the parallel section of the tracks for high-frequency signals is given by:

$$L_m = \frac{\mu_0 L}{\pi} . \ln({}^{d}/_{w})$$

Eq. 4.4: Mutual inductance of two parallel tracks

where L_m is the length which the tracks run parallel to each other, d is the distance between them, and w is the track width.

We can then reuse equation 4.2 to work out the induced voltage in the victim circuit:

$$Coupling\ voltage, V_c = -L_m \frac{dI_{signal}}{dt}$$

Eq. 4.5: Coupling voltage relationship

In practice, two 40mm parallele PCB tracks with a 1mm separation will have a typical mutual inductance of about 30nH. A 10 MHz noise signal will couple about -190 mV into the victim circuit (refer to the Near-field coupling noise interference section where 1nH is coupled with -6.3mV). The effects of inductive coupling can be mitigated in several ways.

The most obvious way is to avoid parallel routing of high-frequency signal tracks close to sensitive or high-impedance tracks. As a rule of thumb, all tracks containing high-frequency signals should have a separation from sensitive tracks of at least 2 W, where W is the track width. As inductive coupling increases with higher dI/dt, coupling will be less if the slew rate is reduced by bringing down the peak current or the slopes of the transitions.

The next mitigating step is to check the total current flow, including return paths, and to minimize the loop area generated by these traces. All loops in which coupling is critical (high-frequency signal lines or sensitive lines) should be as small and as low impedance as possible with every high-frequency signal track paired with a return connection. This is because, the induced voltage is proportional to the loop area:

$$V_{induced,common\ mode} \propto \frac{E.2\pi A}{\lambda}$$

Eq. 4.6: Induced voltage is proportional to the current loop area

where E is the electric field, A is the loop area, and λ is the wavelength of the interference.

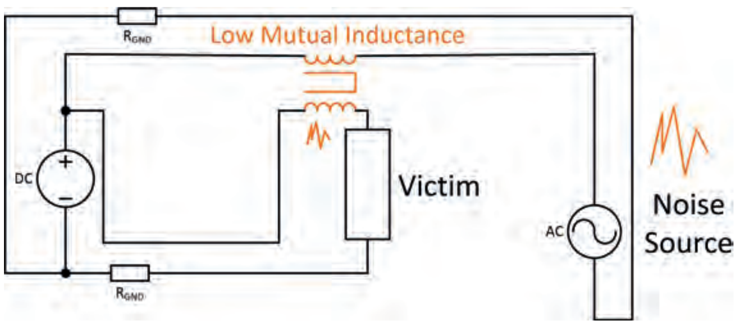


Fig. 4.20: Reduced inductive coupling achieved by reducing the loop areas (by rerouting the current return paths so that they are close to the supply paths and by shortening nearby signal and victim track lengths)

As with capacitive coupling guard rails, adding a guard trace can also reduce inductive coupling. However, you should ensure that the guard connection is not left floating, as a floating guard connection will have very little effect:

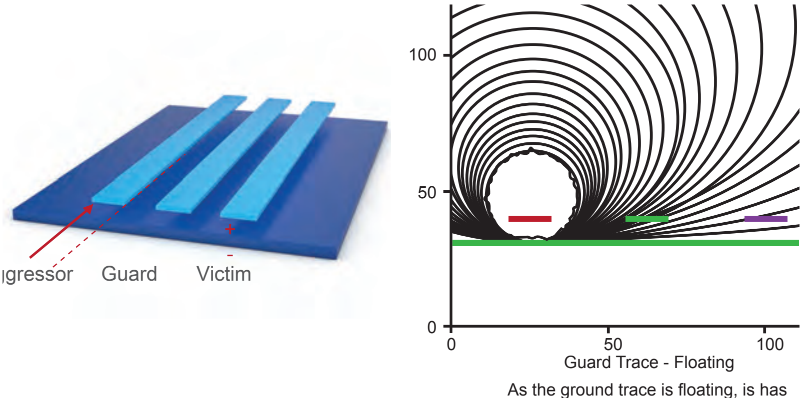
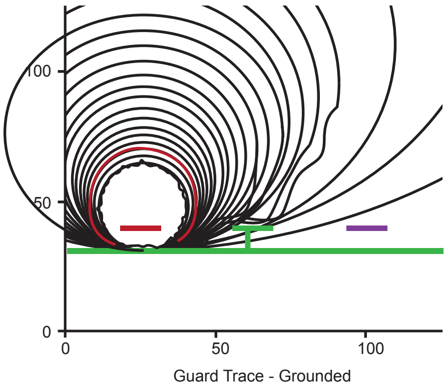


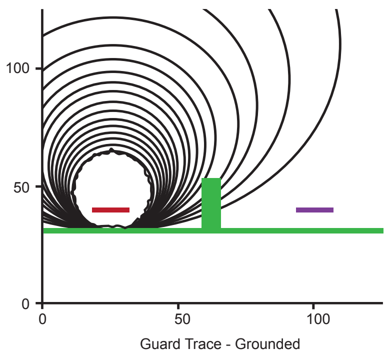
Fig. 4.21: A floating guard rail will have very little effect, while the coupling coefficient will still be high



Grounded trace acts like a dam distorting the field so that the purple trace is in the shadow and therefore protected.

Fig. 4.22: Grounded guard rail

If the guard rail is grounded at both ends, then it can distort the magnetic field interference. The coupling coefficient will be reduced, but will still not be minimal.



The higher the dam, the more protection against magnetic fields.

Fig. 4.23: Massive ground guard rail

A massive guard rail can act like a dam, distorting the magnetic flux and offering more protection to the victim track lying in its ‘shadow’. However, in practice, this method of magnetic shielding has limited use. It is usually cheaper and more effective to simply separate the source and victim tracks further apart or use high permeability magnetic shielding material instead.

4.8 Coupling Noise Overlap

The three types of coupling: galvanic, capacitive, and inductive are not exclusive; a victim circuit can suffer from noise interference from more than one or even all these coupling mechanisms at the same time.

This can make ‘debugging’ a layout to reduce noise very frustrating; changing the layout to reduce, say, galvanic coupling, by improving the ground connections may appear to have little or no effect if noise is ALSO being capacitively or inductively coupled into the victim circuit. On the other hand, if measures were taken to reduce capacitive or inductive coupling, but noise was still being injected via galvanic coupling, then these other coupling reduction measures would also appear to be ineffective.

One way to investigate the source(s) of noise interference is to carry out the following check:

1. Measure the noise and record the levels
2. disconnect the load (zero current, so zero magnetic flux)
3. If the noise disappears, it is primarily magnetic field interference
4. If the noise levels stay the same, it is primarily electric field interference

Use the appropriate H or E near-field probes to locate the source of the interference (see Chapter 9).

SUMMARY #9: In most cases, only when the layout is improved to mitigate against galvanic, capacitive, AND inductive coupling, a solution to the coupling of noise interference can be found.

4.9 ESD Protection

ESD (Electro-Static Discharge) results when charge imbalance is created due to induced voltages or more commonly the triboelectric effect (static electricity caused by rubbing two dissimilar materials together), which then rapidly discharges by arcing or sparking-over. The discharge voltages can easily exceed thousands of volts, potentially damaging any electronic device that lies in or nearby to the discharge path.

A transient voltage suppression (TVS) diode placed across a signal input connection can effectively clamp the ESD transient to a safe level:

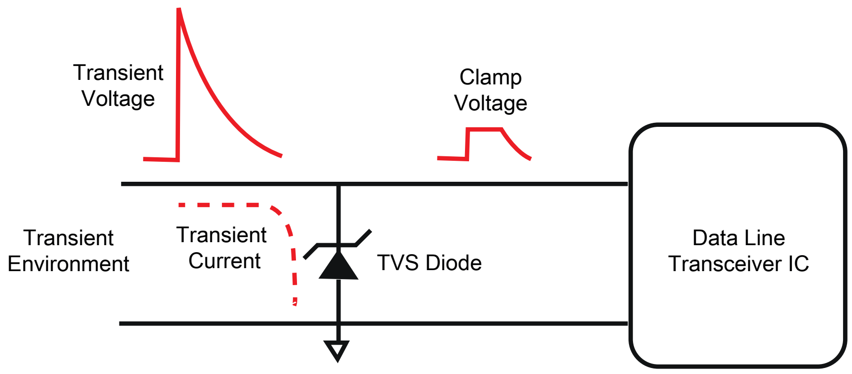


Fig. 4.24: ESD on a signal input with TVS Diode

Another solution is to limit the input voltage to the supply rails using two diodes. In this way the sensitive electronic component (in this example an op-amp input) is protected against both positive and negative voltage transients:

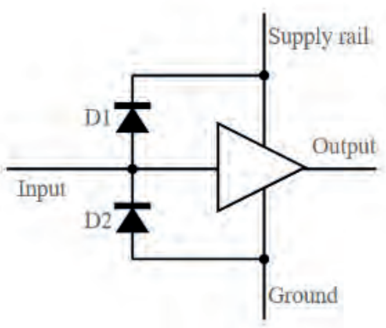


Fig. 4.25: Op-amp input with input clamping diodes

It is important that the protection diodes are high speed with low capacitance as a typical ESD events have very fast dv/dt rise times, in the order of kilovolts/nanosecond (refer to Fig. 8.16). A series resistor can help limit the clamping current for very energetic ESD transients.

Besides fitting TVS protection diodes, there are also several PCB design countermeasures that can help protect electronic circuits from ESD damage:

1. Avoid any long input or output tracks or loops as the resulting track inductances can act as antennas allowing the ESD transient to radiate across to unprotected circuits.
2. Use ground and power planes for the connections of the ESD diodes to allow them to handle the high peak currents effectively.
3. Use thick tracks between the input/output connectors and the TVS diodes and place them as close as possible to the connectors to reduce the track impedances.

4. Direct or air discharge ESD events can create or induce high voltages in the casing which can then couple back into the PCB via stray capacitances, so avoid sensitive tracks running along the PCB edges. Similarly, avoid routing sensitive signal tracks close to the input/output lines to reduce the chance of ESD coupling.
5. If a long input/output track is unavoidable, then place ESD protection diodes at both ends of the PCB track.

4.10 PCB Layout EMI Considerations: An example

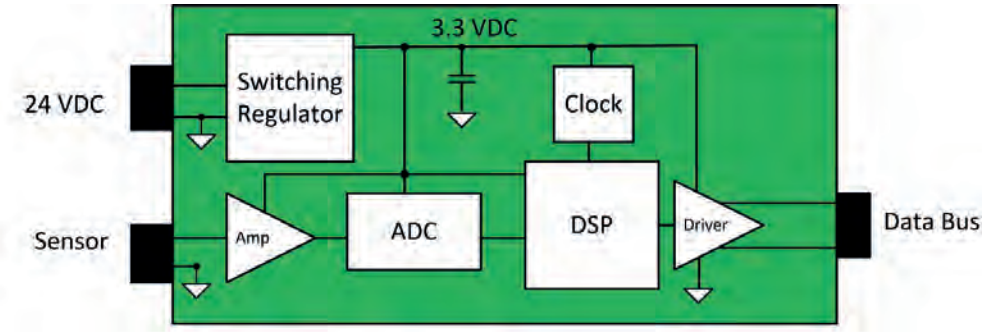


Fig. 4.26: Industrial Sensor Board Layout (poor example)

The system block diagram of a typical industrial sensor board application is shown above. The power supply comes from 24 VDC industrial power supply and is dropped down to 3.3 VDC by a low power on-board switching regulator. The 3.3 V rail then supplies an analogue input amplifier to boost the sensor signal, an analogue-to-digital converter (ADC), a digital signal processor (DSP), a clock IC and a twisted pair industrial data bus driver. It is assumed that the PCB is a double-sided board with a continuous ground reference plane bottom layer. The board is laid out logically with the inputs on one side and the output on the other.

There are several problems with this layout:

1. The ground reference for the low voltage sensor input is connected to the ground plane but not at the same point as the power supply ground. Although there is a low-ohmic connection via the solid ground plane, return currents from the high frequency digital components also share this same plane. As any interference on the sensor input ground will be amplified by the following input amplifier, this node is especially sensitive to noise.
2. The ADC, input amplifier and DSP all share the same 3.3 v supply. Although this supply rail is decoupled at the switching regulator output, there is a long single track between the switching regulator and the supply pins of these components which will have a high impedance, so high frequency noise interference from the DSP will be galvanically coupled into the ADC an input amplifier.

3. The supply rail for the bus driver IC is via the clock IC power supply, so high frequency noise from the clock will be superimposed on the supply for the twisted pair driver.
4. The relatively long PCB tracks between the data bus driver will allow conducted interference from the long external data lines to couple across into other PCB tracks and onto the ground plane.
5. The apparently logical layout arrangement of having the inputs on one side and the output on the other is actually not a good choice. Even if the difference in the ground potential across the PCB connectors is only a few millivolts, the input and output cables will act as a dipole antenna and radiate.

The following diagram shows an improved layout:

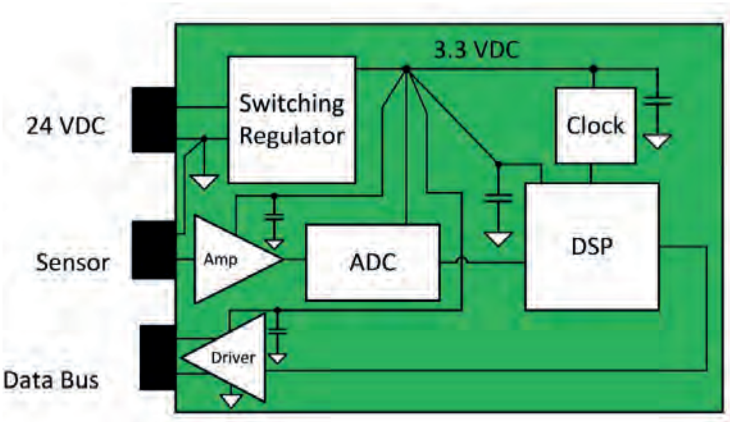


Fig. 4.26: Industrial Sensor Board Layout (improved)

1. the ground reference for the low voltage sensor input is connected at the same point as the power supply ground, avoiding the ground plane. Return currents from the high frequency digital components will not be so easily coupled onto this sensitive node. Also, the sensor amplifier has been moved close to the input connector to keep the sensitive input tracks as short as possible.
2. The ADC, input amplifier, clock IC and DSP all have separate 3.3 V supply tracks which are individually decoupled at the pins.
3. The noisy clock IC has been placed as far away from the other components with the shortest possible high frequency connection to the DSP. It also has its own decoupling capacitor.
4. The driver has been moved close to the output connector to keep the output tracks as short as possible. This means that the input PCB track is longer, but it has been placed well away from the other components to reduce cross-coupling.
5. All the input and output connectors are on the same side, reducing the distance between them to keep current loops as small as possible and any potential differences between the connector grounds as low as possible.

Chapter 5: Noise Reduction Techniques

Knowing which type of noise should be suppressed or eliminated is very important to identify the kind of noise filter that will be effective:

5.1 Differential Mode (DM) Noise

Differential mode (DM) noise is a type of noise interference in which the send and return paths carry opposing noise signals (currents or voltages). So, the noise goes in one direction in the send line and in the other direction in the return line. DM noise can appear independently of a third potential, such as a ground reference, and occur if the circuit was designed to be floating, symmetrically referenced, or unsymmetrically referenced (See figures 5.1 a-c below).

Wanted signals (such as a clock and clock return line) or power supply lines are always DM as the desired current or voltage must flow in a loop with equal currents in the send and return legs.

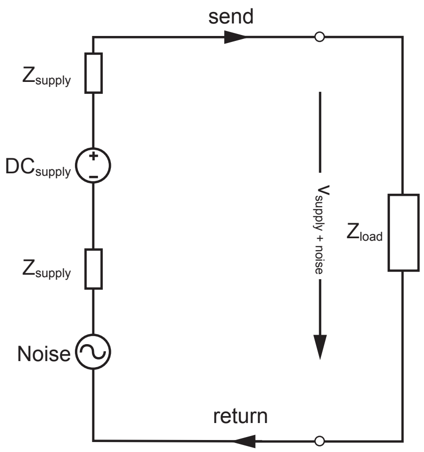


Fig. 5.1a: Floating or independent circuit

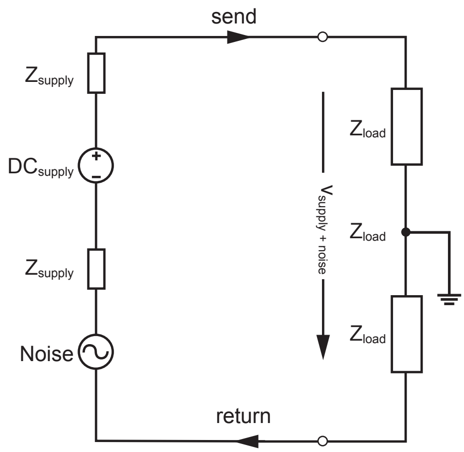


Fig. 5.1b: Symmetrical ground-reference circuit

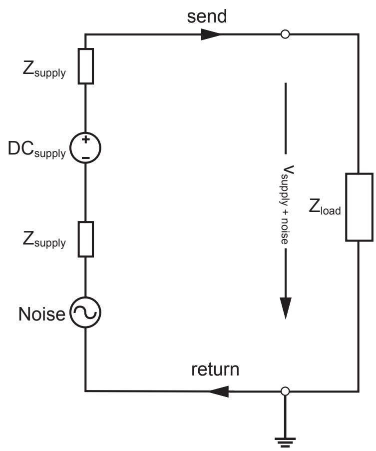


Fig. 5.1c: Asymmetrical ground-referenced circuit

Fig. 5.1a-c: Different forms of load ground referencing. In Figure a, the current path is not referenced to the ground and the load is galvanically isolated. In Figure b, the load is symmetrically split, and the ground reference is at the center point. In Figure c, the ground reference point is located at one end of the load only.

Each of these different circuit ground reference arrangements (Figure 5.1a may still have DM noise to ground caused by parasitic coupling effects, although there is no intentional ground connection) may require different types of DM noise countermeasures.

Depending on the required amount of noise attenuation, DM noise can usually be filtered out using a differential mode choke with one or more capacitors, such as the classic pi-filter:

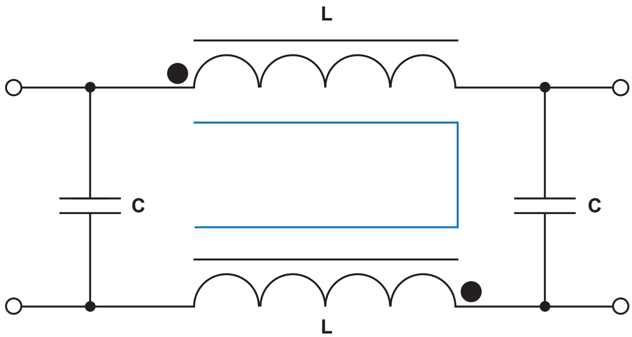


Fig. 5.2: Pi-filter and DM-choke winding arrangement.

The magnetic flux generated by line winding is reinforced by the magnetic flux generated by the return winding because, although the currents flow in opposite directions, the windings are also wound in opposite directions. The impedance is thus high for DM signals. In many cases, an even simpler DM noise filter can be created using just a line inductor and a capacitor. For example, for a DC/DC converter, a DM filter on the output side can be a very effective conducted noise filter:

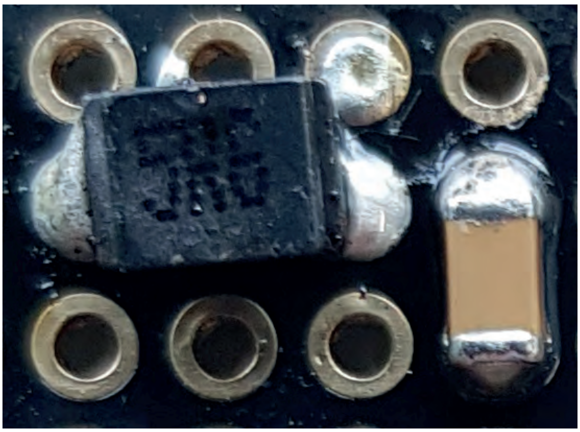


Fig. 5.3: DM-filter using a line inductor

A line inductor can also be used on the input side of a DC/DC converter to block conducted noise back into the supply rails. In this case, the capacitor must be placed before the inductor.

5.2 Common Mode (CM) Noise

Common mode (CM) noise is a type of noise interference in which the send and return paths carry the same noise signals (currents or voltages). So, the noise travels in the same direction in the send line and the return line. CM noise requires a path through a third potential, such as a ground reference.

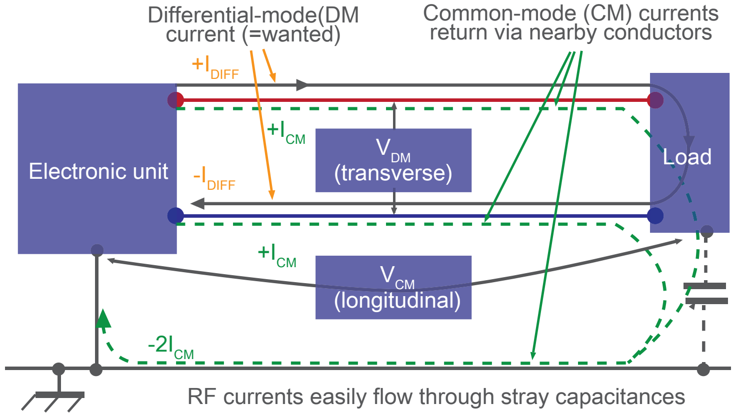
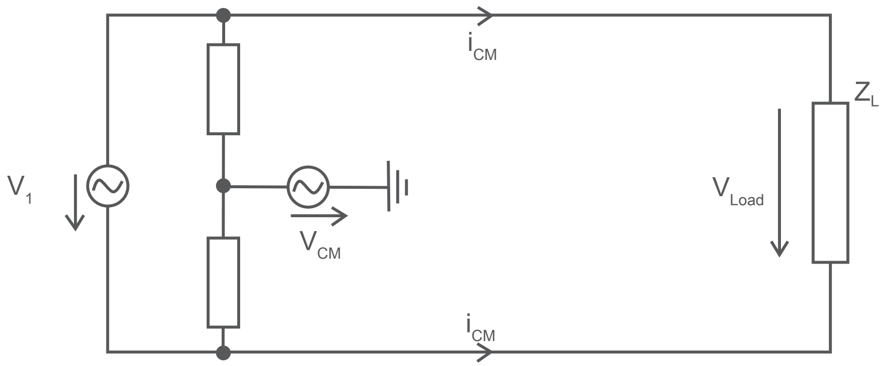


Fig. 5.4: CM-noise current paths

Unwanted signals (such as ground loops) are always CM, as the noise signal flows outside of the desired loop, creating unbalanced currents in the DM send and return legs.

So, for CM noise to occur, at least three different potentials are necessary, so that the noise current flowing on either or both DM send and return legs can flow backward via the third potential. But be careful, as the third potential need not necessarily be intentionally connected to your system; in many cases, stray capacitive or inductive coupling to a metal chassis or PE potential can create the CM current path unintentionally.

The pictures below show two types of CM noise: symmetrical and asymmetrical. For filter design, there is no difference. In both cases, the third potential (in this case, PE) leads to CM noise.



Symmetrical CM path

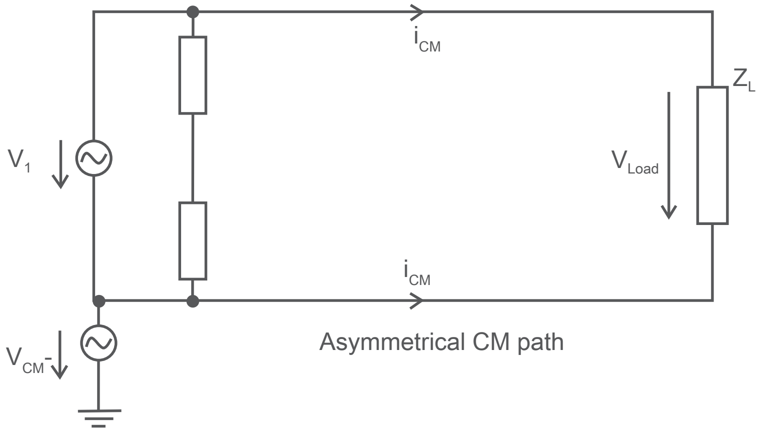


Fig. 5.5: Symmetrical and asymmetrical CM current paths

Depending on the required amount of noise attenuation, CM noise can usually be filtered out using a common mode (CM) choke with one or more capacitors:

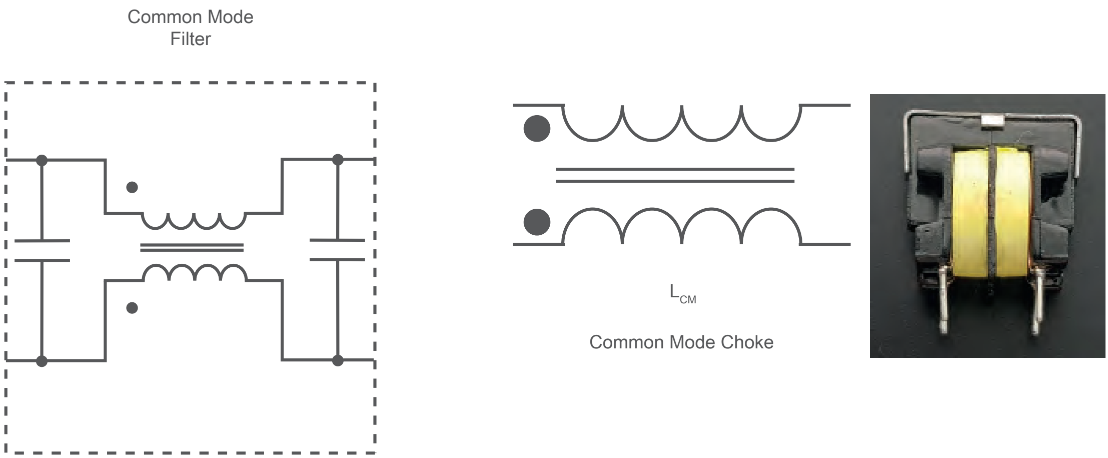


Fig. 5.6: CM choke

The magnetic flux generated by the line winding is counteracted by the magnetic flux generated by the return winding for DM signals, but reinforced for CM signals because the windings are wound in the same direction. Although CM noise is strongly attenuated, DM signals pass through easily (see Fig. 5.7).

