EE 392

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ELECTROMAGNETIC INTERFERENCE AND GROUNDING TECHNIQUES

Thesis work
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1 Introduction

Electromagnetic interference (EMI) is an everyday phenomenon in our electrical environments. A hairdryer is interfering a TV-set and a bad designed amplifier is starting to receive radioprograms. EMI consists of unwanted conducted or radiated electromagnetic signals interfering with electric and electronic equipment. So far grounding- and EMI-problems have unfortunately not been the first thing a designer have had in mind when designing and constructing electrical systems. A fact that has been one of the main reasons for his/her system not working properly, especially together with other electrical systems. –The designer has not considered the electromagnetic compatibility (EMC); saying that every electrical apparatus should be electromagnetic compatible with the different environments it is supposed to work in - it should not interfere with other systems nor be interfered with by other systems or electrical phenomena. To sum up we can say that *if there is EMC there are no problems with EMI.*

After the equipment has been produced these problems can be difficult and expensive to eliminate. Therefore consideration about EMC should be taken already at the introductory design and construction phase.

Today the increasing use of electrical equipment in every kind of environment, e.g in industries, offices, hospitals or laboratories, together with the race for higher frequencies, lower signals and smaller IC:s (VLSI) makes this area a subject of great dignity when educating good electrical engineers. *It is essential that future electrical and electronic design and measurement-tecniques always includes consideration concerning electromagnetic compatibility (EMC).* An indication of the increasing interest about this area is that quite recently standards concerning EMC has showed up in the USA.

The first step towards this EMC-awareness would be this theoretical piece, together with the following laboratory experiments, where the students should discover, analyze and eliminate different kinds of practically simulated grounding- and interference-problems.

2 How does an interference-situation arise?

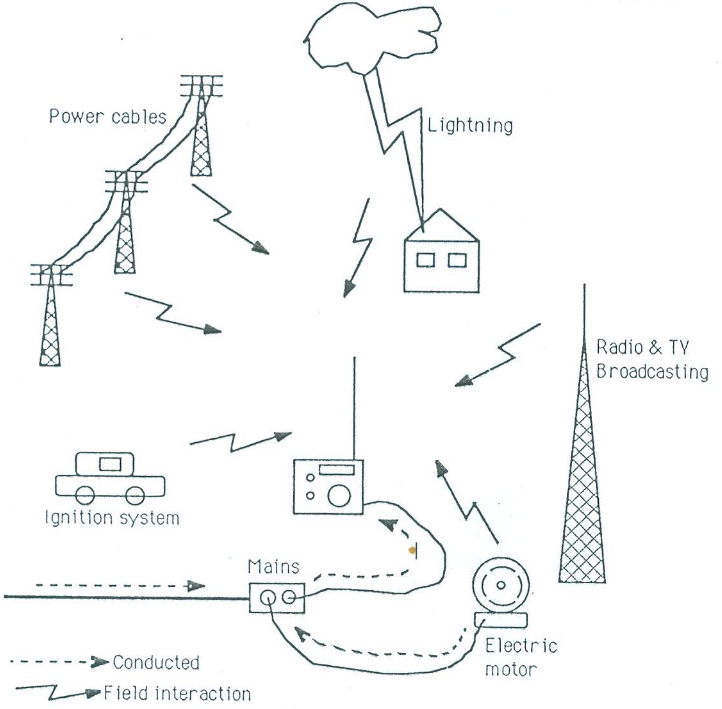


Figure 1. Interference-situations.

2.1 Principles for minimizing an interference-situation

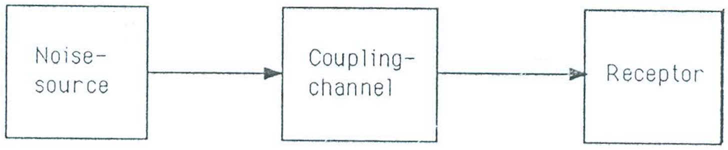


Figure 2. An interference-situation.

An interference-situation is a fact when interfering signals are transported from an interference source to an interference receptor via a coupling path (figure 1 & 2).