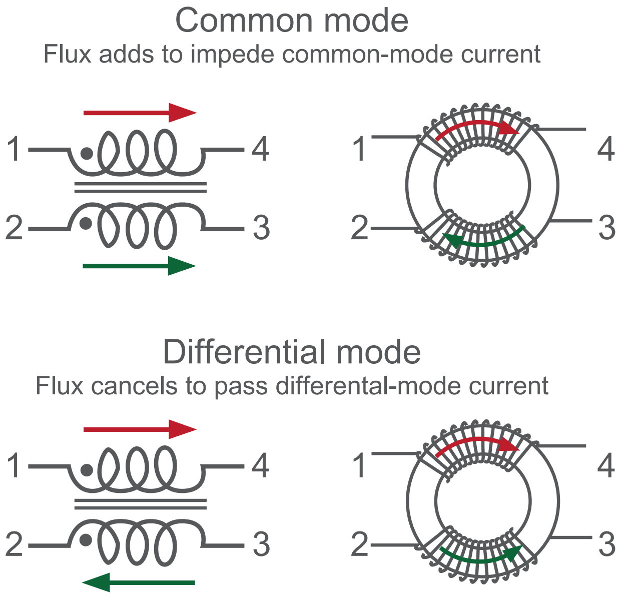


Fig. 5.7: Working of a CM choke with CM and DM currents

Most often, both CM and DM filters are needed in series to block both kinds of interference:

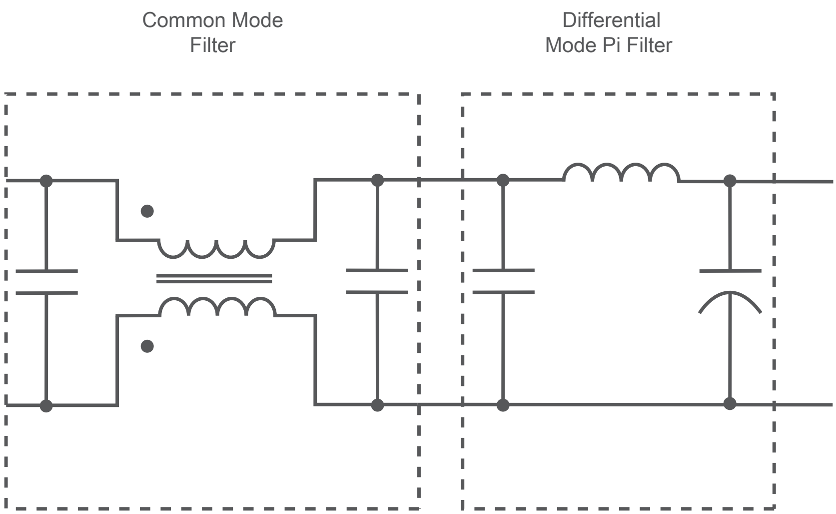


Fig. 5.8: Combined CM and DM filter

You can also use a dual-mode choke that combines both CM and DM types by combining four windings on a single ferrite core:

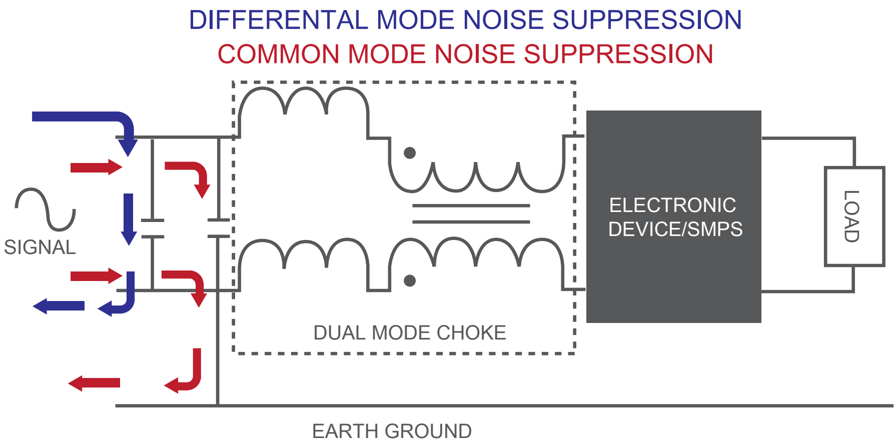


Fig. 5.9: Combined CM and DM choke

Chapter 6: PCB Layout Impedance

6.1 PCB Tracks

The most common conductor used in electronic circuits is copper. The DC resistance of PCB tracks can be calculated using the following formula:

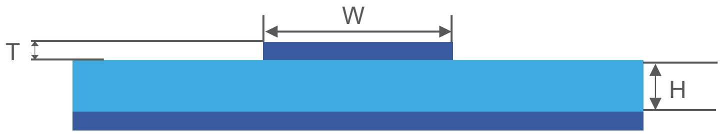
$$\text{Track Resistance} = \text{Resistivity}\frac{\text{Length}}{\text{Thickness} \times \text{Width}}[1 + (\text{TempCo} \times (\text{Temp} - 25))]$$

Eq. 6.1: Copper track resistance

A typical PCB has a copper thickness of 35µm (1.37mil), so a trace that is 1mm wide and 1cm long will have a DC resistance of nearly 5mΩ at 25°C, which can increase to 6mΩ at +85°C (Copper resistance is $1.7\text{x}10^{-6}$ Ω/cm and its temperature coefficient is +0.393%/°C).

In addition to DC resistance, AC track impedance must also be considered. A PCB track has both an inductance and a distributed capacitance to adjacent tracks and nearby components. As already mentioned, this can lead to unexpected results as interference is capacitively or inductively coupled between tracks, copper planes, and other components.

For example, a top PCB track passing over another track on the PCB bottom (or within the PCB if it is multilayer) will have a characteristic impedance, Z_0, and a track capacitance, C_0, represented by the following relationship:



$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98H}{0.8W + T}\right) \text{ ohms}$$

$$C_0 = \frac{2.64 \cdot 10^{-11}(\varepsilon_r + 1.41)}{Ln[5.98H/(.8W + T)]} \text{ pF/m}$$

Eq. 6.2: Characteristic impedance relationship for copper PCB track

For a typical PCB, ε_r = 4, H = 30mil (0.76mm), and T = 1.37mil (35µm); so a 1mm wide track will have a characteristic impedance, Z_0, of around 65 Ohm and a characteristic capacitance of around 82pF/m.

Therefore, it is important to ensure that high-current PCB tracks do not pass over or close to other signal tracks. Ideally, a double-sided or multilayer layout should be used so that a ground plane can be placed underneath these tracks. If the PCB is only single-sided, then the power connections should be kept as short and as wide as possible.

Characteristic impedance and capacitance will affect the signals carried by the copper conductor. If we inject a square wave (e.g., a high-frequency clock signal) into a long track, then the waveform at the end of the track will not be the same:

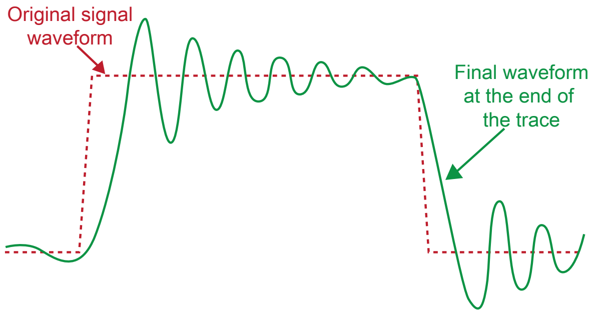


Fig. 6.1: Effect of PCB track characteristic impedance on high-frequency signals

Many engineers and circuit designers refer to this overshoot/undershoot effect as 'ringing'. Ringing can cause electrical overstress damage to many kinds of components, as the peak positive and negative voltages can exceed the maximum specifications.

For EMC, such ringing can also generate radiated emissions, as the clean square-wave pulse or signal generates high-frequency oscillations that lose some of their energy by radiating it to their surroundings. Maintaining signal integrity on a PCB needs careful layouting and separation of power and signals.

Although the majority of the effects of track impedances, parasitics and capacitive coupling only become significant at high frequencies, the spectra of signal harmonics can extend up into the Megahertz region and beyond, often causing unanticipated signal integrity problems even for relatively low frequency signals.

Understanding how signals propagate along PCB tracks and through vias will help mitigate these issues.; in effect, the simple PCB trace will turn into an accidental radio antenna:

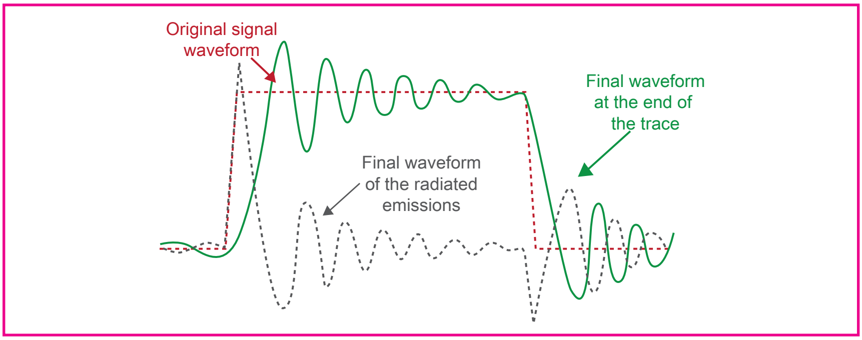


Fig. 6.2: Radiated emissions caused by high-frequency signal ringing

This radiated energy occurs in a range of frequencies over a wide spectrum that is much higher than the original frequency of the signal waveform.
This is a good place to introduce the concepts of spectra and Fourier analysis.

6.2 Fourier Transform

Joseph Fourier (1768–1830) discovered that any periodic signal can be represented by the sum of a series of sinusoidal signals of varying frequency, phase, and amplitude (the Fourier Series). The Fourier Transform shifts information from the time domain to the frequency domain (and vice versa). The result of a Fourier Transform on a periodic signal is the equivalent Fourier Series or spectrum.

The figure below shows the first six harmonics or equivalent component sinusoidal signals of a square wave. If all these harmonics are added together, the result will be the red summed series waveform shown in the diagram. The higher the number of harmonics, the closer the summed waveform will be to the original ideal square wave.

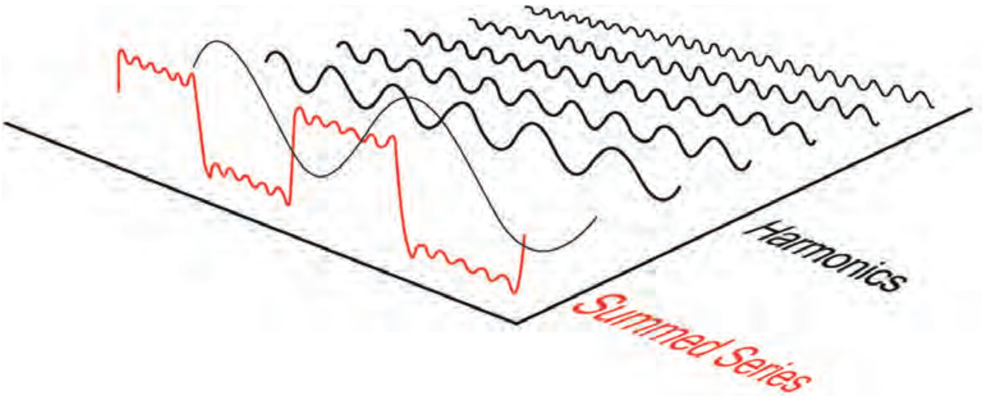


Fig. 6.3: Fourier Series (from DC/DC Book of Knowledge, Fig. 2.12)

Fourier proved that any continuous periodic waveform can be represented by the sum of a series of sine waves:

$$x(t) = \sum_{n=-\infty}^{\infty} \left(c_n e^{j\omega_0 nt}\right)$$

Eq. 6.3: Fourier series representation

where the signal x(t) is represented by the sum of n individual sine waves, with C_n being the nth coefficient (amplitude), ω_0 being the first harmonic in radians ($=2\pi f_0$), n being the nth harmonic frequency, and t being time. n = 0, 1, 2, 3, …

Thus, a Fourier Transform takes a periodic waveform and generates a spectrum of individual frequency strengths, which represent that waveform.

The Fourier Transform is a very useful tool to convert complex waveforms into their component spectrum of frequencies. What makes Fourier Transforms so powerful and useful is that it allows us to precisely identify the frequencies that are causing unwanted interference, allowing us to design the most appropriate filter or reassess the PCB layout or grounding to eliminate the noise.

If you apply the Fourier Transform to the radiated emissions from the long PCB trace, you will get the radiated spectrum of harmonic frequencies:

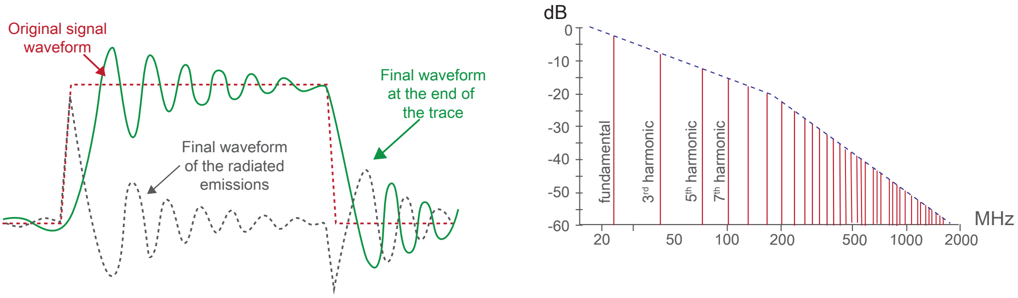


Fig. 6.4: Fourier Transform

Not only the signal and its hamonics have influence on the spectrum, but also rise and fall time can change the emission profile in the higher frequency range. the slower the rise and fall times, the earlier the cutoff frequency will be and vice versa.

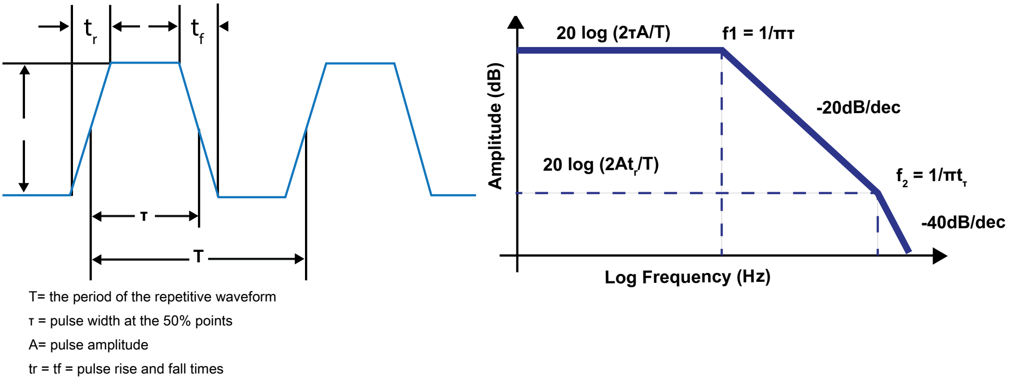


Fig. 6.5 + Fig. 6.6: Fourier Transformation of a trapezoidal signal

SUMMARY #10: A 16MHz clock signal sent along a long PCB trace can create an unintentional antenna with a radiated harmonic emission spectrum continuing up to nearly 2GHz. Even a 50kHz PWM switch-mode power supply can easily generate harmonic frequencies ranging up to 50MHz.

6.3 Vias

It is not just long PCB traces that can cause unwanted oscillations; PCB vias (the vertical connections between tracks) can often cause significant parasitic elements:

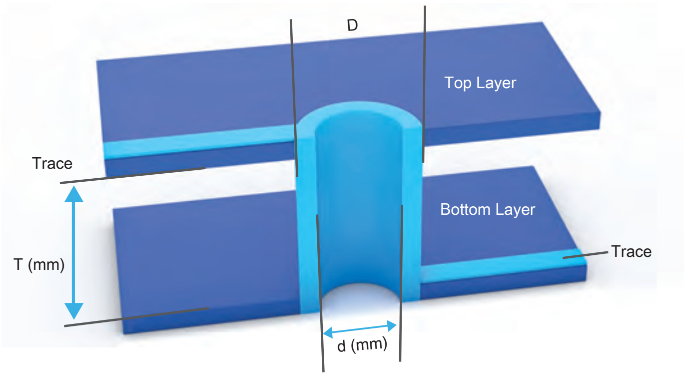


Fig. 6.6: Via dimensions

$$L = 2T\left[\ln\frac{4T}{d} + 1\right]\text{nH}$$

Eq. 6.4: Via parasitic inductance

$$C = \frac{0.55\varepsilon_r T D_1}{D - d}\text{pF}$$

Eq. 6.5: Via parasitic capacitance

Where ε_r is the bulk permittivity (around 4.5 for FR4 boards), T is the board thickness, D is the diameter of the pad surrounding the via, and d is the via clearance hole diameter.

A typical 0.4mm via through a 1.6mm PCB will have a parasitic inductance of around 1.2nH and a parasitic capacitance of 0.33pF, rising to about 0.8pF when the via pads and track connections are taken into account. These parasitic elements of PCB pads, tracks, and vias add significant complexity to the layout, for example:

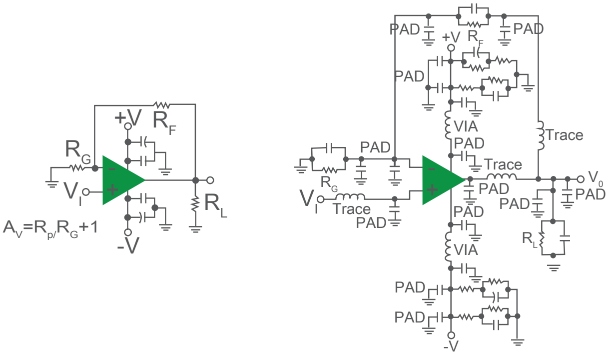


Fig. 6.7: Effect of parasitics on a simple Op-Amp schematic

6.4 EMC Countermeasures - Controlling Track Impedances

The overall impedance of via connections between tracks can be reduced by placing several vias in parallel.

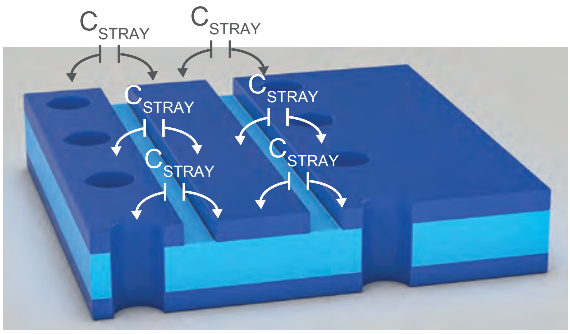


Fig. 6.8: Using multiple vias to reduce overall impedance

For high-speed track connections, PCB track impedance matching between source and sink will reduce reflections and radiated emissions. The characteristic impedance is dependent on the layout dimensions, so a PCB transmission line or ‘microstrip’ can be created by choosing the appropriate track thicknesses and separations.

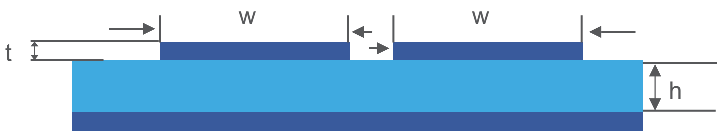


Fig. 6.9: Microstrip dimensions

As a rule of thumb, if the trace is longer than ¼ of the distance traveled during the rise time of the signal, then a microstrip approach should be applied.

For example, if we have a signal with a 0.5ns rise time, then:

$$Propagation\ velocity, v = \frac{c}{\sqrt{\varepsilon_r}} \approx \frac{3.10^{10}}{\sqrt{4}} \approx 15cm/ns$$

Eq. 6.6 : Propagation velocity relationship

The distance travelled during the rise time will be about 15/0.5ns = 7.5cm, so the critical PCB track length will be a quarter of that, or 1.875cm.

Different high-speed interface signals have different target impedance tolerances that need to be addressed to maintain signal integrity.

Signal	Target Impedance	Tolerance
USB 2.0	90 Ohms	±10%
USB 3.1	90 Ohms	±5%
HDMI	95 Ohms	±15%
Ethernet Cat. 5	100 Ohms	±5%
Displayport	100 Ohms	±20%

Target impedances are also relevant for board-level power distribution. With many FPGA and ASICs running on 1V or less supply rails, any oscillation on the supply rails due to current peaks could create an out-of-range supply voltage. The target characteristic impedance can be calculated from:

$$Z_{0,target} = \frac{V_{supply} \cdot V_{ripple}(\%)}{50\%. I_{peak}}$$

Eq. 6.7: Target characteristic impedance calculation.

where V_{ripple} (%) is the maximum allowed deviation in the supply voltage (voltage regulation + transients).

Summary #11: Maintaining signal integrity on a PCB needs careful layouting and separation of power and signals. Although the majority of the effects of track impedances, parasitics and capacitive coupling only become significant at high frequencies, the spectra of signal harmonics can extend up into the Megahertz region and beyond, often causing unanticipated signal integrity problems even for relatively low frequency signals.
Understanding how signals propagate along PCB tracks and through vias will help mitigate these issues.

Chapter 7: Filters

A filter is usually implemented to reduce noise interference by either short-circuiting or blocking out unwanted signals. A filter can be used to protect a sensitive circuit from noise interference generated elsewhere in the circuit or be placed close to a noise source to block the noise signal from being transmitted.

Filters can be categorized by type, topology, grade, and filter mode.
Low-pass filters attenuate high-frequency signals but let low-frequency or DC signals pass. Low-pass filters are commonly used in power supply rails to reduce cross-talk interference through the power supply connections.

High-pass filters attenuate low-frequency signals but let high-frequency pass. High-pass filters are commonly used in high-frequency circuits to block DC offsets but let RF signals pass.

Band-pass filters attenuate low- or high-frequency signals but let medium-frequency signals pass, combining the functions of both low-pass and high-pass filters. Band-pass filters are commonly used in audio amplifier circuits to increase the signal-to-noise ratio.
Band-stop or notch filters block a narrow range of frequencies but let all others pass. They are very effective when they are used to attenuate a strong single-frequency interference source, such as 50Hz or 60Hz mains interference.
In many EMI countermeasure circuits, low-pass filters are commonly used to avoid the transmission of high-frequency disturbances.

7.1 Filter Types

Low-pass filters attenuate high-frequency signals while allowing low-frequency signals to pass. This is the most wanted effect when it comes to EMI filters. A capacitor is effectively a short circuit for high frequencies, so in this case, it will be used in parallel. On the other hand, the inductor works like a barrier for high-frequency signals, and so is used in series for acting as a low-pass filter.

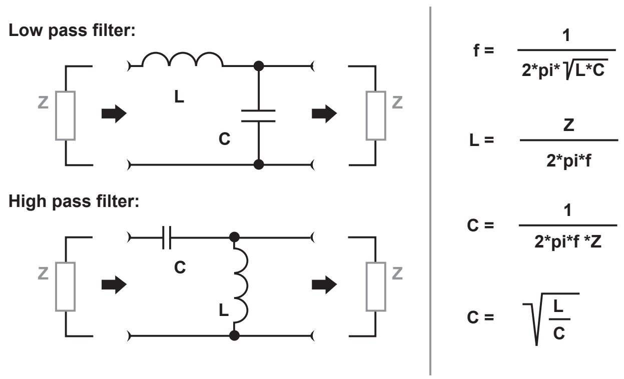


Fig. 7.1: Low-pass and high-pass filters

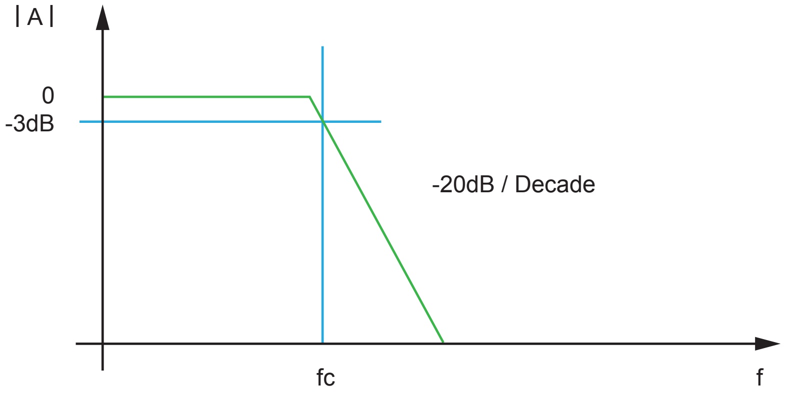


Fig. 7.2: Low-pass frequency response

High-pass filters attenuate frequency signals in the lower frequency band but allow high-frequency signals to pass. High-pass filters are often used to block DC offsets in audio circuits or to act as a ‘short circuit’ for low-frequency noise to ground.

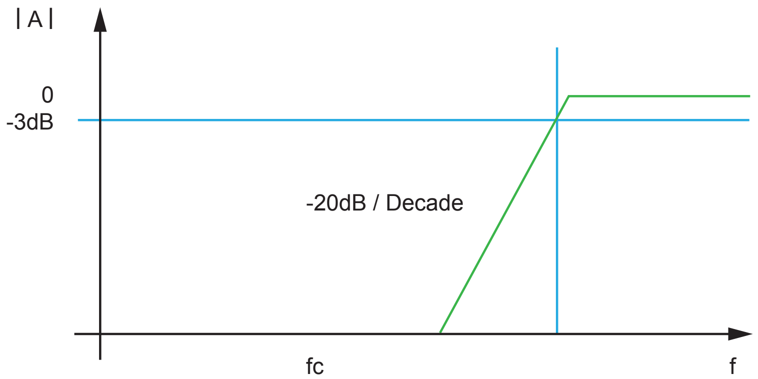


Fig. 7.3: High-pass frequency response

Band-pass/notch filters can be considered as a combination of low-pass and high-pass filters, wherein the band to pass the signals overlaps these two filter types.

This sort of filter is used very often in communication networks let pass the exact frequency required or to block a particular frequency, such as 50/60Hz mains hum.

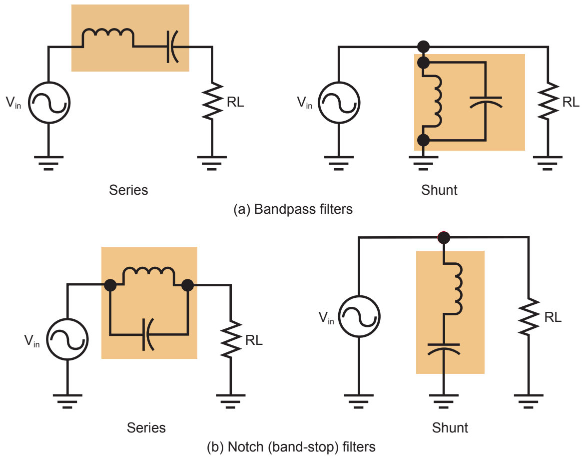


Fig. 7.4: Band-pass/band-stop filters

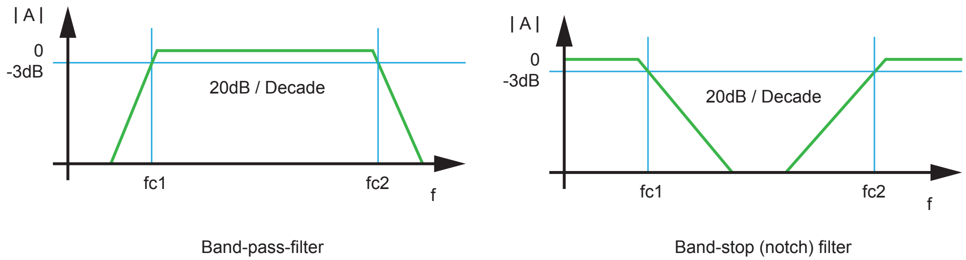


Fig. 7.5: Band-pass/notch filter frequency response

7.2 Bode Diagrams

As inductors and capacitors are reactive components, their impedance changes with frequency. They also cause a phase shift in the signal, meaning that their current and voltage waveforms no longer line up (for a more detailed analysis of reactive phase shifts, refer to the RECOM AC/DC Book of Knowledge, Chapter 4).

If we take our simple low-pass filter, for example, the phase changes from 0° at DC, to -45° at the corner frequency, and approaches -90° as the frequency increases:

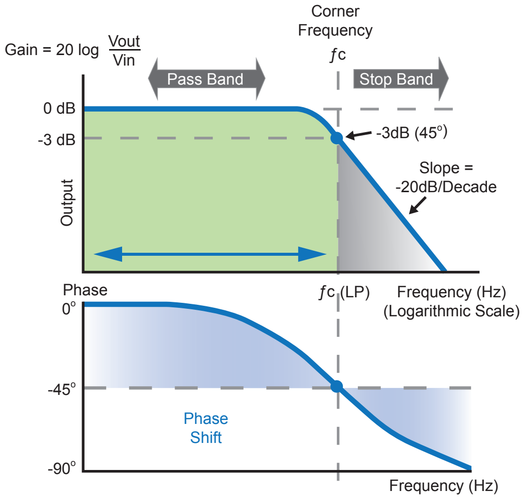


Fig. 7.6: Low-pass filter frequency and phase response

As it is quite difficult to visualize both the amplitude and phase of a circuit at the same time, in the 1930s, Dr. Hendrik Bode invented the Bode Diagram, which is a way of plotting the change in amplitude and phase on the same graph. The horizontal axis is the frequency, shown on a logarithmic scale, common to both graphs. The vertical axes show gain (expressed in decibels or dB) and phase, centered at 0°.

For example, below is a Bode plot for a band-pass filter showing how the amplitude and phase slopes change at each of the two corner frequencies:

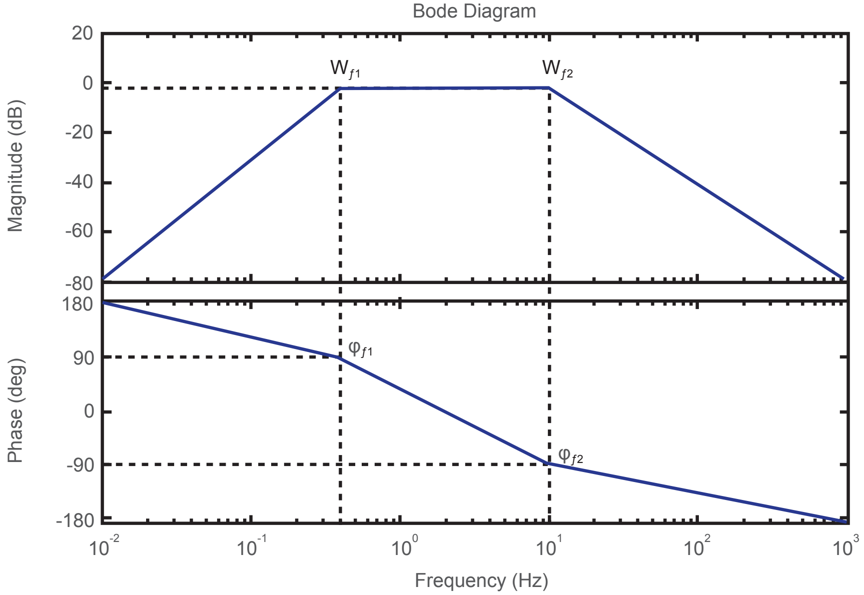


Fig. 7.7: Example of a Bode plot

In this way, amplitude and phase plots can be made for more complex circuits including amplifiers, phase-locked loops, and compensation networks. First- or second-order filters can also be easily visualized.

7.3 EMC Countermeasures

Several basic steps need to be performed to identify and counteract unwanted noise in a circuit:

1. Determine the noise frequencies: This is very important as countermeasures will differ based on the noise spectrum.

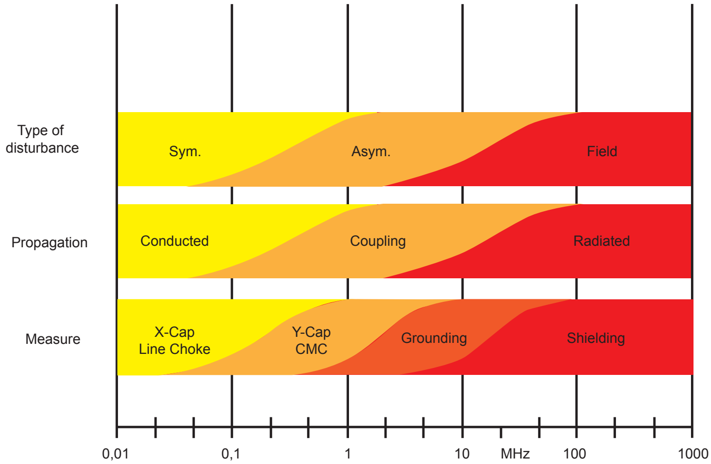


Fig. 7.8: Noise/frequency relationships (Source: Power Supply Meets EMC, RECOM)

2. Determine the source of the interference: For example, is it on the primary side or the secondary side? Is it from ringing on the fundamental switching waveform or coupled across from rising/falling edges?

3. Determine the noise path(s) from the source to the victim: Is the noise path galvanic, capacitive, and/or inductive coupling? Is it a common mode or a differential mode? Is it conducted or radiated?

4. Counteract the noise interference by adding filters, bypass, or decoupling capacitors, or by changing the layout or improving the grounding. A quick test can be done by using a copper foil to add shielding or lower ground impedance.

These four steps may seem simple but in practice, it requires the skill and experience of a good EMC engineer to achieve a solution quickly and effectively.

7.4 EMC Countermeasures - EMI Filters

An active switching circuit, such as a DC/DC converter, will generate conducted switching noise on the output as well as a reflected ripple interference on the input. These disturbances will be a combination of both differential and common mode signals that require different filters to control and limit the interference. The following countermeasures to avoid such interference are largely repeated from the DC/DC Book of Knowledge (DC/DC BoK), but are included here for completeness:

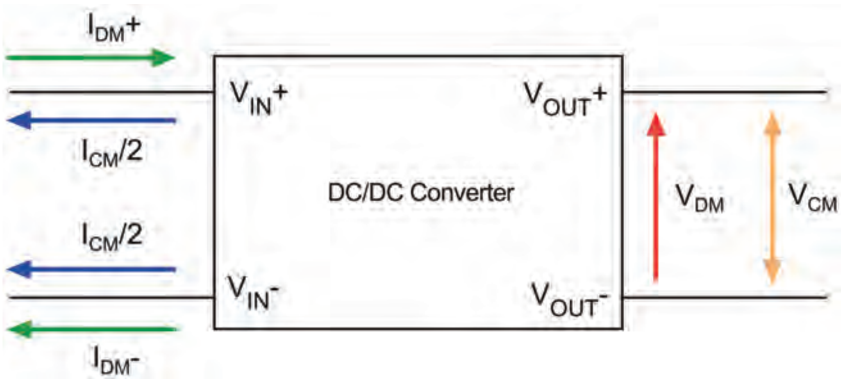
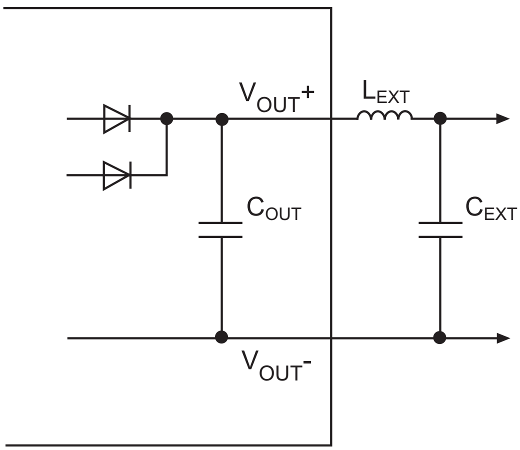


Fig. 7.9: Typical CM and DM interference from a DC/DC converter (Source: DC/DC BoK, Fig. 5.1)

7.4.1 Differential Mode Switching Noise Filters

An effective DM output ripple reduction filter can be created by adding an LC low-pass network to the output of the DC/DC converter:



$$V_{RIPPLE\,,\,p\text{-}p} = \frac{I_{OUT}\,1000}{2\,f_{OPER}\,(C_{OUT} + C_{EXT})}$$

Eq. 7.1: Output ripple

Fig. 7.10: DM output ripple filtering (Source: DC/DC BoK, Fig. 5.12)

If the internal circuit and component values of the DC/DC converter are not known, an effective rule of thumb is to set the corner frequency of the LC filter to 1/10th of the operating frequency.

This can give a useful reduction in output ripple voltage and also help in avoiding unnecessary filter component costs:

$$f_C = f_{OPER}/10 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Eq. 7.2: Corner frequency relationship

where the cut-off frequency fc is the point in the attenuation curve at which the interference signal is already suppressed by -3dB, or already attenuated by 30%.
As an LC filter is a low-pass filter of the second order, if the attenuation curve falls at a rate of -40dB per decade, frequencies that are 10 times higher than the cut-off frequency will be suppressed by a factor of 100.

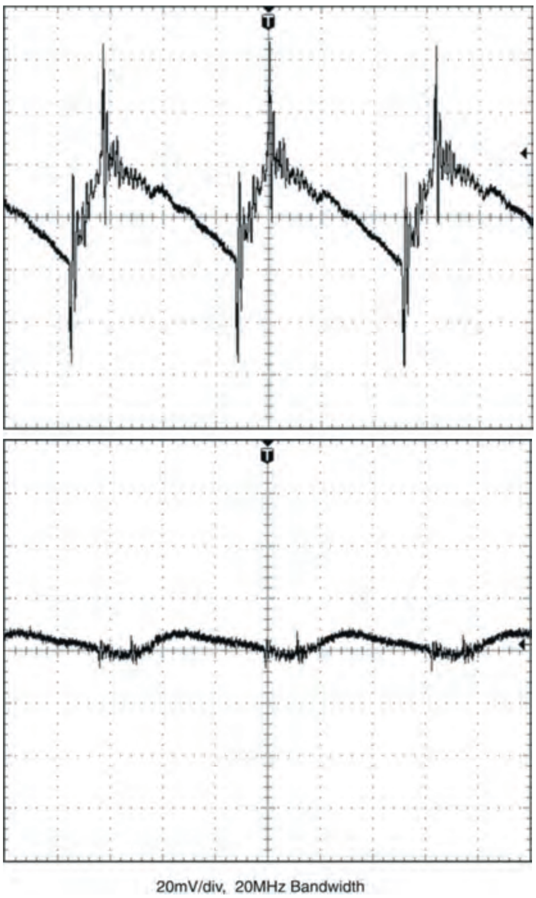


Fig. 7.11: Before and after results of an effective output ripple voltage filter (Source: DC/DC BoK, Fig.5.13)

An LC filter can also be placed on the input (primary) side of the DC/DC converter to attenuate the DM interference:

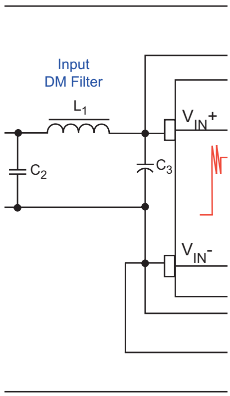


Fig. 7.12: Input DM filter (Source: DC/DC BoK, Fig. 5.19)

More details of DC/DC converter filtering is provided in the DC/DC Book of Knowledge available for download on the RECOM website.

7.4.2 Common Mode Output Filters

Most common mode output noise is caused by the switching spikes on the input side appearing on the output via the transformer coupling capacitance. To reduce this interference, a return path to the input side must be provided via external capacitors. As the output is galvanically isolated, the return path would offer a low impedance at the noise frequencies.

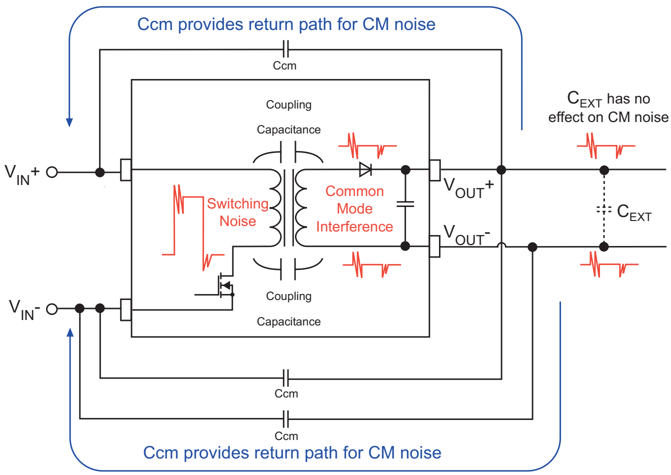


Fig. 7.13: CM noise in a DC/DC converter (Source: DC/DC BoK, Fig. 5.14)

Common mode capacitors are typically in the range of 1–2nF to offer low impedance to the megahertz frequency switching spikes. They need to be rated at the isolation test voltage as they are placed across the isolation barrier.

As the output switching noise is common mode (appears on both Vout+ and Vout- simultaneously), adding an output capacitor or LC circuit will not reduce this interference. However, a Common Mode Choke (CMC) will be very effective:

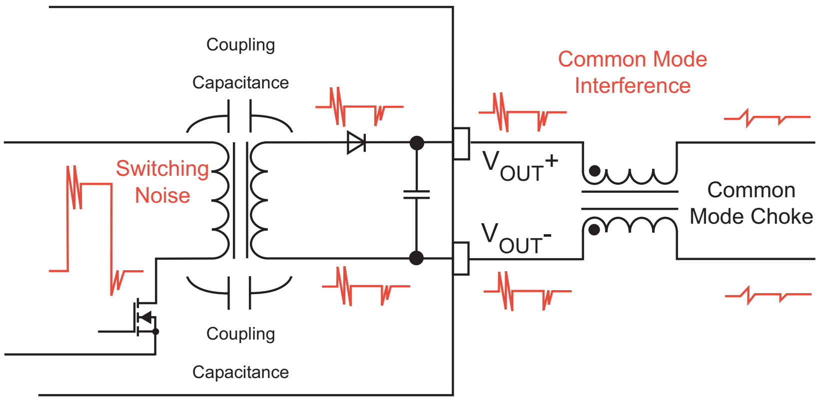


Fig. 7.14: CM noise reduction with an output CMC (Source: DC/DC BoK, Fig. 5.16)

The figure above shows a common mode output choke used with a DC/DC converter. One winding is placed in series with the VOUT+ output and the other winding in series with the VOUT- return.

Common mode chokes will attenuate CM noise over a wide range of frequencies due to the high permeability of the core material. This is important to filter both the main switching frequency and its harmonics.

A common mode choke can also be used on the primary side to combat CM interference.
As the differential input current interference can be very high (inrush as well as reflected ripple current) in relation to the common mode current interference, it may be tempting not to worry about the CM input current; but for EMC compliance, it is often required.

A fully filtered DC/DC converter circuit for conducted emissions is shown below:

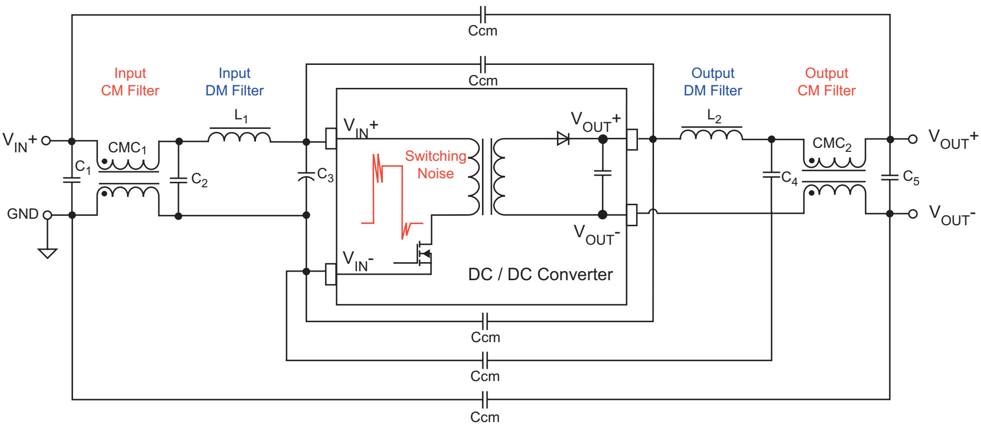


Fig. 7.15: Fully filtered DC/DC converter (Source: DC/DC BoK, Fig. 5.19)

7.4.3 Pi Filter Design

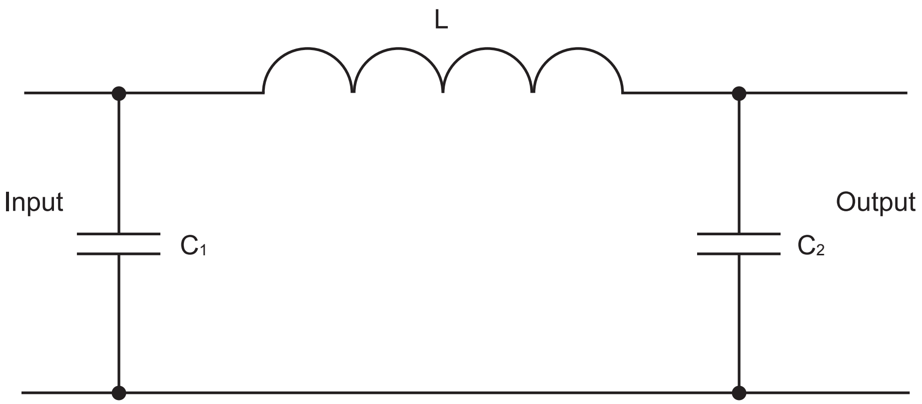


Fig. 7.16: Pi filter

First, measure the frequency of the interference, and then choose a corner or cut-off frequency that is 1/10th of this value:

Rearranging the standard filter equation gives a product for LC (where C = C1 = C2):

$$LC = \frac{1}{(2\pi f_c)^2}$$

Eq. 7.3: LC Product

As it is much easier to achieve a given capacitance value by placing several capacitors in parallel[2] , choose a convenient value for L with a sufficient current rating for the application, then work out the values for C1 and C2.

7.4.4 Radiated Emissions From an Isolated DC/DC Converter Output

Radiated emissions can sometimes occur if the output tracks create an unintentional dipole antenna (a dipole is an antenna consisting of two equal-length conductors oriented end-to-end with a signal injected in the middle; if the overall length is of ½ wavelength, then it will act as a strong antenna).

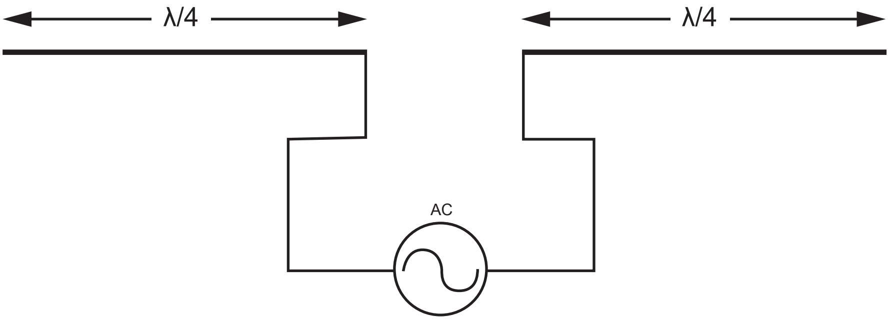


Fig. 7.17: Quarter-wavelength dipole

If the output track layout is symmetrical, then an efficient dipole antenna can be formed, radiating a significant amount of noise:

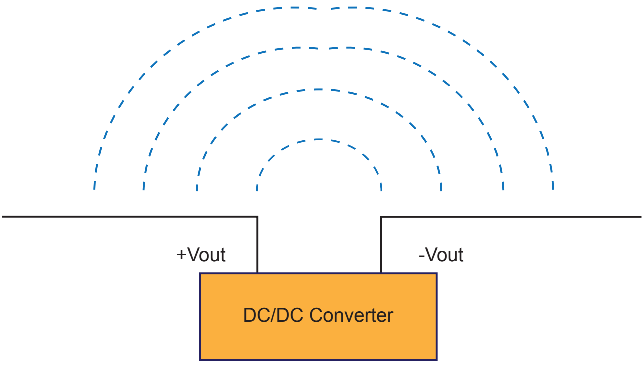


Fig. 7.18: Unintentional dipole formed from the output PCB tracks of a DC/DC converter

[2] Adding capacitors in parallel provides the advantange of lowering the ESR.