To be able to optimize systems with respect to interference (EMC), it is easier and cheaper to do it in the designing and construction phase instead of after the equipment has been produced, when you probably have to deal with very complex and expensive moves to solve the situation. An interference-situation consists of a source, a path and a receptor. Therefore there are three different things to work on:

1. Suppressing the interference signal at the source (shielding, redesigning, grounding etc.)
2. Make the receptor less susceptible to interfering signals (shielding, redesigning, grounding etc.)
3. Minimize the interference signal transmission through the coupling channel (shielded or twisted cables, opto coupling etc.)

It is essential that all three of these parts are considered when you are working with interference suppression techniques. For example if you have suppressed the source and done nothing to the receptor some new equipment may later enter the same room acting as a new interference-source and a new interference-situation will arise because the receptor is still very susceptible to interfering-signals.

2.2 Interference sources and their effects

Interfering-sources can be a wide range of different natural and electrical phenomena, e.g. lightning, the sun (solar spots and eruptions), cosmic radiation, the ignition system in cars, radar, computers, fast digital circuits, mains (causing hum), fluorescent tubes, electric engines, clattering relays and contacts, switching triacs, welding sets, radio-transmitters, a cable carrying current etc.

The fact that the mains supply network, 240 Volt/50 or 60 Hz signal, is one of the "strongest" electric signal in our environment makes it one of the most frequent occurring EMI-sources. The name of the EMI-signal caused by the mains (50 Hz tone) is hum.

2.2.1 EMI-signals

The interference signals are electromagnetic (EM) signals with many faces. The only thing they have in common is that they are unwanted and can cause trouble in electric systems. The interference signal can be a fast transient or a continuous periodic signal, it can have a wide frequency content or just one single frequency. For example lightning, hum, noise and radiosignals. Interferences at radio- (or high) frequencies has got a name of its own; Radiofrequency interference (RFI). Since all EMI-signals are different forms of travelling EM-waves and varying EM-fields some words about EM-fields should be adequate:

Electromagnetic induction and radiation fields surround us every second of our lives and are created when charges (positive or negative) are accelerating or deaccelerating for some reason, e.g. when an electric field is forcing it. This is the case in a lot of different situations, e.g. lightning, electric commutator motor, electrical cables, electronic components etc. The EM-signal consists normally of an electrical part together ("hand in hand") with a perpendicular magnetic part, both transverse to the direction of propagation. Sometimes either the electrical or the magnetic field dominates over the other one so that we consider them as purely electrical or magnetic fields. The characteristics of the fields are determined of what kind of source you have and also the distance between the source and the point where you observe it.

We can split the space surrounding the source into two parts: the near and the far region. The near region is close to the source, "close" defined as $r<\lambda/2\pi$, where r is the distance from the source and λ is the wavelength. The wavelength is related to the frequency and the speed of light as $\lambda=c/f$. In the near region the fields can be considered as "purely" electric or magnetic. In the far region, $r>\lambda/2\pi$, the field is considered as an electromagnetic radiation field, a normal plane wave, with both components present.

The wave impedance, Z, is defined as the ratio $Z=E/H$, where E is electric field intensity (higher the higher voltage) and H is the magnetic field intensity (higher the higher current). The wave impedance for a plane wave in free space is 377 Ω. If the source works with high voltage and low current, like a straight wire antenna, $Z=E/H > 377\ \Omega$, it is considered as a high impedance source, creating an electric field in the near region ($\sim 1/r^3$). On the other hand, if the source works with low voltage and high current, like a loop antenna, $Z=E/H < 377\ \Omega$, it is considered as a low impedive source, creating a magnetic field in the near region ($\sim 1/r^3$). See figure 3.