Adding a ferrite bead that has a high impedance over a wide range of frequencies in the MHz to GHz region, but a low DC resistance will effectively reduce the length of the dipole antenna and its RF emissions:

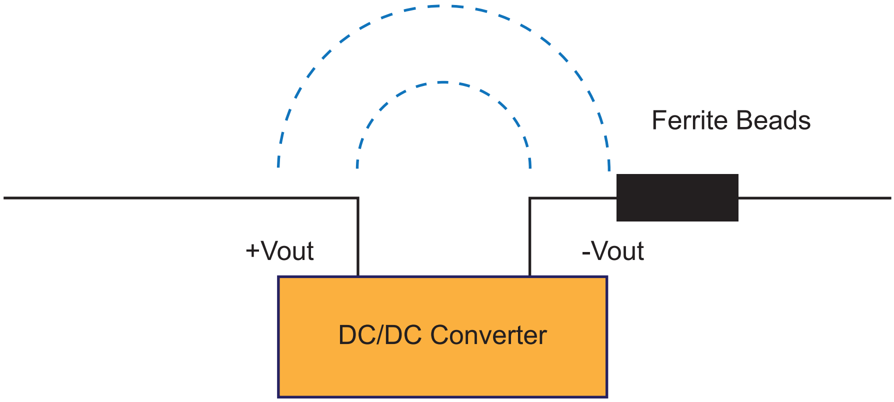


Fig. 7.19: Ferrite bead countermeasure for unintentional dipole

In practice, it is often useful to add ferrite beads to both +Vout and -Vout terminals and add filter capacitors to additionally reduce DM-conducted noise as well as radiated RF emissions:

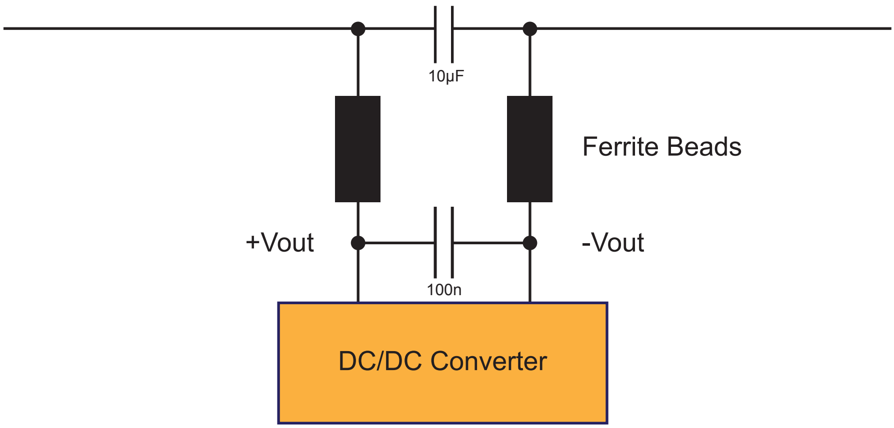


Fig. 7.20: Filtered output countermeasure for unintentional dipole

7.4.5 EMC Countermeasures Through PCB Layout: Some Examples

If we take the example of a simple buck-switching converter, then the circulating currents can cause both DM and CM noise interference, even with LC filters on the input and output:

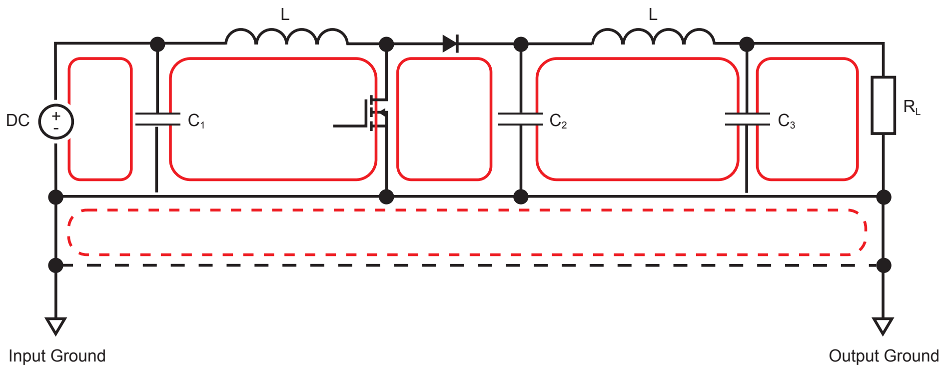


Fig. 7.21: DC buck converter with intentional and unintentional current loops

Rearranging the layout to keep the current loop of the switching node as small as possible and using a star-ground arrangement will reduce noise interference:

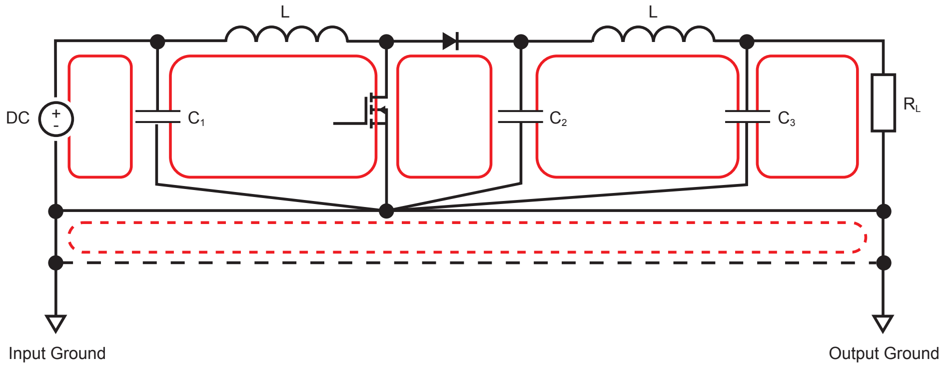


Fig. 7.22: DC buck converter with a star-ground arrangement to reduce external CM loop current

Another common source of noise interference are high-frequency ICs. Sometimes, adding a decoupling capacitor across the supply may not reduce the noise levels sufficiently. Remembering that every track, via, and connection has an impedance allows us to improve the decoupling effect by simply changing the layout:

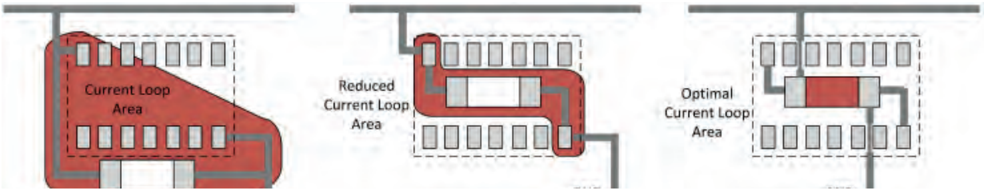


Fig. 7.23: Original vs. improved vs. optimal layout (Source: Power Supply Meets EMC, RECOM)

It is often impractical to place a decoupling capacitor underneath an integrated circuit, so it should then be placed as close as possible to the IC power pins. As a ceramic decoupling capacitor is physically a lot smaller than an IC, this usually means placing them with one end close to the power pin(s) with a via connecting the other end through the PCB to the ground plane. As any series inductance in the connection, including the via, will impair the performance of the decoupling capacitor, it is important to arrange the PCB stackup in a multilayer board arranged to have the ground plane closest to the IC:

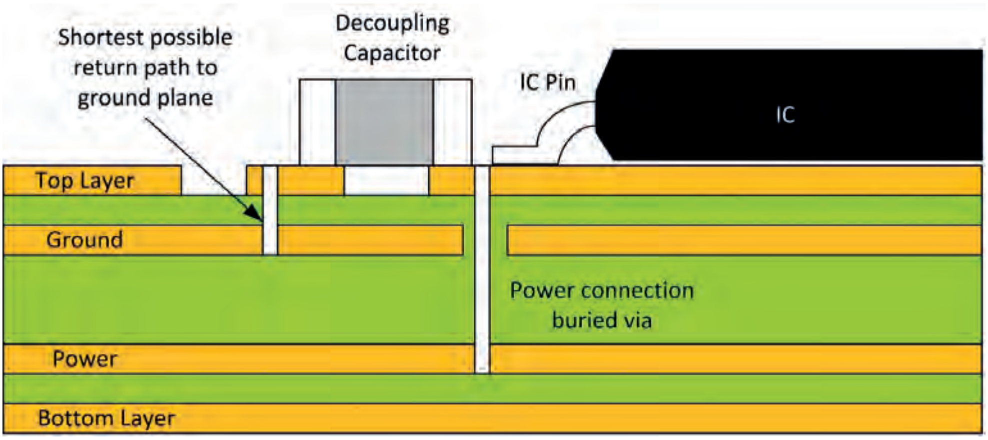


Fig. 7.23a: shortest possible ground via connection due to optimum PCB layer stackup

Another example is the correct orientation of SMD inductors. In the layout of a buck converter, the short lead of the inductor should be connected to the switching node. This is the inductor connection with the smallest parasitics and therefore the lowest noise:

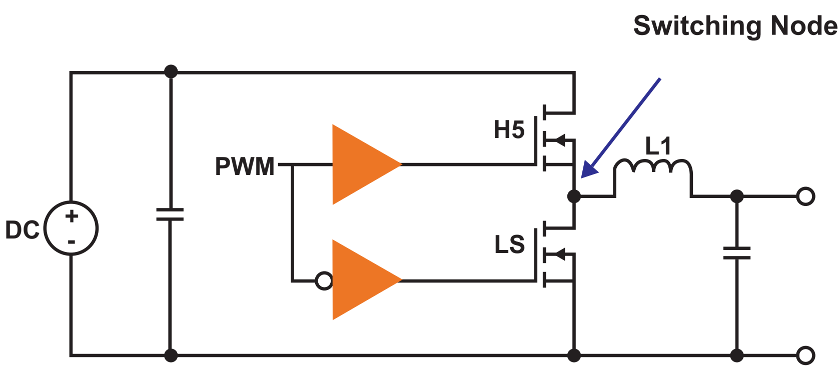


Fig. 7.24: Identification of the switching node in a simple buck regulator circuit

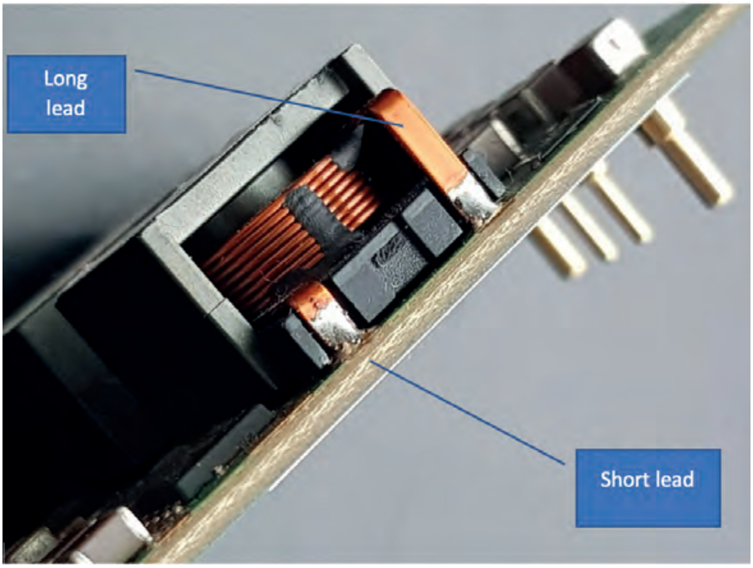


Fig. 7.25: Identification of the short lead in an SMD inductor

Chapter 8: EMC Standards

8.1 Introduction

Most technical standards are defined using a hierarchical structure. The base level contains the basic standard that covers the generic essentials, such as which limits must be met for compliance (for example, CISPR 11), with further subdivisions (for example, CISPR 16-1-1, CISPR 16-1-2) detailing the required testing for compliance, such as how to perform the test, which test equipment must be used, how the test should be set up, and so on.

For example, the IEC/61000 standard has seven parts:

- **Part 1: General (61000-1-*)**
  Basic concepts (fundamental principles, definitions, terminology)—interference model
  Functional safety (what a safety function does and approaches of performing it satisfactorily)
  Measurement uncertainty

- **Part 2: Environment (61000-2-*)**
  Description of the environment
  Classification of the environment
  Compatibility levels

- **Part 3: Limits (61000-3-*)**
  Emission limits
  Immunity limits (insofar as they do not fall under the responsibility of product committees)

- **Part 4: Testing and measurement techniques (61000-4-*)**
  Measurement techniques (without specifying limits)
  Testing techniques (without specifying limits)

- **Part 5: Installation and mitigation guidelines (61000-5-*)**
  Installation guidelines
  Mitigation methods and devices

- **Part 6: Generic standards (61000-6-*)**

- **Part 7: Miscellaneous (61000-9-*)**

Beware: These standards do not tell you which level is valid for your product or if this standard is the most applicable one for your product. More than one EMC standard may be applicable, requiring more than one test setup.

The EMC product standards mainly differ based on the intended use or the intended environment for which the product has been designed. So, you will find different standards for different purposes such as medical, automotive, or lighting applications as well as for different environments such as residential, industrial, or commercial.

Many of these product family standards include further standards that are specific to certain use cases. For example, the IEC/EN 61000-3-x EMC limits part has the sub-parts IEC/EN 61000-3-2 (limits for harmonic current emissions ≤16A per phase) and IEC/EN 61000-3-12 (limits for harmonic current emissions >16A and ≤75A per phase).

If you cannot find a product family standard for your product, then you need to check where your product will be used and find answers in the generic standards. It is the responsibility of the manufacturer to identify the most appropriate standard(s) that need to be complied with.
The standards are very often divided in parts between emission and immunity testing. For example, EN55014-1 is applicable for household equipment emissions and EN55014-2 is applicable for household equipment immunity.

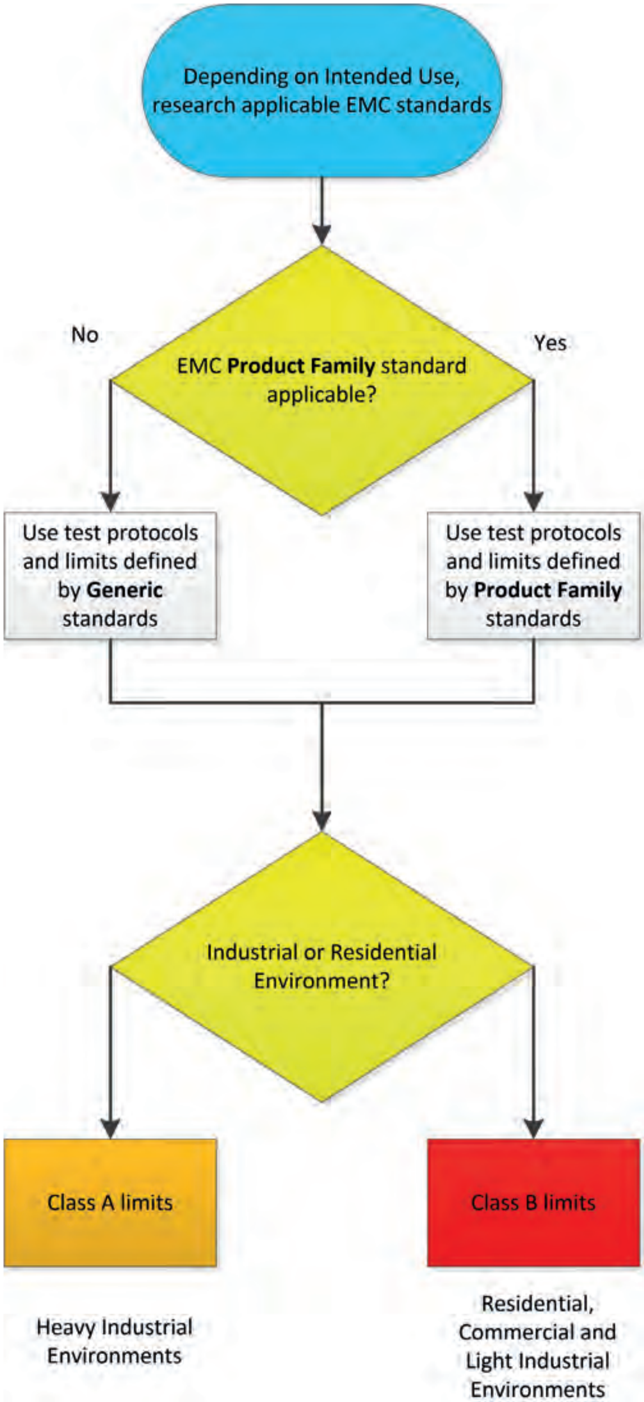
PRODUCTFAMILY STANDARD	GENERIC STANDARD	BASIC STANDARD
CISPR 32 & 35	IEC61000-6-1	CISPR 16
CISPR 14-1 & -2	IEC61000-6-2	IEC61000-3-2
IEC61000-3-2 or -3-11	IEC61000-6-3	IEC61000-3-3
IEC61000-3-3 or -3-12	IEC61000-6-4	IEC61000-4-2
IEC60601-1-2	…	IEC61000-4-3
IEC61204-3		IEC61000-4-4
…		IEC61000-4-5
Particular Standards		IEC61000-4-6
IEC60601-2-27		IEC61000-4-8
IEC60601-2-34 ...		IEC61000-4-11

Fig. 8.1: Organization of standard families

8.2 Product Family and Particular Standards

Product family standards define which tests out of the basic standards are applicable to a product and how they are applicable. In most cases, the standards will focus on the environment in which the devices will be operated. For example, a device that is meant to be used in a hospital will be used in a very different environment when compared to that of an electrical vehicle. A product family standard will also differ based on the intended operating conditions. For example, the testing provided by the product family standard for power supplies will differ between devices used in an industrial environment and those used in a residual or light industry environment.

Medical standards additionally define tests according to the location of use of the device. Especially with respect to immunity, the levels are different for equipment that is used in hospitals or for home healthcare, and those that are used in special environments, such as ambulances. The following decision flow chart can be used to to find the most appropriate EMC standard for a product:



8.3 Emissions Testing

For a more detailed decision process required to meet CE marking requirements for EMC, refer to the EU 'Blue Guide' , currently called "19 December 2018 Guide for the EMCD (Directive 2014/30/EU)"

8.3.1 Conducted Emission (Radio Frequency)

Conducted emission testing is usually done in the lower frequency band—usually up to 30MHz—and must be measured on all ports of the device under test. This is an important point because often, during pre-qualification testing, emission measurements are carried out on the input and output connections only, and other ports, such as enable input or status output, are ignored.

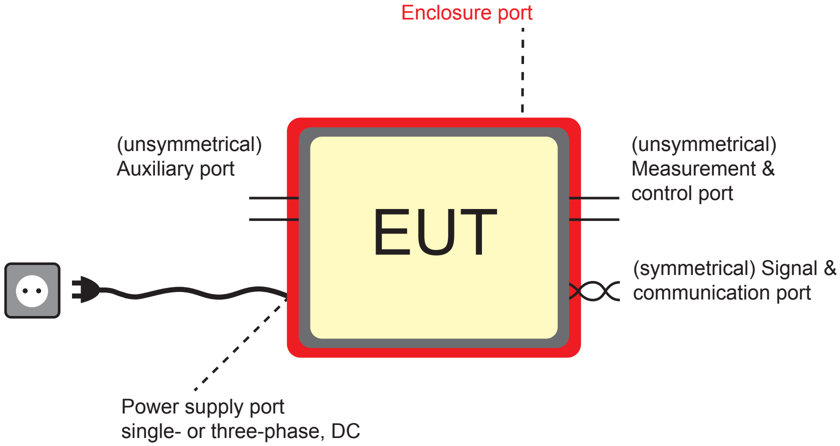


Fig. 8.2: Simplified conducted emission test setup

Class A
Class A is given in emission standards like EN55011 (ISM), EN55022 (ITE), and EN55032 (multimedia equipment), and is applicable when the device will be used in a heavy industrial environment, where higher limits are allowed, when compared to Class B defined in the same standards.

Class B
Class B is applicable when a device will be used in residential areas and therefore must keep within more strict limits and only less distrubance can be accepted.

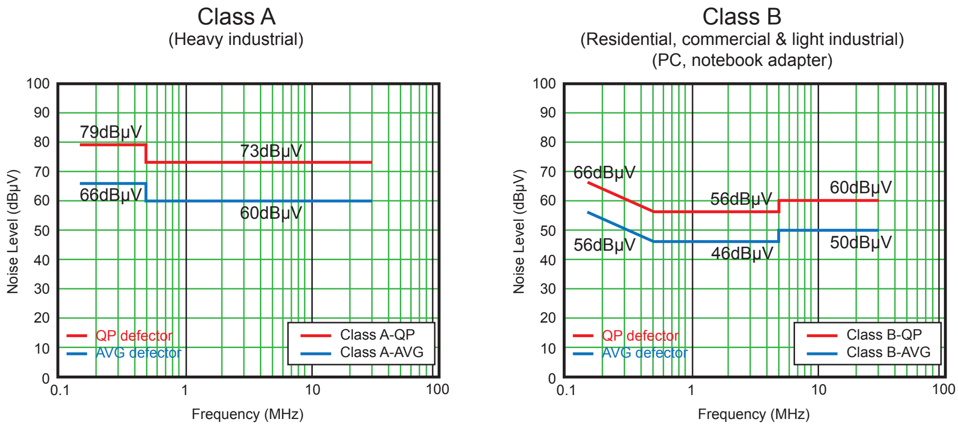


Fig. 8.3: EN55032 Class A and Class B conducted emission limits

Other standards can have different limits; for example, the Class A and Class B limits in the American FCC standard differ from that in the European CE standard:

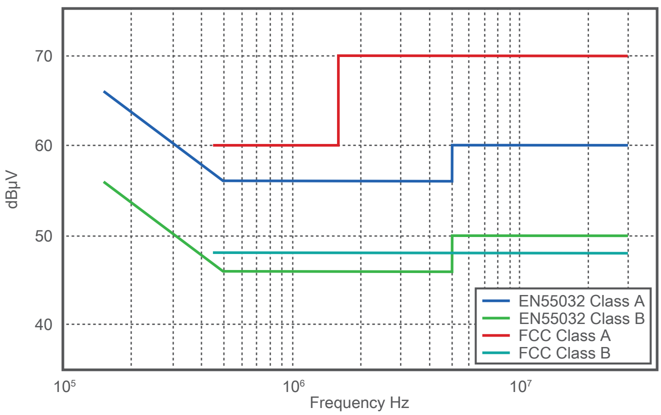


Fig. 8.4: FCC Class A and Class B conducted emission limits

SUMMARY #12: Class A and Class B refer to the environment in which the device will be used and do not have any fixed limits. Depending on the standard used, the limits will differ, so it is very much possible for a product to pass FCC but fail CE!

8.3.2 LISN Impedance Network

As the results of conducted emission tests can be skewed by the impedance of the power supply (for example, if an AC/DC power supply was powered by a bank of car batteries wired in series, then the internal impedance of such a set of wet lead-acid batteries would be so low that almost any disturbance would be swallowed by the supply and even noisy devices

would appear to pass), conducted emission test must be carried out using a Line Impedance Stabilization Network (LISN) to achieve repeatable results across all supply voltages, test laboratories, and devices.
A LISN is a standardized model of a low-pass filter with a predefined RF measurement port:

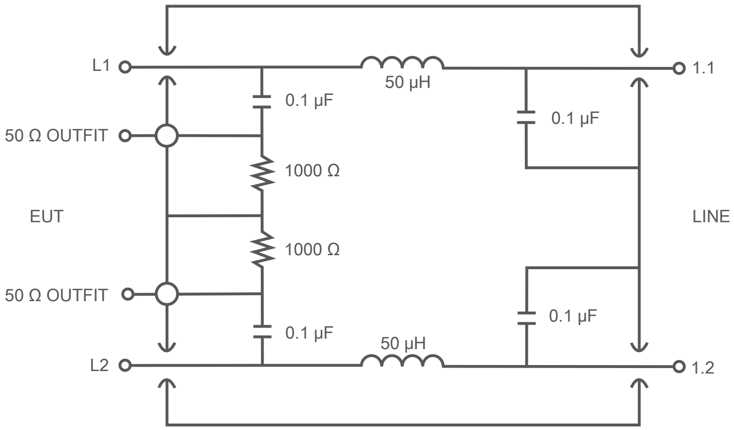


Fig. 8.5: Industrial LISN network

The LISN unit usually contains two ports so that noise on both supply lines (DC plus and minus or live and neutral) can be monitored at the same time. LISNs and ISNs are covered in more detail in Chapter 9.

8.3.3 Harmonic Currents

Pulsating currents in input conductors can be a source of harmonic interference, which can affect the mains voltage quality. These harmonics are typically created by switch-mode power supplies or other non-linear loads such as motors, dimming ballasts, or inverters, which have a power factor not equal to unity.

The harmonics test is one of the most important tests that we must manage as a power supply manufacturer. This measurement indicates if there is a harmonic current distortion superimposed on the fundamental mains frequency of 50Hz (or 60Hz).

IEC EN 61000-3-2 defines the limits for 50Hz 230VAC supplies with less than 16A per phase according to an A, B, C, or D classification:

Class A: Balanced three-phase equipment, household appliances (except equipment listed under Class D), electric tools (excluding portable tools), and audio equipment, plus everything else that is not included in the other classes.
Class B: Portable (handheld) electric tools and arc welding equipment that are not in continuous use.

Class C: Lighting equipment and dimmers.