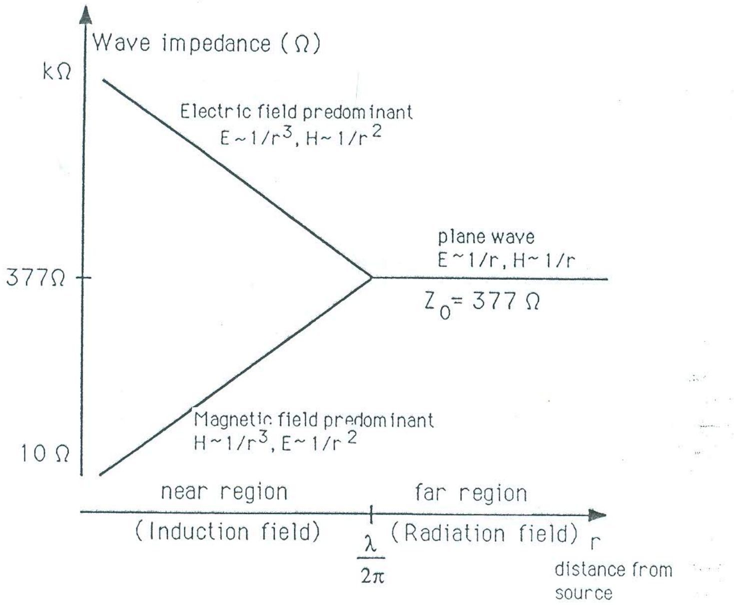


Figure 3.Asymptotes for magnetic and electric fields. Near and far region.

Observe that the transition point between near and far region is frequency dependent. For example when f=100 kHz, $\lambda/2\pi$=477 m and when f= 100 MHz, $\lambda/2\pi$= 0.477 m. It means that approx. half a meter and further away from a 100 MHz radio-antenna (transmitter) the field can be considered as normal electromagnetic radiation.

2.2.2 Mains and hum

The mains is as told one of the most frequent occuring EMI-signal in our electrical environment. Beside the 240 V 50 Hz sinusoid signal, it can be "polluted" by other signals, e.g. transients and voltage dips, from other EMI-sources. These interfering signals in the mains supply network, are of both common mode and normal mode type and are causing many errors in electrical systems. Sometimes the mains voltage is to high, over-voltage, or to low, under-voltage, which might damage electrical equipment or make it work improperly.

To protect electrical equipment from dips, glitches, spikes transported via the mains, over or under voltage, a magnet-stabilizer or even better a noise protection transformer (NPT) can be used. This magnet-stabilizer or the NPT is connected between the mains socket and the equipment.

The magnet stabilizer works as a full transformer with the secondary winding saturated (leaving almost constant voltage out) and a capacitor storing some charge needed when voltage-dips appear (max ≈ 10 ms). This magnet stabilizer attenuates transients, spikes and glitches approx. 30-70 dB.

The NPT is a better version of the magnet stabilizer. It works with the same principles (saturated secondary winding), but has also shielded windings and some filtering features. It attenuates 50-100 dB depending on the frequency of the interference signals and if they are symmetrical or asymmetrical.

A mains analyzer can be used to analyze the quality of the mains supply. This can be programmed to start storing the voltage versus time outlook whenever dips, glitches, spikes, over or under voltage appear.

The transformer is often a severe field-emission-source in most electrical systems. To reduce the emission of interfering fields it is better to use a toroid-transformer instead of the rectangular kind. The doughnut-shaped toroid-transformer has a minimum leak-field, because the path for the magnetic flow inside it is very smooth without any discontinuities. The path for the magnetic flow in the normal squareshaped rectangular transformer will go partly outside the transformer due to its reluctance-discontinuities.

2.2.3 Electrostatic discharge (ESD)

Electrostatic discharge (ESD) due to electrostatic charging phenomena appears in many modern environments, especially those with fitted carpets (synthetic material) and low air humidity (due to central heating), e.g. in offices and flats. ESD is not merely a modern environmental phenomenon though, in old days ESD:s where used by magicians who started fires with small ESD:s and did a number of other electrostatic and ESD tricks.

Electrostatic charging comes from two phenomena called contact-electricity and tribo-electricity (tribo comes from the Greek word `tribein` and it means rub). When two "fitting" materials are in contact or are rubbed against each other, charge (electrons) may be transported from the material with a few electrons more than the last filled shell (loose tightened) to the material with a few missing electrons in the last shell (eager to capture some). Note that the materials are neutral (not charged) before they are in contact.

The two phenomena both contributes simultaneously. Contact-electric charging is a common phenomenon when bringing two materials in contact. The effect can only be seen if the materials are "fitting". Usually the charge equalizes very fast when the materials are separating. Tribo-electric charging is more complicated. It is a result of mechanical stressing that tears fragments of material apart and local heating of the materials, which increases the number of loose electrons.

When the materials are separated they will remain charged (if they are of the right insulating kind, i.e. the charge will not be equalized or transported away). If this electrostatical charged material comes close enough to a susceptible electrical system and/or the voltage is high enough the electrical field strength (V/m) will exceed its breakdown limit and an ESD may take place; charge will be fast transported from one pole to the other. This electric discharge-pulse may seriously damage electronic components as e.g. integrated circuits (IC) or cause software errors in computer systems.