Class D: Personal computers, monitors, and TVs (Note: Class D equipment must have a power level between 75W and 600W).

The compliance limits are a complex set of rules related to each harmonic number and the maximum amplitude permitted:

Harmonic Number (n)	Class A (Amps)	Class B (Amps)	Class C (% of mains current)	Class D (mA/W)
2	1.08	1.62	2	-
3	2.30	3.45	30 x -λ (power factor) or 2-whichever is lower.	3.4
4	0.43	0.645	-	-
5	1.14	1.71	10	1.9
6	0.30	0.45	-	-
7	0.77	1.155	7	1.0
8-40 (even harmonics)	0.23 x 8/n	0.345 x 8/n	-	-
9	0.4	0.60	5	0.5
11	0.33	0.495	3	0.35
13	0.21	0.315	3	3.85/13
15-39 (odd harmonics)	0.15 x 15/n	0.22 x 15/n	3	3.85/n

Table 8.1: Harmonic limits according to class

The measurement is made using a shunt sense resistor and a clean (low noise) supply—usually an AC generator or a heavily filtered AC mains supply.

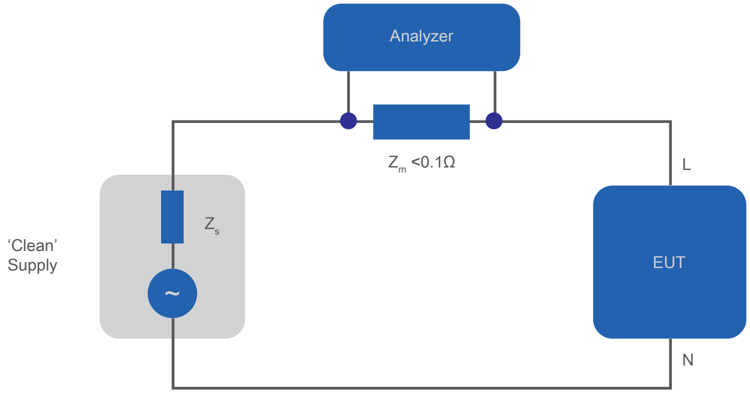


Fig. 8.6: Simplified harmonic current test setup

8.3.4 Flicker

A device that consumes very high energy within short periods of time can cause voltage dips that may cause problems for other devices connected to the same main power line. The pass or fail criteria for such high peak energy consumption was determined empirically back in the 1890s, when failing electric lamps started causing other lamps on the same circuit to 'flicker' or dim erratically. The IEC EN 61000-3-3 pass criterium is based on the magnitude of the drop and the frequency of the event; so, the voltage drop caused by a device is allowed to occur many times per second if the drop is small; but if the magnitude of the drop is large, it is allowed to occur only infrequently.

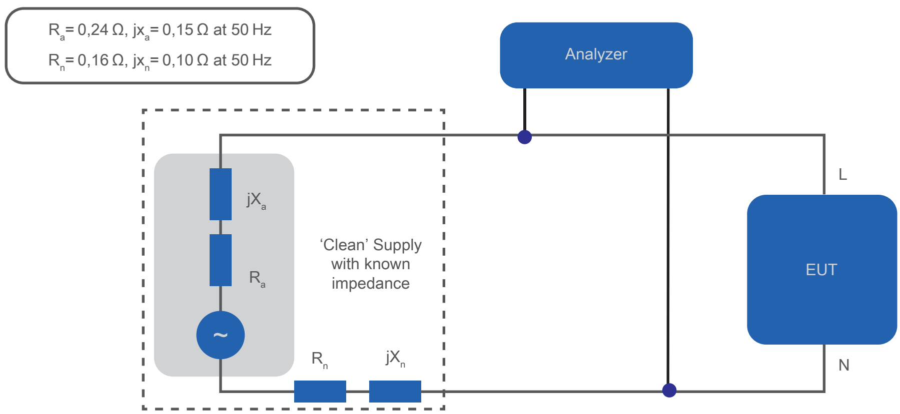


Fig. 8.7: Simplified flicker test setup

8.3.5 Magnetic Field Emissions

Magnetic field emissions are included in EMC standards but are not often required. An exception is for professional audio equipment wherein the varying magnetic fields from speakers could cause interference in other circuits. IEC EN 61000-4-12 covers the requirements related to magnetic field emissions.

8.3.6 Radiated Emissions (Radio Frequency)

Radiated emissions is an enclosure test, wherein the whole E-field or H-field emission of a device is measured. IEC EN 61000-4-3 describes the testing and measurement techniques required for compliance with IEC/EN standards, while FCC Part 15 Subpart B covers both the limits and the methods of measurement for US regulations.

As with conducted emissions, the radiated emission limits are split into Class A and Class B, based on the intended environment:

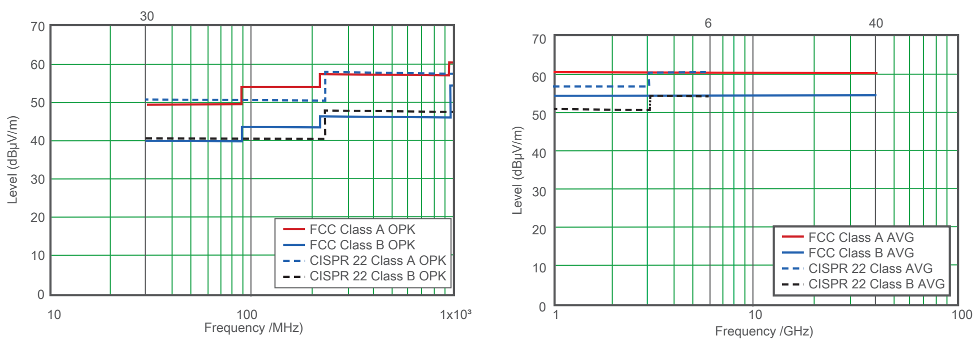


Fig. 8.8: FCC Part 15 and CISPR 22/32 comparison

Automotive

The automotive radiated emission limits applicable in Europe are defined by the United Nations Economic Commission for Europe (UNECE) Regulation 10 requirements. The R10.05 emission tests are split into broadband (BB) sources, such as ignition systems, electric motors, and onboard battery chargers, and narrowband (NB) sources, such as on-board power supply and communication networks:

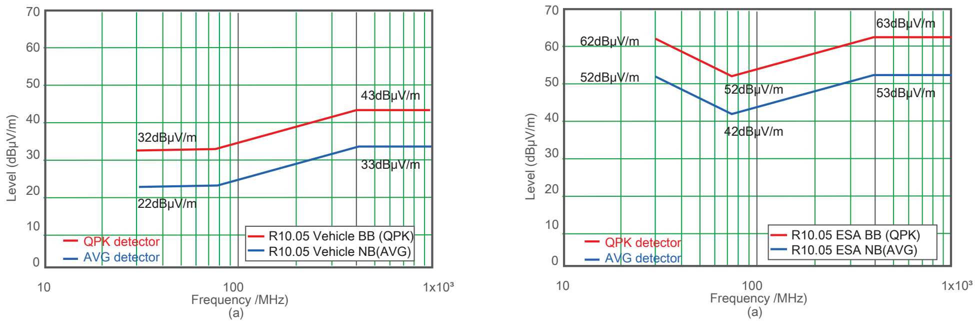


Fig. 8.9: UNECE Reg.10.06 limits (a) is for a 10m chamber for whole vehicle testing and (b) is for components tested at 1m.

The R10.05 limits are aligned with CISPR12 and CISPR25 limits.

ISM

Another classification is for ISM (Industrial, Scientific, and Medical) devices, which covers a wide range of applications including devices that radiate energy intentionally. Group 1 includes devices that are not intended to radiate electromagnetic energy, whereas Group 2 includes devices that are designed to radiate electromagnetic energy, e.g., for communications or power transmissions such as Wi-Fi beacons, microwave ovens, and wireless charging pads. The limits are similar for CISPR 11, EN55011, and FCC Part 18.

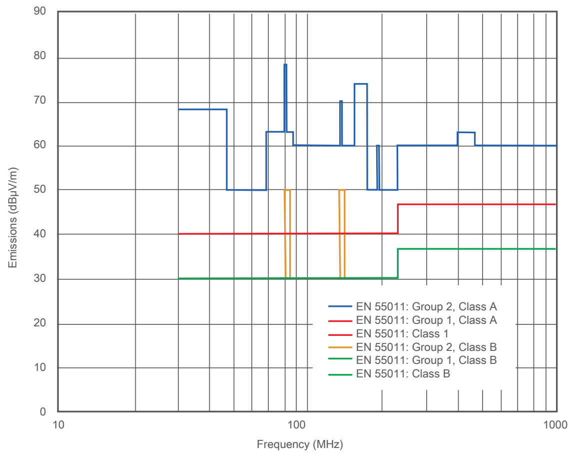


Fig. 8.10: ISM limits for different groups and classes

For other equipment that do not fall under multimedia, ISM, and household or lighting equipment categories, the generic IEC EN 61000-6-3 (emission standard for residential, commercial, or light-industrial environments) or IEC EN 61000-6-4 (emission standard for industrial environments) apply:

PRODUCT SECTOR		IEC/CISPR standard	EN standard	FCC standard
Vehicles, boats & devices with internal combustion engines	Off-board receivers	CISPR 12	EN 55012	–
	On-board receivers	CISPR 25	EN 55025	–
Multimedia Equipment		CISPR 32	EN 55032	Part 15
ISM		CISPR 11	EN 55011	Part 18
Household appliances, electric tools & similar apparatus		CISPR 14-1	EN 55014-1	–
Luminaires, lighting equipment		CISPR 15	EN55015	Part 15/18
Equipment with no product-specific standard	Commercial/light-industrial	IEC 61000-6-3	EN 61000-6-3	–
	Heavy-industrial	IEC 61000-6-4	EN 61000-6-4	–

Table 8.2: Common emission standards

8.4 Immunity Testing

8.4.1 Conducted Immunity (Radio Frequency)

When power or signal cables are positioned close to each other, capacitive or inductive coupling can allow CM disturbances to cross over between them. IEC EN 61000-4-6 defines a test setup in which a coupling/decoupling network (CDN) transducer injects disturbances into the cables to test the effectiveness of the input/output filter networks.

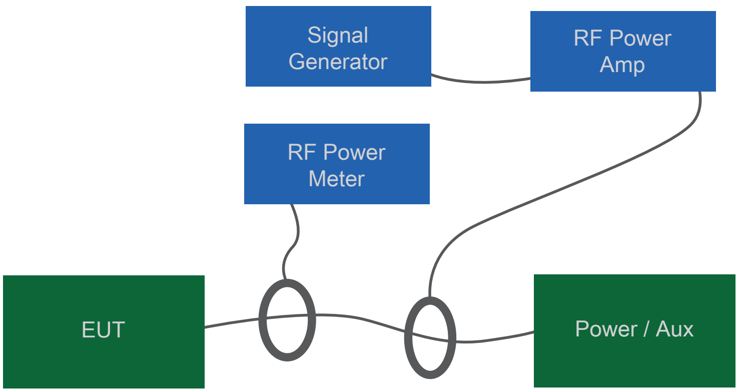


Fig. 8.11: Simplified CI test setup

EN 61000-4-6 specifies different intensity levels for the injected disturbances:

FREQUENCY RANGE 150kHz - 80MHz

Level	Voltage Level of the disturbance	
	V rms	dB (µV)
1	1	120
2	3	129.5
3	10	140

Table 8.3: Conduced RF immunity limits

8.4.2 Surge Immunity

The IEC EN 61000-4-5 surge test applies a pulse with a specific shape utilizing galvanic coupling onto the lines of the tested device. The purpose is to test the robustness of the device against indirect lightning strikes. Unless otherwise stated, the test levels must be applied according to the environment in which the device is used. The pulse of the surge test has a moderate maximum voltage amplitude (up to +/–4 kV) and extends over a relatively long time (µs range), which leads to the dissipation of a high amount of energy. This high energy is the critical part of this test, as it can easily damage the device.

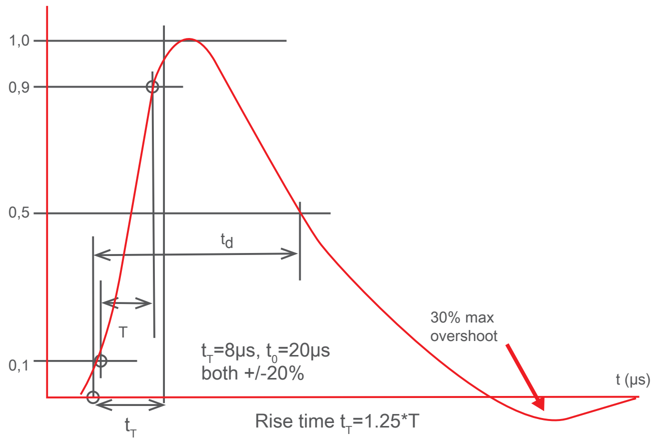


Fig. 8.12: Surge test waveform

8.4.3 Burst Immunity

The IEC EN 61000-4-4 burst test is similar to the surge and ESD (Electrostatic Discharge) tests. The pulse itself is short in time (ns range) like the ESD pulse but is of lower maximum voltage amplitude (±4 kV max.) similar to the surge pulse. However, this pulse is repeated at specific intervals over a fixed period of time.

The burst test simulates the brush sparking of a motor. Although the pulse is fast with a rise time in ns, since the coupling is capacitive, the device does not have to drain the current directly; this is the least harmful of the transient tests.

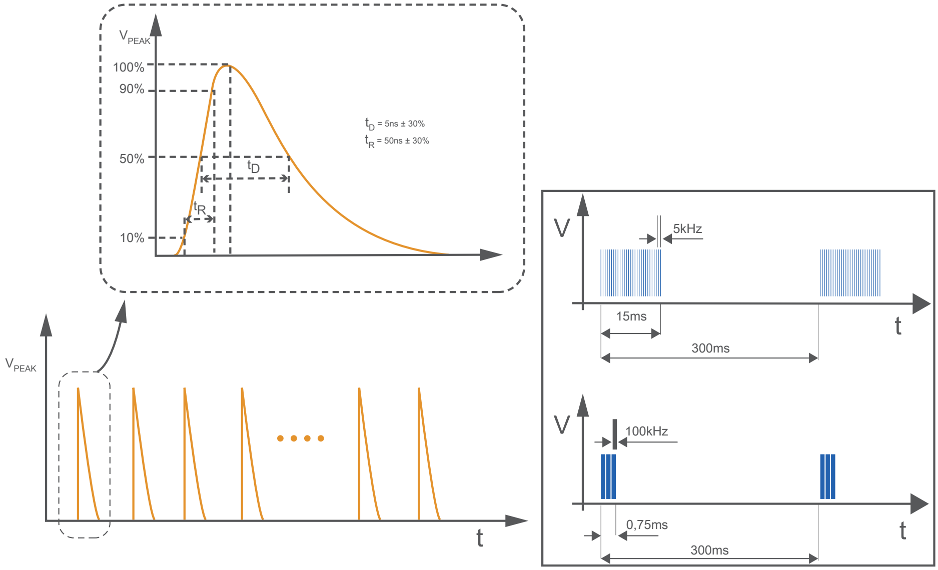


Fig. 8.13: Burst immunity test waveform

8.4.4 ESD Immunity

For the IEC EN 61000-4-2 ESD test, a pulse with a specific shape is applied directly to conductive parts of the device (contact discharge) and to conductive metal parts nearby at a specified separation distance (air discharge), as well as to non-conductive but touchable parts of the device.

ESD TEST DISCHARGE VOLTAGES

Contact Discharge		Air Discharge	
Level	Test Voltage (kV)	Level	Test Voltage (kV)
1	±2	1	±2
2	±4	2	±4
3	±6	3	±8
4	±8	4	±15
x	Custom	X	Custom

Table 8.4: ESD test voltages according to Level

These discharge pulses cause concentrated E-fields and high currents over a very short time, which might lead to an interrupt, a shutdown, a reset, or other unwanted behavior in the system.

Therefore, the DuT should be designed to withstand these electromagnetic phenomena, for example, by adding ultra-fast diodes to clamp the inputs to the supply rails (both to the supply and ground) or by fitting spark gaps into the PCB to divert energy away from the more sensitive components.

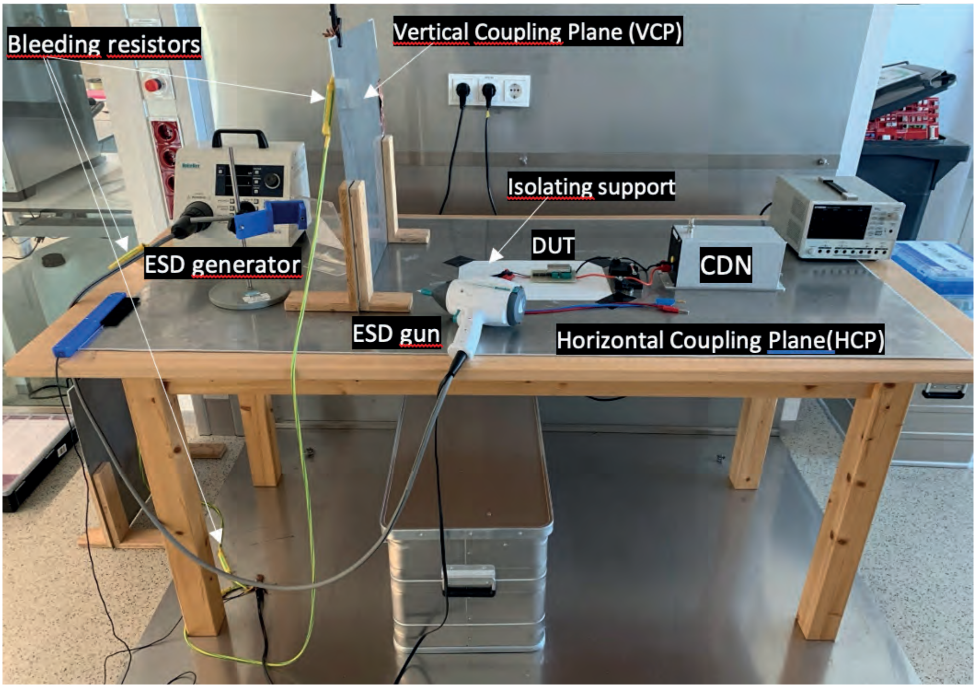


Fig. 8.14: ESD test setup

The shape of the ESD waveform is based on the Human Body Model (HBM), in which a person that has picked up an electrostatic charge can discharge themselves by touching the DuT.

SOURCE	LOW HUMIDITY	HIGH HUMIDITY
Walking across carpet	35.000V	1.500V
Walking across vinyl floor	12.000V	250V
Operator at bench	6.000V	100V
Removing Plastic wrapping	20.000V	1.200V
Getting up from chair	18.000V	1.500V

Table 8.5: Examples of ESD voltages with low and high air humidities.

Other ESD event models are the Charged Device Model (CDM), in which electrostatic charge is transferred between devices, and the Machine Model (MM), in which the moving machine generates an electrostatic charge, which is then discharged to the ground.

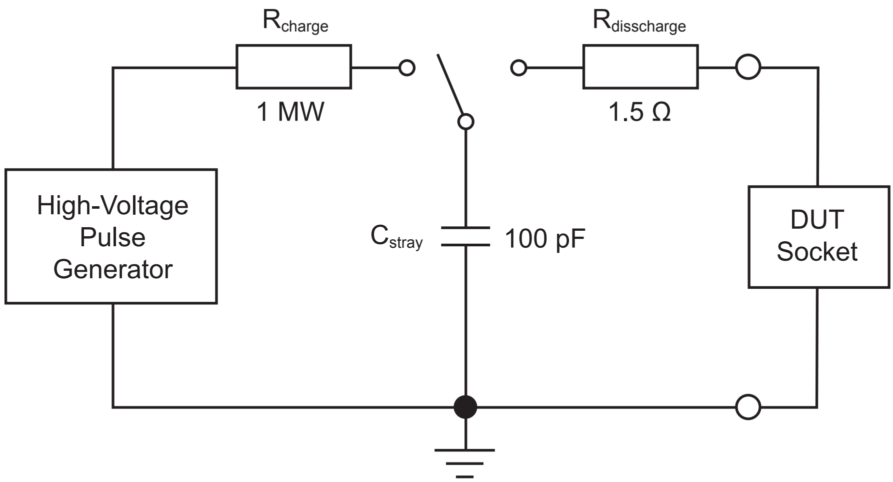


Fig. 8.15: Simplified Human Body Model test setup

The ESD pulse has a high maximum voltage (up to +/–15 kV) and occurs over a short time (ns range). As this very fast pulse is applied directly and indirectly to the device, this test is considered one of the most critical EMC tests. Refer back to section 4.9 for ESD protection countermeasures.

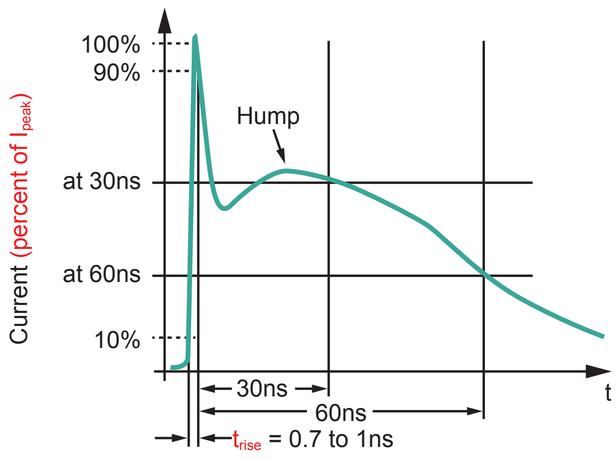


Fig. 8.16: ESD test waveform

Care must be taken when using an ESD gun to make these tests. the initial spike or crest is high voltage with fast slew rates, which means that it is very sensitive to stray capacitances. Different waveforms may occur if the gun is not held straight, or if the ground cable touches the operator, or if the gun is not held correctly by using the grip one-handed.

Equally, if the DuT has a painted surface, then the ESD gun must touch an unpainted spot when contact discharge tests are made, or false results may occur.

8.4.5 Radiated Radio Frequency Immunity

IEC EN 61000-4-3 and 61000-4-6 provide the requirements for radiated field immunity compliance. A directional antenna is positioned at a distance of 1 m to 3m from the Device under Test (DuT) and used to generate a strong external RF field in the frequency range of 80–1000 MHz (61000-4-3) or 150 kHz to 80 MHz (61000-4-6). Higher RF frequencies of up to 6 GHz may also be used if the DuT should not be influenced by factors such as mobile phone signals.
The RF carrier wave can be unmodulated or modulated with a 1kHz sinewave to a depth of 80%, which may be continuous or pulsed, according to the type of test being conducted.

TEST LEVEL	RF FIELD STRENGTH [V/m]
1	1
2	3
3	10
4	30

Table 8.6: RF field strength test levels

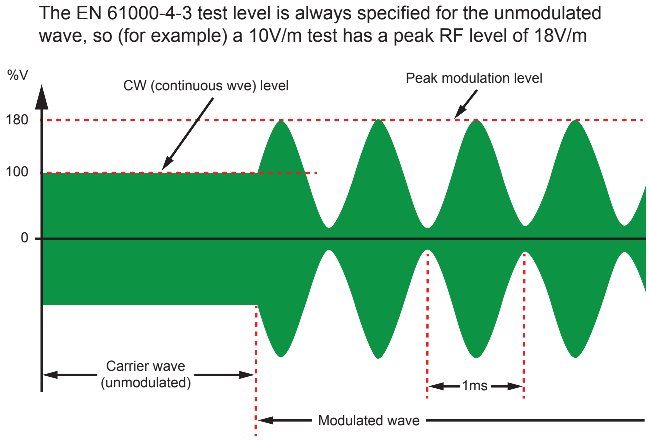


Fig. 8.17: RF immunity test waveform

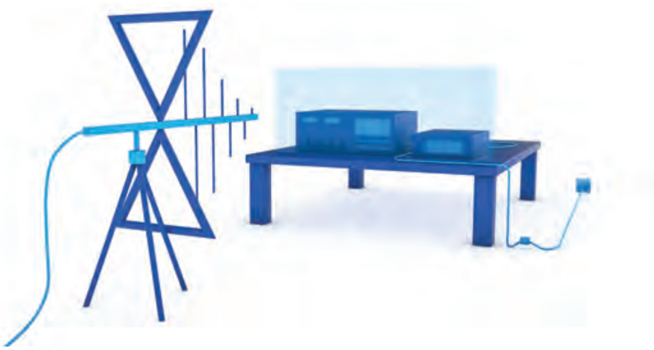


Fig. 8.18: RF immunity test setup

The objective of this test is to check if the performance of the DuT is degraded by externally applied RF fields. This immediately gives rise to the question—what is meant by 'degraded', and at what point does the DuT stop behaving 'normally'?

The test set-up is also complicated—the high-intensity RF fields can affect other monitoring equipment nearby and cause false results. It is also difficult to ensure a uniform EM-field across larger-sized devices without an expensive anechoic chamber or a specialized GTEM (Gigahertz Transverse Electromagnetic Mode) cell.

Small changes in the position of the 'specified cable' can affect the results; therefore, specifying a realistic 'engineering margin' or amount of uncertainty headroom above the limits is not simple.

8.4.6 E-field Immunity

The E-field immunity test is complementary to the radiated emission test. Here, the device is tested if it is immune against external electromagnetic fields that can be produced by other electric equipment. The test is typically performed by applying a homogenous E-field in a frequency range from 80 MHz to several GHz, depending on the applicable standard. The applied field is an amplitude-modulated signal with 80% modulation at 1 kHz.

8.4.7 Magnetic Power Field Immunity

The magnetic power field test simulates a homogenous magnetic field with a frequency of the main power supply of 50/60 Hz. When placed in a magnetic field typically produced by a Helmholtz coil, the device must work properly. Some older devices, such as cathode tube monitors, were highly affected by this test.

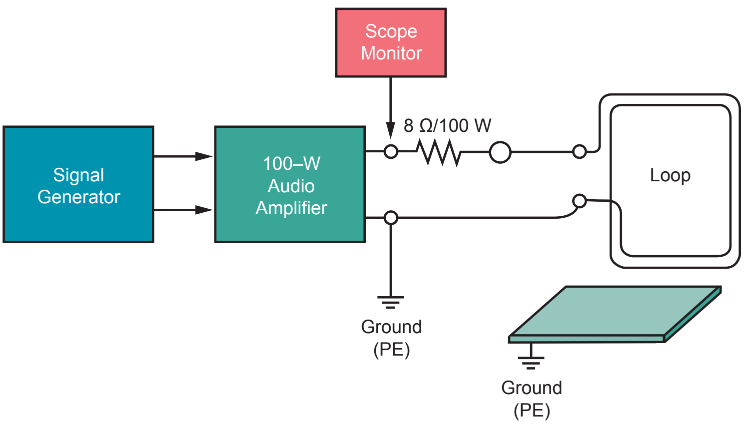


Fig. 8.19: Magnetic power field test setup

8.4.8 Voltage Dips, Variations, and Interruptions

The IEC EN 61000-4-11 test determines how an electrical device behaves when the main power supply voltage changes. There are three different parts to this test, each with different types of voltage variations.

First, the response criteria that specify how the device should behave in response to voltage fluctuations must be selected. For example, depending on the application of the device, it may be acceptable for the device to shut off in response to a voltage fluctuation. In contrast, the device can also be required to remain operational despite of occurring voltage fluctuations.

Voltage dips are applied to check the influence of an abrupt voltage drop on the device.

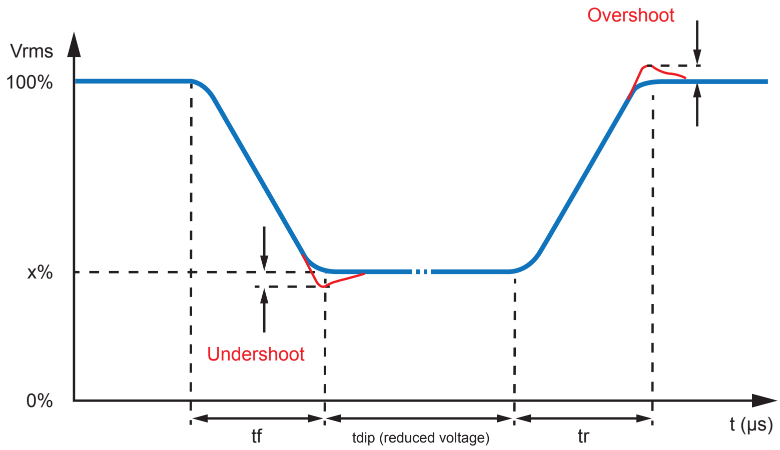


Fig. 8.20: Voltage dip waveform

8.5 Conflicts Between Different EMC Standards

When beginning a new design, you should clarify which EMC standards are applicable and design the circuit with these limitations in mind. However, integrating an input filter or EMI reduction elements can lead to conflicts with other standards. A common request we get as a medical power supply manufacturer is to provide a compact double or reinforced isolation DC/DC converter with built-in Class B EMC filtering. These two specifications are diametrically opposed—a highly isolated transformer design will have a large coupling capacitance across the insulation; however, Class B limits can be realized only with a bulky Y-capacitor across it, which is against the medical safety standard's strict limits on leakage currents. A multi-stage input filter with both DM and CM chokes can help avoid the need for a Y-capacitor; but then the design will no longer be compact or particularly cost-effective.

Even if the leakage current limits can still be complied with while using Y-capacitors, both the medical and household safety standards require two Y-capacitors (for double insulation) to be fitted in series to provide two independent methods of protection. However, two Y-capacitors often cannot be physically fit inside a small case size, as ceramic disc types need to be used to meet the voltage withstand specifications.

Multiple certifications are often obtained for AC/DC converters to facilitate their use in several different environments. For example, an industrial-grade power supply, EMC certified to EN 55022, might also be certified to EN 55014 for household applications, as this standard is also applicable for systems installations in buildings. Also, a medical-grade converter, safety certified to IEC EN 60601-1 for medical devices, can also be certified to the less strict EN 62368-1 safety standard for industrial use. However, the reverse is often not true: an industrial-grade power supply may not meet medical-grade safety or EMC standards without an extensive redesign.

SUMMARY #13: Before you start on a new design, decide which safety and EMC standard(s) apply, as compliance to different standards often entails physical changes to the PCB (increased creepage and clearance distances), changes to the design (CMC chokes instead of LC filters), and changes to the Bill-of-Materials (fitting components with higher ratings).

Chapter 9: Power Factor Correction

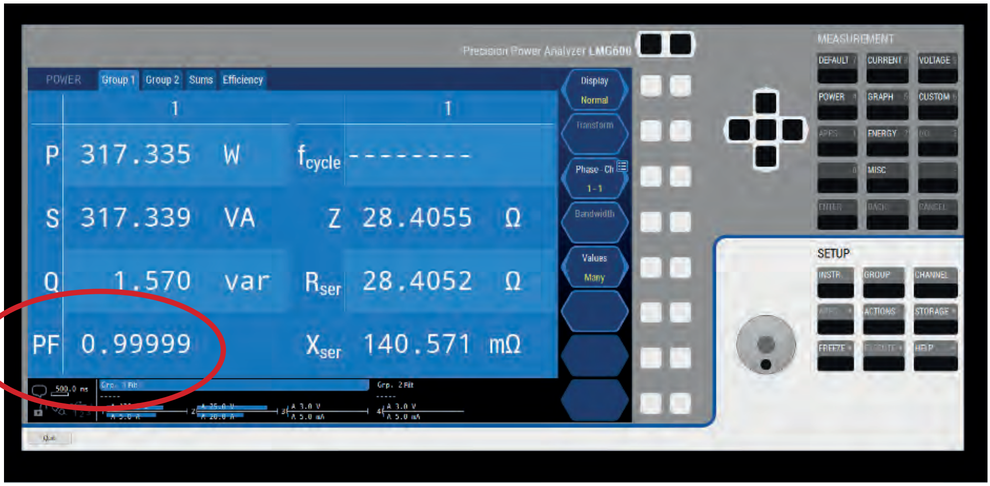


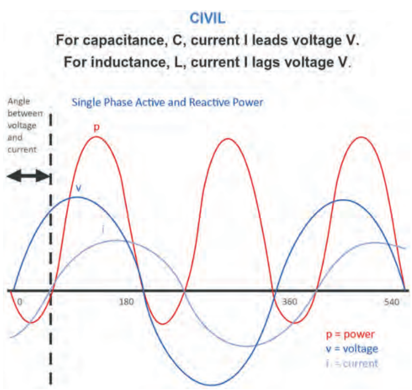
Fig 9.1: A power analyzer display showing a power factor (PF) figure of 0.99999

9.1 Apparent, Reactive, and Active Power

Electrical power can be measured in Watts by multiplying voltage times current, but it is an accurate calculation of usable power only in purely resistive circuits. When input current and voltage waveforms are misaligned or out of phase due to the reactance of an energy storage element (i.e., an inductive or capacitive load), then this simplistic relationship no longer holds true.

The effect of misaligned voltage and current waveforms is that the full amount of applied power (apparent power) cannot be delivered to the load as useable or active power because some of the energy is recirculated or reflected back into the supply as reactive power.

The figure below demonstrates this graphically and provides a nice mnemonic (CIVIL) for remembering the current/voltage lead or lag relationship based on the type of reactive element.



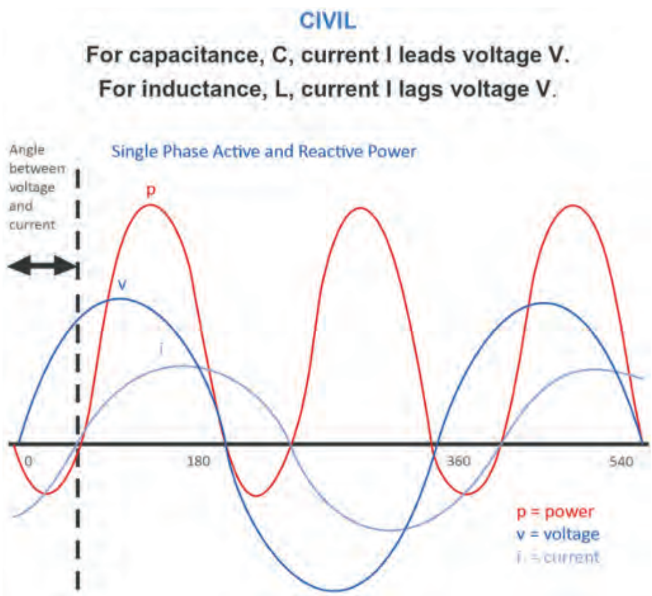


Fig. 9.2: AC voltage, current and apparent power for a mainly inductive load. The current lags the voltage and the reactive power can go negative (the load is supplying power back into the source)

These concepts and their relationship are highlighted in the figure below both mathematically and graphically, in terms of a beer glass (the head on a beer does no "work").

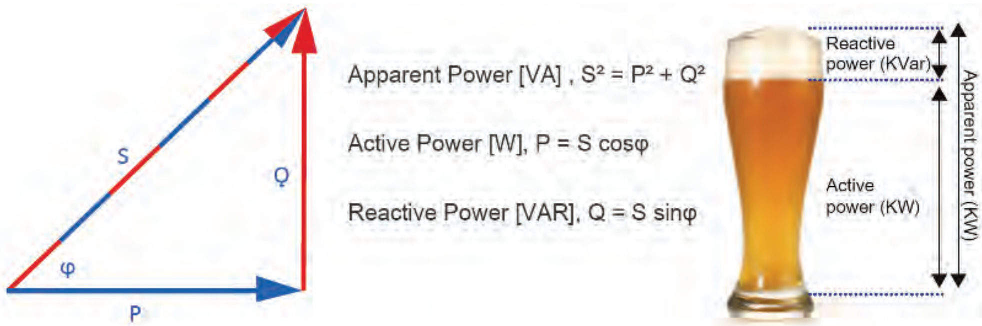


Fig. 9.3: Apparent power vector diagram. Reactive power does no useful work – like the head in a beer glass

Power factor (PF) is defined as the ratio of active power to apparent power (or cosine of the phase angle between the waveforms shown as ϕ in the figure above). Think of it as the percentage of available power that actually makes it to the load, which raises the following question: What happens to the rest of the power (1 – PF)? Physics tells us if this "other" power is not going to the load, then it must go elsewhere, i.e., it is reflected back into the supply and not used. An ideal PF (1) can only be achieved when there is a phase angle of 0° between the voltage and current waveforms, meaning all the supplied energy is used by the load and none of it is reflected back into the supply.

$$Power\ Factor = \frac{Active\ (or\ Real)\ Power}{Apparent\ Power} = \cos\varphi$$

Eq. 9.1: Defining Power Factor, where ϕ is the phase angle

9.2 What is Power Factor Correction (PFC)?

So, if the power factor is as close to one as possible, we maximize the usage of the supplied power. Power factor correction (PFC) is the term given to circuits that realign the current and voltage waveforms to improve the power factor. PFC solutions can be either passive (e.g., adding inductance to counteract the effect of a mainly capacitive load) or active (using switching transistors to control the current waveforms) – see section 9.4.

Something to note is the motivation for power factor correction. Most electricity meters only measure the active power consumed and ignore the reactive power; however, the electricity utility provider must still supply enough headroom to cover the instantaneous power consumption, including the reactive elements. Therefore, minimum PF requirements are typically dictated by edict (e.g., rules and regulations) due to the pressure from utility providers to cut their electricity generation and transmission costs. Otherwise, no manufacturer would opt to add cost (or even take a small, overall efficiency hit) to their power supply. PFC solutions will mostly go against the cardinal value propositions of maximizing the size, weight, and power (a.k.a. – SWaP) factors since a PFC front end takes up space and adds to the overall losses. So, in short, most engineers add it because they must, not because they want to!

To meet the EU EMC Directive and other international regulations, the active power factor correction is often required to comply with the maximum values set by IEC EN 61000-3-2 or one of the other international standards. In practice, active PFC is required for AC/DC power supplies ≥100W and either passive or active PFC for LED lighting gear ≥5W (as of May 2022).

9.3 Harmonics & THD

We will now get back to the question about where all the reactive power goes. The input voltage and current root-mean-square (RMS) waveforms are sinusoidal waveforms that can be represented as being comprised of an infinite series of periodic functions at harmonic frequencies of the fundamental (these harmonics are called the Fourier Series [2]). Even-numbered harmonics cancel out, so all this harmonic energy is seen at odd-numbered harmonics only. The majority will typically be seen at the third harmonic (i.e., the first odd harmonic after the fundamental), which tends to decrease as you go up in the series. These harmonics distort the input voltage and current waveforms, the sum of which is known as total harmonic distortion (THD). A lower PF implies greater distortion on the input line, which is why use cases that may install many power supplies on the same input circuit have higher PF minimum rating requirements.

NOTE: Power solutions meeting all proper regulatory limits can still be a liability to power line quality when scaled to too many units in volume. Even with very high PF (i.e., >0.98), the cumulative effects of the reactive components will eventually become significant in high enough volumes.

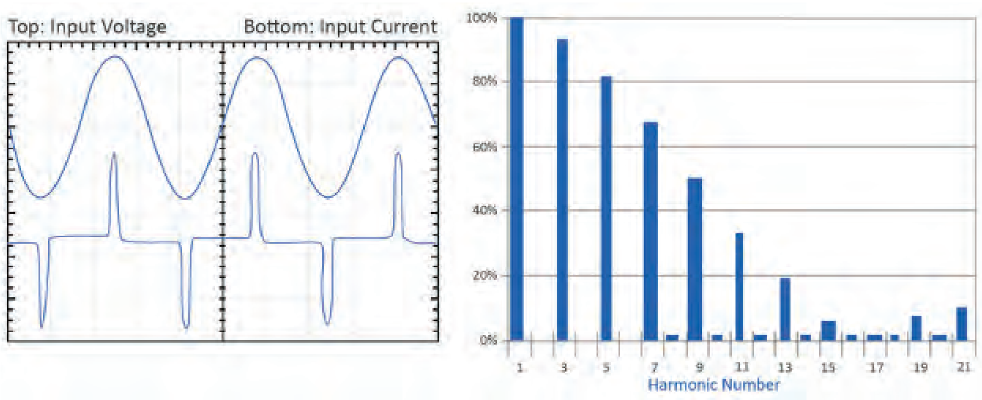


Fig. 9. 4: Non-corrected input current waveforms & associated harmonic profile.

9.4 PFC Solutions

If you recall from our CIVIL mnemonic, capacitance causes the current waveform to lead the voltage waveform and vice versa for inductance, which means that we can use these elements to shift the phase angle in one direction or the other in pursuit of maximum PF. Directly using these energy storage elements on the input of a power supply is known as passive PFC. Using elements with a semiconductor switch (essentially adding an extra switching power supply at the input) is known as active PFC.

The simplest form of passive PFC is adding a series inductor (a.k.a. – PFC choke) before the rectification stage of the power supply as shown in the figure below with the resulting waveform. While this is simple, its disadvantages include typically requiring a larger/heavier inductor, along with limiting the max achievable PF to ~0.7 (versus ~0.4 without any PFC). Additionally, the PFC choke must be sized for a limited input voltage range, which is undesirable for supporting universal AC input scenarios and driving a larger/heavier solution.

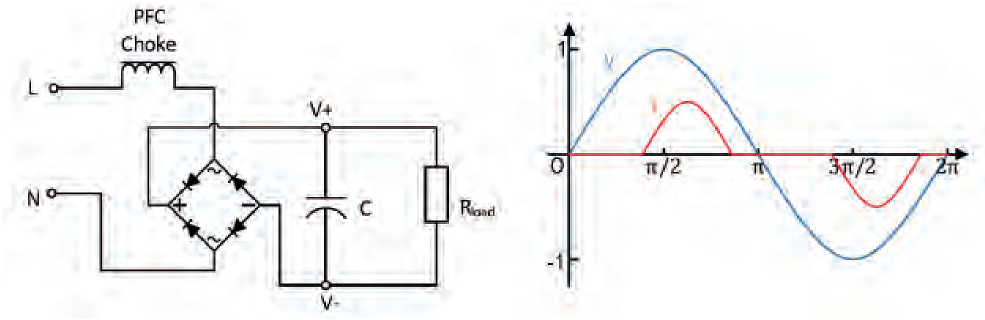


Fig. 9. 5: Passive PFC circuit and associated waveforms

The PFC choke partially cancels out the phase shift caused by the output capacitor C. The resulting voltage/current graph shows how the input current has been “delayed” by the PFC choke to give a better overall PF value.

Active PFC solutions mitigate most of the disadvantages just mentioned. The most common topology for active PFC is the boost (a.k.a. – step-up) converter. Within this class of power conversion are a handful of topologies (i.e., discontinuous conduction mode or DCM, continuous conduction mode or CCM, and critical conduction mode or CrCM or boundary mode) for implementing active PFC, but a comprehensive overview of these is beyond the scope of this discussion and can be found in the RECOM AC/DC Book of Knowledge.

A boost converter will increase the voltage on the input capacitor and keep it charged across a wide range of input voltages, thus supporting universal AC compatibility. It will try to achieve unity PF by ensuring that the average input current through the PFC choke closely follows the input voltage via one of the topologies referenced above. Each topology has its own tradeoffs regarding SWaP factors and EMI impact. The figure below shows an example of an active PFC circuit driven by a dedicated controller with input and output voltage waveforms.

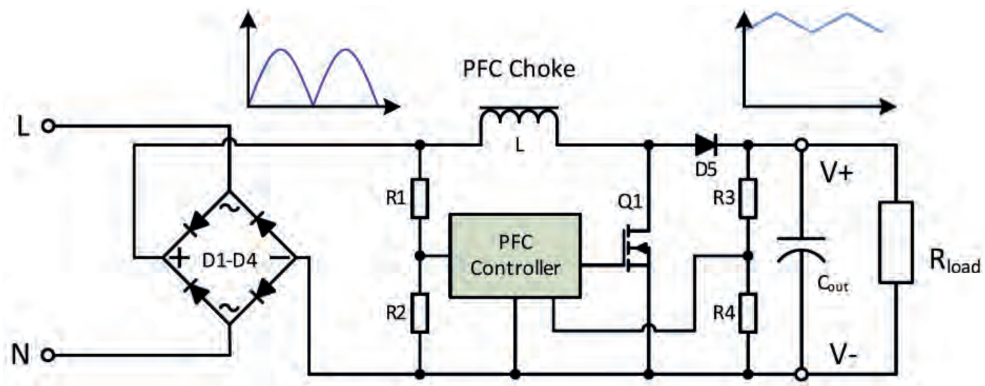


Fig. 9. 6: An active PFC circuit

A more modern take on the active PFC takes advantage of a unique property of gallium nitride (GaN) switches, which lack a body diode (unlike silicon MOSFETs) used to form a rectifier bridge and thus enable a higher-efficiency PFC implementation. This is known as a bridgeless PFC (a.k.a. totem-pole PFC), and an example circuit with its controller block is shown in the figure below, showing the difference between the GaN and Si switches.

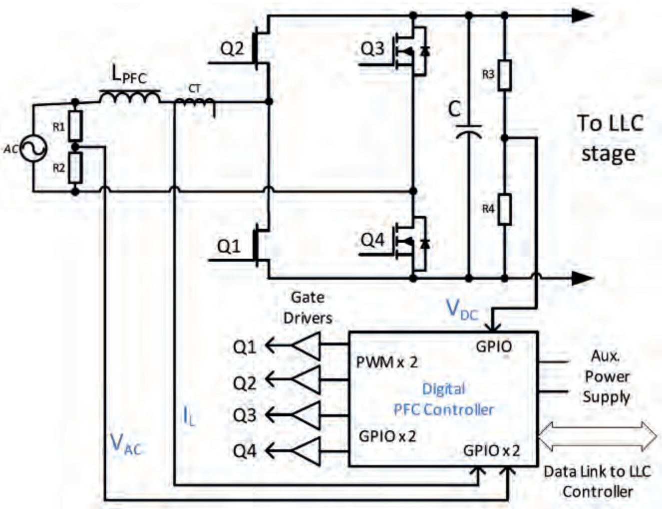


Fig. 9. 7: Block diagram of a bridgeless PFC controller (with digital control) Q1/2 are GaN & Q3/4 are Si-FETs (with body diodes)

A final consideration for PFC implementations is to take advantage of the benefits offered by multiphase power converters, such as reduced thermals and component stresses, by halving the current processed by each leg and combined at the output out of phase with each other. A larger PFC (typically characterized/dominated by the magnetics) can be sized for half the full-rated current and interleaved in two equal phases.

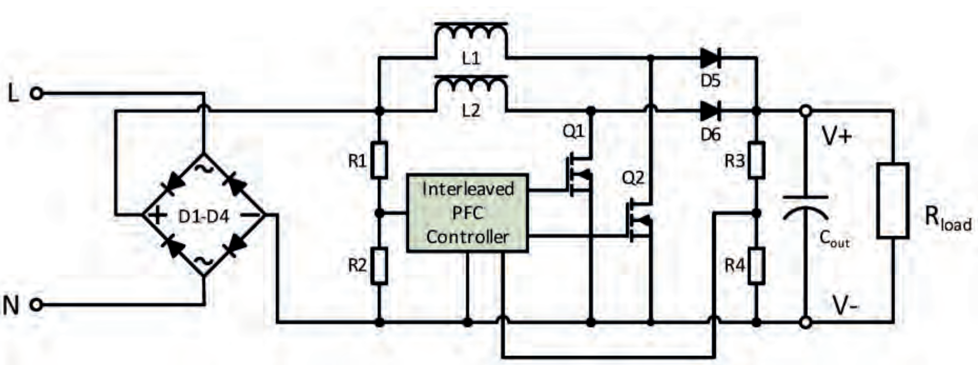


Fig. 9. 8: An interleaved PFC circuit

Whether one is trying to maximize their EMC performance and/or ensure acceptable line quality on distributions with high numbers of units on a single input bus, PFC is more than a “nice-to-have” feature and should be given serious consideration as part of an overall power solution and deployment.

Chapter 10: Measuring EMC - Equipment Needed

10.1 Anechoic Chambers

Anechoic chambers does not only avoid interferences from the emission of other equipment nearby to influence the results of the EUT (Euquipment under test) in emission testing, but also does it prevent the field generatred for immunity testing to interfere with the equipment near by.

The absorbers, in most cases, are a combination of ferrite tiles and carbon-coated foam in the shape of cones, as you can see in the example pictures. EM waves that hit these surfaces get absorbed, which is why they are called ‘absorbers’. The ferrite tiles absorb frequencies in the ‘lower’ frequency range, up to 1–3 GHz, whereas the hybrid broadband pyramidal absorbers can absorb frequencies in the MHz range and also up to 40 GHz.

The difference between a Fully Anechoic Chamber (FAC) and a Semi Anechoic Chamber (SAC) is the floor. In a FAC, the floor is also covered by absorbing material such as hybrid absorbers—so that all EM waves are fully absorbed, except the ones going directly from the EUT to the antenna. In a SAC, the floor forms reference ground plane.

Fig. 10.1: RECOM Gmunden SAC -3m distance

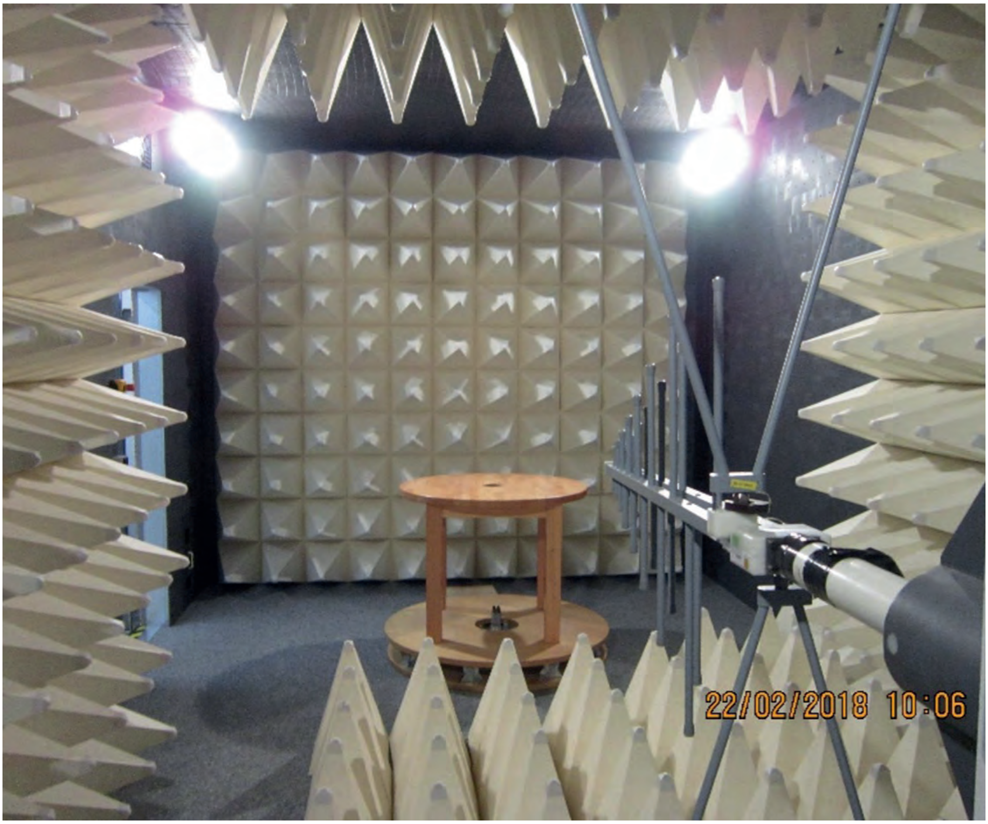


Fig. 10.2: RECOM Vienna FAC - 3m distance

10.2. Introduction to Antennas

Antennas are transducers that convert the voltage from a transmitter into a radio signal and/or intercept radio signals and convert them into a voltage for amplification in a receiver. While many antennas are used unidirectionally, either as transmitter or receivers, they are fundamentally bidirectional. Indeed, many cell phone antennas are used to transmit and receive radio signals simultaneously.

Another important function of an antenna is to orientate and focus the transmitted or received RF signal. An EM wave has a magnetic field at right angles to the electric field, so if the antenna is constructed so that the electric field is vertical with the earth's surface then it is vertically polarized, and if the electric field is horizontal with the earth's surface, then it is horizontally polarized. It is possible to multiplex two different signals on the same frequency by sending them with different polarisations.

The signal can also be circularly polarized so that both horizontal and vertical antennas can intercept the signal. Such antennas are commonly used on satellite transmitters. Again, it is possible to multiplex two different signals on the same frequency by sending them with different orientations (right-hand circular polarization or left-hand circular polarisation). Circular polarisation antennas usually have a helical structure rather than the flat two-dimensional antennas commonly used as TV receivers, for example.

When used as a transmitter, a radio frequency signal is applied to an antenna to create both a near-field and far-field. The near-field stays within a few wavelengths of the surface of the antenna, but the far-field "breaks away" and generates the desired radio signal.

When used as a receiver, the weak far-field signal is either focussed by a parabolic reflector (for example, a satellite receiver dish) or by carefully placed reflectors and director elements to create a stronger near-field across the receiving element, typically a dipole. A dipole consists of two quarter wavelength conductors placed end-to-end with an overall length of one-half wavelength (λ/2).

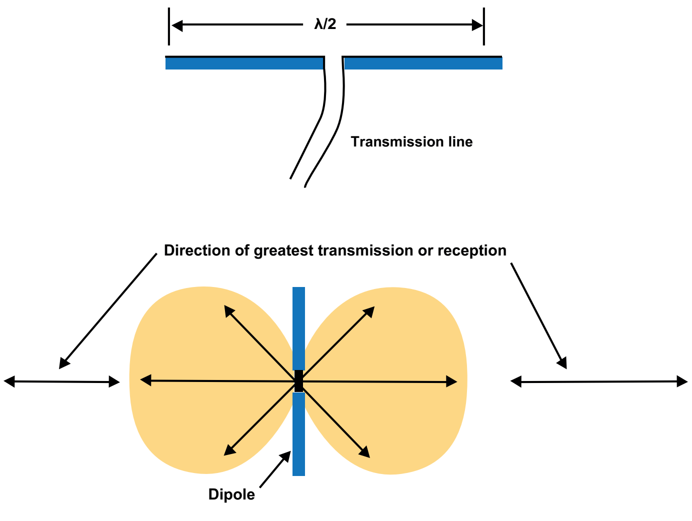


Fig. 10.3: A dipole element and its radiation pattern

Fig 10.3. shows that the most radiation or best reception occurs at right angles to the dipole element in both directions. If a unidirectional antenna is required, then a reflector can be placed behind the dipole to concentrate more of the signal in just one direction. For optimal performance, the reflector size should be larger than one wavelength and placed at a quarter to half a wavelength distance behind the dipole.

Fig. 10.4: Dipole antenna with flat plate reflector (source Schwarzbeck)

The corner reflector antenna uses two reflectors placed at 90° set at around a half wavelength behind the dipole. The reflectors do not need to be solid planes if the spacing between the rods is less than 6% of the wavelength.

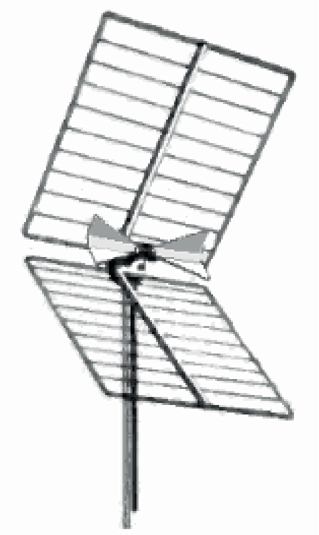


Fig. 10.5: Corner reflector antenna
(Source Wikipedia Public Domain)

Another common dipole design is the Yagi antenna. A Yagi antenna consists of a central boom with a dipole element, a reflector, and one or more directors. The greater the number of director elements, the greater the gain and directivity. It is commonly seen used to receive TV signals on the roofs of houses.

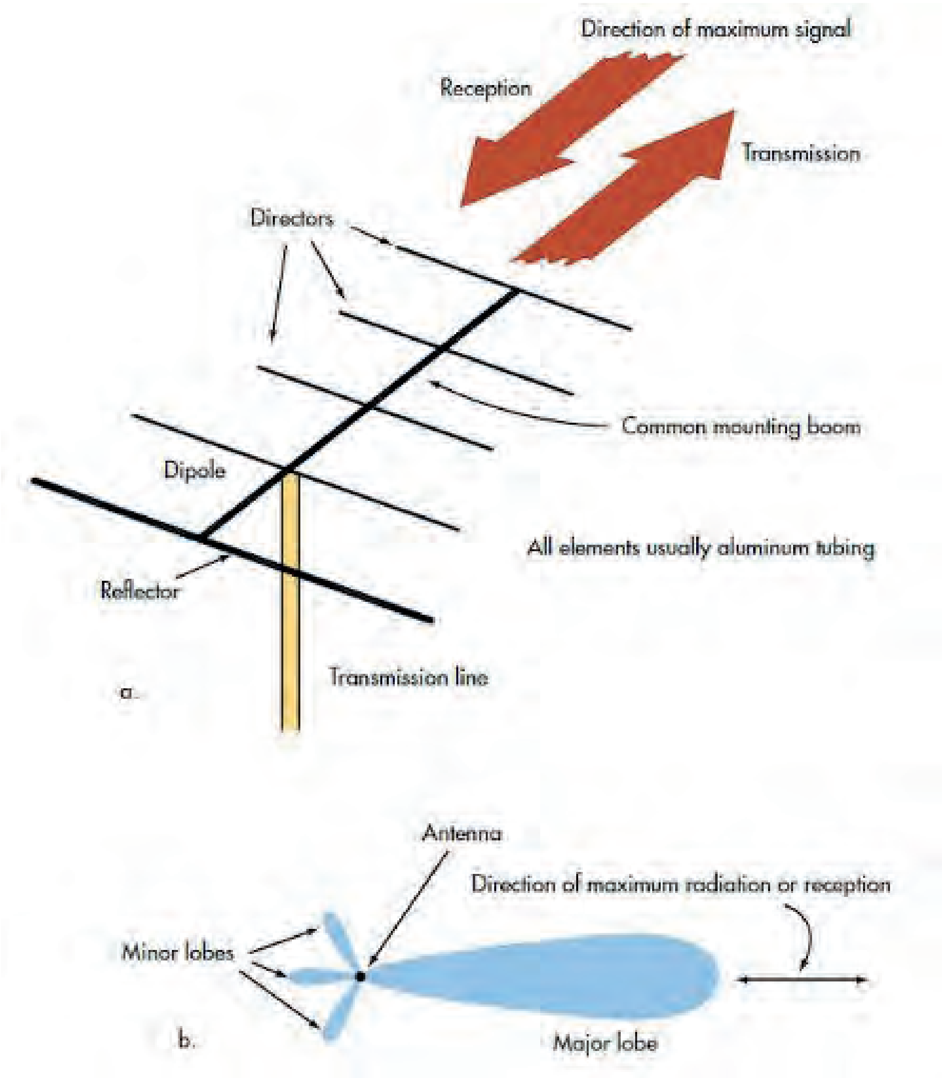


Fig. 10.6: Yagi antenna and it's beam pattern.

There are many other forms of dipole antenna which have different features such as wide bandwidth or high gain which are illustrated later on in this chapter.

10.3 Antennas for EMC testing

Antennas are needed for two types of tests. One is for measuring the emission of an EUT and the other is for generating a homogenous external field that is applied to the EUT.
Depending on the frequency range and the field of application, different types of antennas are used.

10.3.1 Near-Field Probes

Near-field probes are very useful for detecting the localized noise source in a system or on a PCB. For this reason, they are also called sniffing probes.

Fig. 10.3: Set of E-field and H-field sniffer probes

10.3.2 Rod Antenna—Monopole

This kind of antenna is mainly used for measurements in the lower frequency range. It is a very simple type of antenna that can be found in analog radios and old-model remote-controlled toy cars.

Fig. 10.4: Monopole antenna

Source: Schwarzbeck (Schwarzbeck VAMP9243 Vertikal Active Rod Antenna.jpg)

10.3.3 Dipole Antenna

The half-wave tuned dipole antenna is matched for one frequency; however, it can also detect other frequencies (lower and higher), but less efficient. This equipment is used more for testing communication systems rather than in general EMC testing.

Fig. 10.5: Dipole antenna
Source: Schwarzbeck (Dipoles (schwarzbeck.de))

10.3.4 Biconical Antenna

A biconical antenna is optimized for a frequency range of a decade (e.g., 30 MHz to 300 MHz); so to avoid the need of using several different-sized antennas to effectively cover a wider frequency range.

Fig. 10.6: Biconical antenna
Source: Schwarzbeck (Schwarzbeck BBA 9106 elements with VHBB 9124 Antenna Holder.

10.3.5 Log-Periodic Antenna

A log-periodic (LP) antenna is a series of dipole antennas arranged in an array to create a broadband antenna with almost constant gain over a wide frequency range. Although the LP antenna looks similar to a Yagi antenna, they do not operate in the same way. Adding elements to a Yagi design increases its directionability, but adding them to a log-periodic Antenna increases its bandwidth.

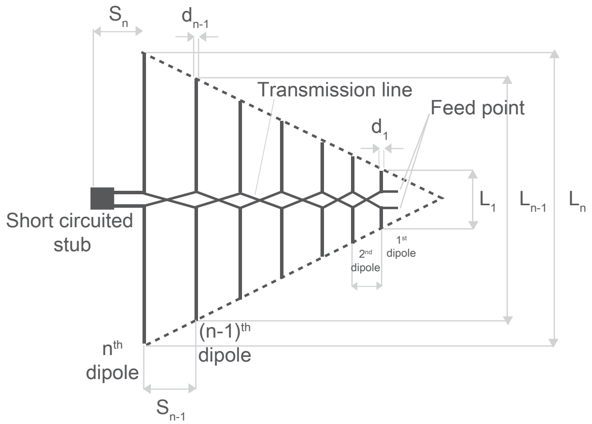


Fig. 10.7: Log-periodic antenna

10.3.6 Log-Periodic Hybrid Antenna

This antenna is a combination of the logarithmic periodic and biconical antennas. This type of antenna can cover quite a large frequency range from about 30 MHz to several GHz.

Therefore, you will find this antenna in every EMC lab, as it is used for the most common EMC tests—emission as well as immunity.

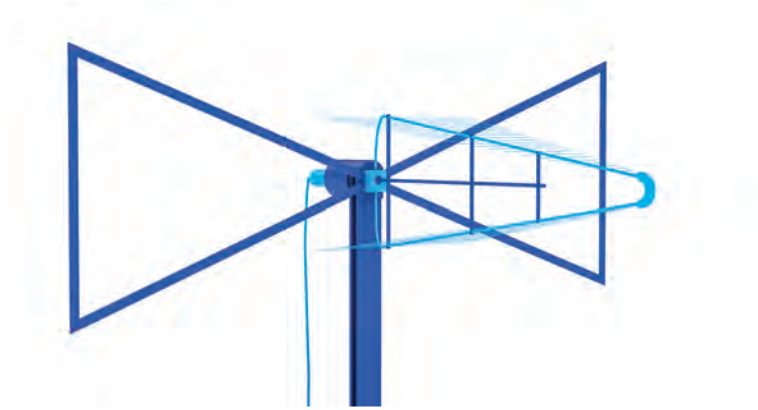


Fig. 9.8: Hybrid antenna

10.3.7 Loop Antenna

The loop antenna catches H-fields, which is common for testing Group 2 equipment according to the ISM Standard (CISPR 11). Group 2 includes equipment that is intended to radiate electromagnetic energy, not only for communication purposes but also for other reasons, such as therapeutic reasons.

Fig. 10.9: Loop antenna
Source: Schwarzbeck (Schwarzbeck FMZB1513 active magnetic loop antenna.jpg)

10.3.8 Horn Antenna

Horn antennas are used for higher frequencies. In EMC labs, this type of antennas is used mainly for immunity testing at frequencies above 1GHz. Horn antennas can cover a range of up to about 40GHz.

Fig. 10.10: Horn antenna
Source: Schwarzbeck (Double Ridged Horn Antennas (schwarzbeck.de))

10.4 Receivers

A receiver is required to measure the signal coming from the antenna. Depending on the requirements of the standards, different settings such as specific RBW (resolution bandwidth) and frequency steps are needed for receivers. All these settings are mainly defined by the applicable standards.

On the input side, a preselector is needed, followed by a band-pass filter. To measure the amplitude of the selected frequency spot in the signal, the mixed signal will first get amplified before being filtered according to the resolution bandwidth. Although this sounds easy, it can be quite tricky and very sensitive in practice, as linear and wide bandwidth electronics are required inside such receivers or spectrum analyzers, which can make them very expensive.
The stepping through the required frequency range happens automatically and depending on the processing capability of the analyzers. The results for each individual measurement point are available almost instantly; however, the testing process itself can take some time. For example, for quasi-peak (QP) measurements, at least 1sec dwell time is required for each frequency;

To reduce this testing time, maximum peak measurement can be done, which does not require a minimum settling time between the steps. If the maximum peak measurements are all below the limit line, the quasi-peak can also be considered as a pass, as the quasi-peak will never exceed the maximum peak value. If the maximum peak is above the limit, at least these frequencies have to be retested with Quasi Peak detector. If this measured QP value is below the limit, the EUT is considered to have passed, and if it is above the limit, then it is considered to have failed; but at least the problem frequency bands would have been identified, which will make the implementation of countermeasures easier.

So, the sequence is as follows:

1. Quick scan using maximum peak measurements. If it passes with a 6dB margin, then the EUT is a pass.
2. If there are any frequencies above the 6dB margin, then rescan using QP measurements. If that passes with a reduced margin, then the EUT is a pass.
3. If there are any frequencies above the limits with QP measurements, then the result is a fail and EMC countermeasures will be required.

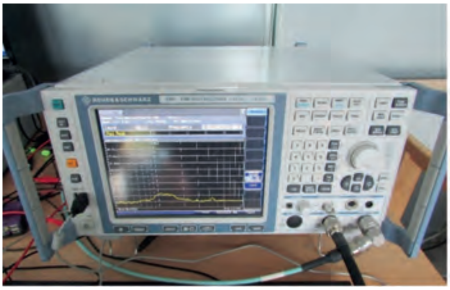


Fig. 10.11: Spectrum analyzer

10.5 QP, AV, etc.

The peak or maximum peak value is the maximum value measured at a certain orientation of the EUT with respect to the antenna at a certain frequency. Quasi-peak values are obtained by measuring the signal for over 1 second. A low-pass filter is used to show if the signal is permanent or intermittently emitted. If it is permanent, the value is equal to or close to the maximum peak value. A signal that is only emitted from time to time will show a lower quasi-peak value when compared to the maximum peak value as the value drops over the low-pass filter within the 1-second observation period. The value of the averaging detector is proportional to the pulse frequency ratio.

10.6 Turntables

Turntables are used to figure out the azimuth angle, at which the emission is strongest. Each device has to be tested 360° for compliance; to rotate the device in an easy and defined way, a turntable (manual or automatic) would be very useful.
The advantage of an automatic turntable is that the change in the azimuth angle can be determined exactly and it is also much faster than the manual turntable.

10.7 LISN

LISN is the abbreviation for Line Impedance Stabilization Network. Its purpose is to ensure a defined impedance for the EUT that firstly, is standardized globally so that results from different test houses in different countries are comparable as conducted emission results can vary significantly with different supply impedances.
The standard LISN for supply lines has quite a high impedance of 50Ohm in the higher frequency range, which also means that it is sort of worst case, considering that most AC mains supplies have a much lower impedance and that batteries for DC supplies have an extremely low internal impedance. So, if it passes with that worst case setup, the device probably will not cause any trouble elsewhere.

Fig. 10.12: LISN for AC and DC supply lines

For higher input voltages like those in the photovoltaic (PV) industry, a different LISN will be required. In such cases, the impedance is higher (150Ohm) and it would be possible to test several modes.
Common voltages in the PV industry go up to 1500 VDC or more, so the PV LISN has to be able to cope with higher input voltages than standard LISNs.

Fig. 10.13: LISN for PV testing

The LISN for automotive testing is also very different from the ones already mentioned, as you will mostly need two of them—one for each power supply line. The impedance of an automotive LISN is also only 5Ohm, as the cable distances in a car, truck, or whatever is very short and massive. So, no higher impedances would be expected.

Fig. 10.14: LISN for automotive testing (Source: Schwarzbeck)

For other special purposes, there are special ISNs such as for telecommunication, LAN networks, etc. Each type of ISN or LISN is designed to simulate a stable impedance that is common for the application being considered.

Fig. 10.15: VP (Voltageprobe) for specialized testing

All other lines that need to be measured but cannot be accessed using a LISN or has no appropriate LISN or ISN, can be tested using a combination of voltage probe and current probe. In some standards, the test with a voltage probe alone is sufficient, like in the EN 55015 for DC output.

Chapter 11: Glossary of Commonly Used EMC Terms

3-Phase	In a three-phase power supply system, three live conductors carry an-alternating current of the same frequency and voltage but with a phase difference of one-third the period (120°). The common reference can be earth because if the load is the same on all three phases, the net result will be zero. Therefore, a neutral connection is not required (L1/L2/L3 + PE), compared to single phase, which has only L, N, and PE connections.
62368-1	The replacement for the IEC 60950-1 standard. The standard is Hazard-Based (HB), which means that in addition to the electrical and fire safety tests, an extra risk assessment must be conducted to safeguard against any serious consequences of faults and abuse.
60601-1	The main safety standard that covers medical-grade power supplies. The international (IEC60601-1), North American (AAMI/ANSI 60601-1), and European versions (EN60601-1) of the standard are all very similar but carry separate certificates. The current version is the third edition (3rd Ed.)
60601-1-2	The main EMC standard that covers medical-grade power supplies. The current version is the fourth edition (4th Ed.)
61010-1	The main safety standard that covers measurement, control, and laboratory equipment. This standard has UL, CSA, IEC, and EN versions.
61010-2-201	The safety standard that covers the particular requirements for control equipment. UL 61010-2-201 replaces the popular UL 508 standard.
60355-1	The main safety standard that covers Safety of Household Equipment (often also required by building automation applications). This standard has UL, IEC, and EN versions.
61558-1 / 61558-2-16	Power supply safety and switch-mode power supply safety standards. Often used in conjunction with 60355-1.
8750	UL8750 is the UL safety standard for LED lighting power supplies.
61347-1/ 61347-2-13	The main international safety and EMC standard for LED lighting power supplies. The international (IEC61347-1) and the European versions (EN61347-1) are very different from the UL8750. IEC/EN 61347-2-13 covers EMC and harmonics interference.

50155	EN50155 is the European standard for railways (rolling stock) and is commonly accepted worldwide.
AC	Alternating current. Single-phase mains (115V in the USA, 230V in Europe) alternates its polarity 60 times a second (USA) or 50 times a second (EU).
Air Discharge	A method for testing ESD protection, in which the ESD generator creates a spark, which arcs over to the device under test (DUT).
Antenna Factor	Antenna Factor is the ratio of the incident electromagnetic field to the output voltage from the antenna (gain).
Amplitude Modulation (AM)	A broadcast signal that varies the amplitude of the carrier wave to carry the signal information. It is used by AM broadcast stations and requires an AM receiver. The AM frequency range is 530 to 1710kHz.
ANSI	American National Standards Institute
Balanced Line	Balanced lines are less prone to interference than unbalanced lines. One of the signal wires carries the signal, while the other carries an out-of-phase inverted duplicate. When the signal reaches the destination, the inverted duplicate is flipped and added to the original. Any noise added by interference is also inverted. When combined with the non-inverted noise, the two noise signals cancel each other.
Bandwidth	Bandwidth (BW) is a range of frequencies or information that a circuit can handle or the range of frequencies that a signal contains or occupies. When measuring low-frequency ripple and noise, high-frequency interference can give false readings; so, for example, the input of oscilloscopes is often restricted to a bandwidth of 20MHz using a special filter: “20 MHz B/W Restricted”.
Bass	The lower end of the music scale: 60-250Hz.
Buck Converter	A ‚buck‘ or ‚step-down‘ switch-mode voltage regulator is one in which the output voltage is always lower than the input voltage.
Buck-Boost	A switch-mode voltage regulator in which the output voltage can be above or below the input voltage.

Burst Mode	If an AC/DC converter is operated without a load, it may have a burst mode function wherein the main oscillator is switched on only for a short burst and then switched off. This reduces the no-load power consumption considerably.
CENELEC	European Committee for Electrotechnical Standardization
CISPR	International Special Committee on Radio Interference
Conducted Emissions	EM energy generated by a circuit or equipment that is conducted on its wires and cables.
Conducted Immunity	EMC tests in which energy is directly coupled onto cables and wires to determine the ability of equipment or circuits to withstand or reject electrical noise.
CSA	Canada Standards Association
Crosstalk	A phenomenon in which a signal on one conductor is inductively or capacitively coupled to an adjacent conductor (the victim).
Capacitor	A capacitor is a passive electronic component that consists of two conductive plates or foils separated by an insulating dielectric. A voltage applied to the plates creates an electric field across the dielectric and causes the plates to accumulate a charge. When the voltage source is removed, the field and the charge remain; energy is stored until discharge. Capacitance is measured in Farads, but typical values are microfarads (µF) or nanofarads (nF).
Class A EMC	Class A EMC limits define the maximum emissions (conducted and radiated) and the required immunity to interference (conducted and radiated susceptibility) for industrial applications.
Class B EMC	Class B EMC limits define the maximum emissions (conducted and radiated) and the required immunity to interference (conducted and radiated susceptibility) for domestic and commercial applications. Class B limits are harsher than Class A limits.
Contact Discharge	An ESD test method in which the ESD generator makes direct contact with the device under test (DUT).
DC	Direct Current

DUT	Device under test
EN	European Standards
EM	Electromagnetic
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge. Release of stored static electricity. ESD is generated when two surfaces rub against each other to build up charges of thousands of Volts, which then suddenly discharge by producing a spark.
ESD Protection	Devices added to the input and output lines/pins on a device/IC to protect the internal circuitry from the damaging effect of electrostatic discharge.
ESR	Effective Series Resistance (or Equivalent Series Resistance) is the resistive component of a capacitor's equivalent circuit. A capacitor can be modeled as an ideal capacitor in series with a resistor and an inductor. The resistor's value is the ESR.
EUT	Equipment under test
FCC	Federal Communications Commission
FFT	The Fast Fourier Transform (FFT) is a common algorithm for translating a signal from the time domain (signal strength as a function of time) to the frequency domain (signal strength as a function of frequency). It shows the signal's spectral content, divided into discrete frequency bands.
Filter	A filter blocks a certain range of frequencies. It can be low-pass (only low-frequency signals get through; e.g., a bass filter), high-pass (only high-frequency signals get through; e.g., a treble filter), or band-pass (only a certain frequency range of signals get through; e.g., an equalization filter). Low-pass filters are commonly used to block EM interference.
Floating	An output is said to be "floating" if it is not connected to any input voltage supply, ground, or ground-referenced signal source.
FM	Frequency modulation. A technique for adding information to a carrier wave by varying its frequency.

Gain	The amount of amplification accomplished by an amplifier circuit, antenna, or transistor. For instance, a gain of 200 would mean the output current is scaled to 200x the amplitude of the input current.
GTEM	Gigahertz Transverse Electromagnetic Mode. A kind of EMI test chamber.
H	Henry. The unit of inductance. Most EMC filters require inductors or “chokes” in the range of µH (microHenries) up to a few mH (miliHenries).
HF/VHF/ UHF	HF (High Frequency) is anything above 2 MHz. VHF (Very High Frequency) is anything in the range of 30-300 MHz, and UHF (Ultra High Frequency) is 300 MHz to 3 GHz.
Hi-Z	Hi-Z (or High-Z or high impedance) refers to an output signal state in which the signal is not being driven. The signal is left open, so that another output pin (e.g., elsewhere on a bus) can drive the signal or the signal level can be determined by a passive device (typically, a pull-up resistor).
Human Body Model	An ESD test method in which the ESD generator consists of a 100pF capacitor and a 1.5kOhm series resistor that match the real-life values of a charged human being.
Hz	Hertz. A measure of frequency. An older term is cycles per second, or cps.
IEC	The International Electrotechnical Commission (IEC) prepares and publishes international standards for all electrical, electronic, and related technologies. IEC standards are accepted in 34 countries (including Europe, Australia, Canada, USA, India, Israel, Korea, and USSR) and are also known as “CB Reports”, in which CB stands for IECEE Certification Board approved.
IEEE	The Institute of Electrical and Electronics Engineers (or Eye-triple-E) is a non-profit, professional association that has more than 360,000 individual members from approximately 175 countries. IEEE also sponsors many electrical and electronic standards.
Impedance	Impedance, represented by the symbol Z, is a measure of the opposition to electrical flow. It is measured in Ohms. In DC systems, impedance and resistance are the same (R=V/I). In AC systems, “reactance” enters the equation due to the frequency-dependent contributions of capacitance and inductance. Impedance in AC systems is also measured in ohms and represented by the equation Z = V/I, but V and I are frequency-dependent.

Inrush Current/ Soft-start	A momentary input current surge that is measured when the power supply is initially turned on. This current reduces to a lower steady-state current once the input capacitors are charged. The inrush current can be very high (10x steady-state input current) but usually lasts only for a few milliseconds. If a converter has a soft-start circuit, the inrush current peak can be substantially reduced.
Internet Protocol	Standard method for data transfer used on the Internet. Also known as IP or TCP/IP.
IPv6	Internet Protocol Version 6. Internet Communications protocol with a 128-bit address space, multi-casting, and auto-configuration. Its ability to uniquely address up to 3.4×10^{38} individual devices is essential for the IoT (Internet of Things) concept.
ISM	Industrial, Scientific, and Medical. Radio frequency bands made available for use by communication equipment without license, within certain maximum emitted power limits. Equipment that use the ISM band must tolerate interference from other such equipment. ISM is commonly used in WiFi (802.11a, b, and g) and cordless phones.
ISO	International Organization for Standardization
Isolation coupling capacitance	Between any two separated conductors, there will exist an isolation resistance that can pass DC current and a coupling capacitance that can pass AC current. In DC/DC converters, the isolation resistance is 100MOhm or higher, so can usually be ignored. The isolation coupling capacitance can range from 200pF to as low as 4pF, depending on the transformer construction. Low coupling capacitance is desirable in fast-switching circuits in which the DC/DC converter "sees" external high voltage and high slew rate signals on its output.
Leakage Inductance	Leakage inductance in a transformer is an inductive component that results from the imperfect magnetic linking of one winding to another. In an ideal transformer, 100% of the energy would be magnetically coupled from the primary to the secondary windings. Imperfect coupling reduces the signal induced in the secondary windings. The electrical equivalent of this phenomenon is some self-inductance in series with the primary windings that are properly coupled. This series inductance is called "leakage inductance".
mA	MilliAmpere or milliAmp. 1/1000 of an Ampere. Ampere is the basic unit for measuring electrical current. For milliAmpere the "m" is always lower case, otherwise it would mean MegaAmpere.

Metal Oxide Varistor	A Metal Oxide Varistor (MOV or surge-suppressor) is a discrete electronic component that diverts excessive voltage to the ground and/or neutral lines. It is commonly used on the inputs of AC/DC modules to suppress input voltage surges. An MOV can divert a lot of energy, but reacts slowly, so it is often used in combination with a transient suppressor diode that reacts quickly, but has limited power absorption ability.
MIMO	A Multiple Input, Multiple Output (MIMO) system has multiple antennas and multiple radios. MIMO is used in the implementation of the 802.11n wireless LAN standard.
Multipath	In radio transmission, multipath refers to the simultaneous reception of two copies of a signal that arrives via separate paths with different delays. A common example is when a signal bounces off a building or other object and is received along with the direct (unbounced) signal. In television reception, this causes “ghosting” - a faded echo is horizontally displaced from the main image on screen. One of the main reasons why GPS does not work well in NYC is the multipath signals bouncing off all the tall buildings.
Murphy’s Law	Hypothesis that everything that can go wrong, actually will go wrong.
mW	MilliWatt(s) is 1/1000 of a Watt.
MW	Megawatt(s) is 1 million watts. (Upper case “M” or lower case “m” can make a BIG difference!)
nA	NanoAmpere(s). Unit of measure. A billionth of an Amp.
NC	Not Connected. Used to denote a pin that is present only to provide mechanical stability. Usually, an NC pin is not electrically connected internally - but this is not a hard and fast rule. If a pin says “NC”, it should be soldered onto its own isolated pad and not connected to anywhere else.
NRE	Non-Recurring Engineering cost - one-time engineering costs associated with a project (usually for the design effort or for tooling or EMC certifications).
NTC	Negative Temperature Coefficient thermistor. A resistor whose resistance decreases with increasing temperature. The nominal resistance value is always given at 25°C (room temperature).

Nyquist	In A/D conversion, the Nyquist principle (derived from the Nyquist-Shannon sampling theorem) states that the sampling rate must be at least twice the maximum bandwidth of the analog signal in order to allow the signal to be reproduced. The maximum bandwidth of the signal (half the sampling rate) is commonly called the Nyquist frequency.
OATS	Open Area Test Site
OCP	Overcurrent Protection. A converter that can protect itself from being damaged by an overload condition. Typical techniques of doing this are either by limiting the power output (the output voltage is allowed to fall with increasing current) or by hiccup protection (the output is turned off and then back on again after a delay, and if the overcurrent condition still exists, the cycle repeats).
OEM	Original Equipment Manufacturer. A manufacturer making products for other companies to brand-label as their own.
Ohm	The unit of resistance, represented by the Greek letter Omega (Ω).
Op amp	Operational amplifier: An amplifier has positive and negative inputs, which allow circuits that use feedback to achieve a wide range of functions. Using op amps, it is easy to make amplifiers, comparators, logarithmic functions, filters, oscillators, data converters, level translators, voltage references, and more. Analog mathematical functions like addition, subtraction, multiplication, and integration can also be easily accomplished using op amps. A rail-to-rail op amp can work with input signals up to its own supply voltage.
Open-drain	An open-drain or open-collector output is driven by a single transistor, which can clamp the output only down to ground. The output must be pulled up to +V by the load or by an external pull-up resistor.
OR-ing Diode	OR-ing diodes are used to connect the outputs of two separate power supplies to a single load. Thus, if either PSU1 or PSU2 is active, then the load will have power. OR-ing diodes are used to add supply redundancy to critical circuits to make them fail-safe.
Overvoltage Protection, OVP	Overvoltage Protection (OVP) refers to a circuit that protects downstream circuitry from damage due to excessive output voltage. At its simplest, it is a clamping Zener diode across the output. A more fail-safe technique is to add a separate optocoupler, which is triggered by an output overvoltage condition to shut down the power supply on the input side when the regulation fails.

p-p	Peak-to-peak. Often used as a measure of the output voltage ripple.
Partial Discharge	A non-destructive way of testing for isolation strength. A Hi-Pot test is very destructive because if an insulator fails, the arc-over destroys the part. Whereas, PD testing measures the charge migrating through the insulation layers and will stop the test before any permanent damage occurs.
pC	pC: PicoCoulomb, a unit of electrical charge (10-12 coulombs). Used as a measure of partial discharge in insulation testing.
Peak Inverse Voltage	Peak Inverse Voltage (PIV) or Peak Reverse Voltage (PRV) refers to the maximum voltage a diode or other device can withstand in the reverse-biased direction before breakdown. Also called Reverse Breakdown Voltage.
PFC	Power Factor Correction. A passive or active circuit that synchronizes and shapes the mains input current to better match the mains input voltage. When current and voltage are perfectly aligned, the power factor (PF) equals unity. Passive PFC circuits can typically improve the PF to around 0.4 to 0.7, while active PFC circuits can achieve >0.99. EMC standards requires PFC for AC/DC power supplies of >75W, but for LED drivers, the limit is 25W.
PFM	Pulse-Frequency Modulation. A pulse modulation technique in which the frequency is varied with the input signal amplitude. The duty cycle of the modulated signal does not change. PFM is commonly used to reduce the quiescent input current in a converter by reducing the switching frequency at low loads.
PFMEA	Process Failure Mode and Effects Analysis. A methodology for assessing the weaknesses in production processes and potential effects of process failures on the product being produced.
PLL	A phase-locked loop (or phase-lock loop) is a control system that generates a signal, which has a fixed relation to the phase of a “reference” signal. A phase-locked loop circuit responds to both the frequency and the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched in both frequency and phase.
p-MOS	A p-channel metal-oxide semiconductor (p-MOS) transistor is one in which p-type dopants are used in the gate region (the “channel”). A negative voltage on the gate turns the device on.

PoE	Power-over-Ethernet. A means for delivering power to a remote device using the same cable lines that are used to deliver Ethernet data. Can be used to power remote devices (such as cameras, LED lighting, and door entry systems) over a single combined power and bi-directional data cable. The nominal PoE voltage supply is 44-57VDC, so a DC/DC converter is required at the end device. This DC/DC must negotiate with the primary power supply to release enough current for its needs (available power is restricted between 4W and 100W depending on a complex sequence of signature resistances offered by the DC/DC negotiation IC). The relevant standard defining this interface is called IEEE 802.3af /at/bt. Many opine that PoE is the future of indoor LED lighting.
POL	Point-of-load power supplies deliver high peak currents and low noise margins, as required by high-performance ASICs and µcontrollers, by placing individual power supply DC regulators close to their point of use.
POK	Power-OK
Potentiometer	Variable resistor in which a wiper sweeps from one end of the resistive element to the other, causing a resistance that is proportional to the wiper's position. Commonly abbreviated as "pot".
Power Fail	A feature in a microprocessor supervisory circuit that provides early warning to the microprocessor about imminent power failure.
PCB	Printed circuit board. The most common PCB material is FR4 - a glass fiber-reinforced laminate that is flame-resistant in compliance with UL94V-0.
PTC	Positive Temperature Coefficient (PTC). When the resistance of a component rises with temperature, it is said to have a positive temperature coefficient. Example: Hewlett-Packard's first commercial product, an audio oscillator, used a common light bulb as a PTC element in the feedback circuit to maintain constant output amplitude regardless of frequency.
PWM	A fixed frequency square wave signal that is variable on time. In DC/DC switching regulators, the pulse width oscillator driving the main power switch (and hence, the duty cycle) is varied to maintain the desired output voltage.

Q Factor	A measure of the quality of a resonant (tank) circuit. A “high-Q” circuit has mostly reactive components (inductive and capacitive), with low resistance. It resonates strongly with little damping, and will have low bandwidth relative to its center frequency (that is, it will have a narrow bandwidth vs. frequency curve). Q = 2π* (Energy stored / Energy dissipated per cycle).
Quasi-Resonant	A flyback topology in which the transformer primary winding is not switched off when the output current falls to zero, but kept on until the primary voltage starts to resonate. The primary winding is then disconnected at one of the resonant minima (valley switching) where the voltage stress across the switching transistor is at a minimum. Q-R switching is thus highly efficient.
Qrr	Qrr is reverse recovery charge - the charge that accumulates on a PN junction when it is forward-biased. The current needed to overcome the Qrr when a transistor or diode is switched off can cause significant losses.
Quiescent current	The current consumed by a converter when it is in a no-load state, but still enabled.
RC	Resistance-Capacitance product. An RC network is a network composed of resistors and capacitors in a series-parallel combination to filter or delay a signal.
RE	Radio Emissions. The EM energy generated by a circuit or equipment, which is radiated directly from the circuits, chassis, and/or cables of the equipment.
RF	Radio Frequency. EM radiation in the range of 30kHz up to 30GHz.
RS	Radio Susceptibility. A term used to describe EMC tests in which energy is coupled to the product through radiated (or field-coupled) RF to determine the ability of equipment or circuits to withstand or reject radiated electrical noise.
Reflected Ripple Current	DC/DC converters contain power oscillators that draw current peaks in every cycle. The difference between the steady-state input current and the current peaks is the ripple current. As the input current is load-dependent, the input current “reflects” the output load current.

Resonant Circuit	A resonant or tuned circuit combines an inductor and a capacitor to make a circuit that resonates at a particular frequency. Depending on the configuration, the circuit can have a high or low impedance at the resonant frequency and operate as a band-pass or band-stop filter, or an oscillator. It may be called an LC, LLC, or LRC circuit because of the inductive (L), resistive (R), and capacitive (C) components used.
Reverse Recovery Time	When switching from the conducting state to the blocking state, the stored charge of the diode junction must first be discharged. This discharge takes a finite amount of time known as the Reverse Recovery Time, during which the diode does not block the reverse current. When dealing with high-frequency oscillators or very steeply rising signals, reverse recovery time can cause significant losses in a circuit.
RFI	Radio Frequency Interference. Unwanted noise from RF sources.
RFID	Radio Frequency Identification. A method for remotely identifying an object using a tag or module that carries a unique ID code, which can be activated by an external RF field that powers the tag and also reads the code back.
RMS	Root mean square. Vrms is the effective constant voltage that delivers the same power as the varying AC input (the average value of a 50/60Hz sine wave is zero as positive and negative half-cycles cancel out, so RMS must be used instead). For example, 115Vac is the RMS value of the mains supply. The peak voltage is ≈163V.
RDS(on)	RDS(on) is the drain-to-source resistance of a switching FET when it is turned on. The lower the RDS(on), the lower the conduction losses will be in the transistor.
RTC	Real-time clock. An integrated circuit that contains a timer that supplies the time/date. The RTC usually contains a long-life battery that allows it to keep track of the time even when no power is applied.
S, s	Siemens (S). Standard unit for conductance (the opposite of resistance). Second (s). Lower case s is the standard abbreviation for seconds.
Sense or Shunt Resistor	A resistor placed in a current path to allow the current to be measured. The current passing across the sense resistor is proportional to the voltage that is being measured Typical value is in milliOhms. A Kelvin shunt has separate current and voltage connections to increase the measurement accuracy.

Signal-to-Noise Ratio	The ratio of the amplitude of the desired signal to the amplitude of noise signals. Usually expressed in decibels, dB. The larger the number, the better.
SMD	Surface Mount Device. An electronic component that is mounted on the surface of a printed circuit board (as opposed to “through-hole” or THT components, which have pins that are inserted into holes).
SMPS	Switch-Mode Power Supply. Much more efficient than linear power supply, so almost exclusively used for anything above a few watts (with the exception of broadband RF amplifiers in which the switching harmonics would interfere).
Snubber	A device that suppresses voltage transients and spikes. Usually a capacitor and resistor in series.
Soft Start	A feature in some switching power supplies that limits the startup inrush current at the initial switch-on.
SPICE	Simulation Program with IC Emphasis. Software that allows a circuit to be simulated to predict its real-life behavior.
Spread Spectrum	Spread-spectrum techniques can be used to reduce electromagnetic interference by dithering the clock frequency so that emissions are no longer concentrated in one frequency.
Star Ground	A layout or wiring technique in which all components connect to the ground at a single point.
STB	Set top box. Typically a cable or satellite receiver.
Step-Up DC-DC	A switch-mode voltage regulator in which the output voltage is higher than the input voltage.
Switch Mode	Topology with a switching transistor and inductor to regulate the voltage/current.
Switching Regulator	A voltage regulator that uses a switching element to transform the supply into an alternating current, which is then converted to a different voltage using capacitors, inductors, and other elements, then converted back to DC.

Synchronous Rectification	In switch-mode power supplies, the output rectifier diode is replaced with a FET switch to reduce losses and thereby increase efficiency. The FET is turned on and off synchronously to reproduce the effect of a diode.
TCP/IP	Transmission Control Protocol/Internet Protocol. The protocols or conventions that computers use to communicate with each other over the Internet.
Tempco	Temperature coefficient, the amount a value drifts with temperature in %/°C.
Tesla	Tesla (abbreviated as T) is a measure of magnetic flux density (B-field), named after engineer and inventor Nikola Tesla.
THD	Total Harmonic Distortion. A measure of signal distortion which assesses the energy that occurs on the harmonics of the original signal.
Three-State or Tri-State	A three-state output has three electrical states: One, zero, and “Hi-Z” or “open”. “Tri-State” is a registered trademark.
Through-Hole	A method for mounting components on a printed circuit board (PCB) in which the pins on the component are inserted into holes in the board and soldered in place.
TVS	Transient Voltage Suppressor. Semiconductor device designed to protect a circuit from voltage and current transients. Typically implemented as a large silicon diode operating in avalanche mode to absorb large currents quickly.
VA	Volt Ampere(s). If the voltage and current are not in phase because the load is inductive or capacitive, then the power is measured in VA and not Watts.
Vcc, Vss	The supply voltage for a circuit is often given as V plus a double-letter suffix. The double-letter is usually related to the lead of the transistors that are commonly connected to that supply, e.g., Vcc is a positive-voltage supply and connects to the Collector terminal of bipolar transistors. VSS connects to the Source terminal of a FET, etc. V+ and V- are also used.
Volt (or Volts)	Unit of measure for electromotive force (EMF), the electrical potential between two points. An electrical potential of 1 Volt will push 1 Ampere of current through a 1 Ohm resistive load.

VSWR	Voltage Standing Wave Ratio. A measure of the degree to which a load is impedance-matched to its transmission line that is determined by dividing the voltage at the peak of a standing wave by the voltage at the null in the standing wave.
W	Watt is the unit for measuring power. One Watt is one Joule of energy transferred or dissipated in one second. Electrical power is calculated as: Watts = Volts x Amps x Power Factor The power factor can be disregarded for DC circuits and for AC circuits that have a resistive load (it is 1 in those situations).
WLAN	Wireless Local Area Network
X Cap, Y Cap	X-capacitors are certified to be used across mains inputs. Y-capacitors are certified to be used between mains and ground or across an isolation barrier. They are designed to self-repair after an over-voltage condition (called self-healing). Y-caps have extra insulation (double or reinforced), so are more expensive.
ZIGBEE	A standard for short-distance, low-data-rate, mesh (not point-to-point) communications. Created and maintained by the ZIGBEE Alliance Group.
ZVS	Zero voltage switching. A switch that operates only when the AC input passes through 0V (Zero voltage crossing: ZVC).

About the Authors

Steve Roberts was born in England. He obtained a B.Sc. in Physics and Electronics at Brunel University, London (now the University of West London), and then moved on to work at the University College Hospital. He later served for 12 years at the Science Museum as Head of Interactives, during which time he completed his M.Sc. at the University College, London. More than 20 years ago, he made his personal Brexit and moved to Austria, where he now works as an Innovation Manager at the RECOM Group in Gmunden.

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- ‘DC/DC Book of Knowledge’ and
- ‘AC/DC Book of Knowledge’

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Josefine Lametschwandtner was born in Austria. She obtained a B.Sc. in Electronics Engineering from the FH Joanneum in Kapfenberg. She worked at GE Healthcare for 4 years, where she was responsible for analyzing the EMC behavior of medical devices. She joined RECOM in 2014 as Team Leader for RECOM’s EMC Engineering Lab in Gmunden, Austria. She is responsible for running the EMC Lab, holding our “Power Supply Meets EMC Know-How” courses, and speaking at international EMC conferences.
In her spare time, she loves to listen to very loud heavy metal music, play with Lucy, her White Shepherd dog and concoct herbal teas to cure everything from an upset stomach to COVID.

About Recom

About 30 years ago, we presented our first hand-made DC/DC converter to a leading German manufacturer of cellular phones. The product passed all the tests successfully and a few weeks later, we received our first order for 8000 pieces. A new product category was born, ‘DC/DC converters’, in the form of a module.

At that time, the shift from analog to digital electronics accelerated the demand for DC/DC modules due to the need for standardized on-board switching power supplies. In addition, I/O ports or amplifier channels required isolation to increase safety or to eliminate earth loops—another important requirement that DC/DC converters could fulfill. RECOM was there from the very early days to supply reliable, efficient, and modular solutions for customers who did not want to invest time and effort designing their own discrete converters.

From 2006, RECOM extended its portfolio to include AC/DC converters—primarily for existing customers who again did not want to invest time and effort in certifying their own discrete converters. In the meantime, RECOM started offering AC/DC converters from 1W up to 1kW in a variety of different form factors such as PCB-mount, wired, low profile, and DIN-rail mounting for use in both single-phase and three-phase supplies. RECOM plans to expand the AC/DC range beyond the existing low- and mid-range products to break through the 10kW barrier—in effect, offering a ‘one-stop shop’ for all DC/DC and AC/DC products for industrial, medical, transport, and household applications.

Today, RECOM’s ultra-modern campus-style headquarters in Gmunden and a separate R&D Centre in Vienna provide room for expansion to meet these ambitious goals. A team of international engineers works in well-equipped, state-of-the-art labs to create a constant flow of new products and customer solutions. We have also invested heavily in our own EMC test chambers in Gmunden and Vienna to be independent from external facilities.

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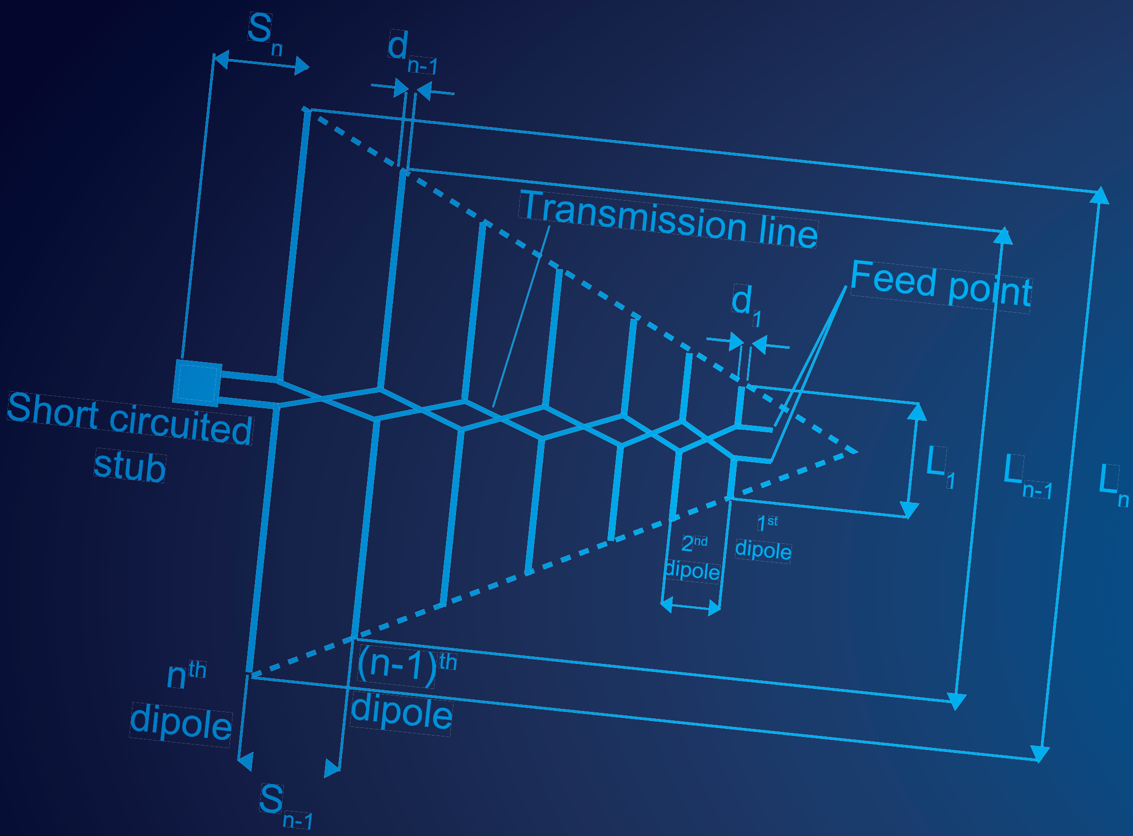

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