The amount of charge created depends on the combination of materials (see table 1: The triboelectric series), the surface cleanliness, pressure, amount of rubbing, size of surface area in contact, smoothness of surface, speed of separation and air humidity.

Table 1. The triboelectric series.

Positive charging

Air (if low airhumidity)
Skin on a human being
Glass
Hair on a human being
Nylon
Wool
Silk
Aluminium
Paper
Cotton
Wood
Rubber
Acrylic
Polyester
Polyurethane foam
Polyethylene
PVC (vinyl)
Silicon
Teflon

Negative charging

Noticed by almost everybody is when you walk across a carpet, sitting "nervously" in a chair or taking off a sweater, this kind of "rubbing" occurs together with the normal contact-charging and you get charged. These situations can create voltages up to approximately 20-50 kV (which is quite high, isn`t it?) if the conditions are the right. An electrostatic discharge (ESD) takes place (noticed as a small electric spark) when you approaches e.g. a door-handle. The outlook of a discharge-pulse from a person with 150 pF to ground, loaded to 20 kV and 500 Ω resistance path can be seen in figure 4. The analyze-model for a discharge from a human body is a RC-circuit. If the person is discharging via a piece of metal, e.g. a screwdriver, the resistance will be smaller and thus the discharge faster.

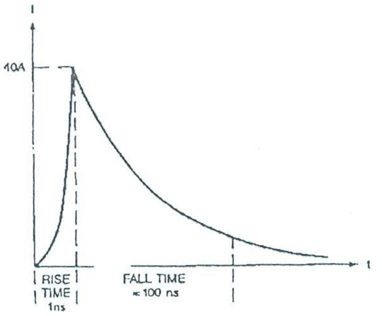


Figure 4. The outlook of a discharge-pulse from a 150 pF, 500 Ω, 20 kV human body.

An energy-example: if a person with 100 pF earth capacitance is loaded to 5 kV he/she has an electrostatic energy of $CV^2/2 \approx 1$ mJ, which is a large energy compared to how big an energy shock a component can withstand (see table 2: Damaging energies for some components, chapter 2.3).

Also in a normal cable triboelectricity may appear if the cable is mechanically bent. When bending, charge may be transported on to the isolating dielectric material covering the conductor. When enough charge has been moved an ESD can take place between the dielectric material and the conductor causing glitches in the signal transported by the conductor or even cable damaging.

Lightning is also a form of ESD. When a cloud is enough charged and the electrical field strength between the cloud and earth exceeds its breakdown-limit (approx. 28kV/cm at sea-level, lower inside the cloud), a discharge between the earth and the cloud may take place and the charge will be transported very quickly from one pole to the other. Discharge or lightning can also occur between two opposite charged clouds or inside a cloud if it is locally opposite charged. This accelerating charge will create electromagnetic (EM) radiation with wide bandwidth and high energy content - a strong interference source. Some of this EM radiation is in the visible region seen as lightning flashes.

To minimize these charge build-up phenomena (and the number of ESD:s) in indoor environments these advices can be considered: normal airhumidity (not too high because of corrosion problems), avoid synthetic textiles (use cotton), use earthen wristbands and carpets when working with electronic components.

To protect susceptible systems against ESD:s, shielding, insulating and grounding techniques should be considered. Note that some modern IC:s has built-in ESD-protecting-networks based on diodes and varistors etc. These can only prevent damage to some extent.

2.3 Interference receptors

The interference-receptor is a more or less susceptible component or electrical system, e.g. EKG-equipments, radio receivers, amplifiers, computers etc.

Damaging an electronic component in an electrical system does not require an especially large amount of energy. Many components are quite sensitive, which can be seen in table 2. Note that valves are very endurable compared to e.g. FET transistors. The valve can withstand a 10 000 times bigger energy shock than a FET-transistor.

Table 2. Damaging energies for some components.

Damage	Component	Damaging energy (J) (approximate values)
Burnout	Microwavediode	$1*10^{-7}$
	Analog IC	$8*10^{-6}$
	FET-transistor	$1*10^{-5}$
	Digital IC	$8*10^{-5}$
	Tunnel diode	$5*10^{-4}$
	Rectifying diode	$6*10^{-4}$
	Silicon diode	$3*10^{-4}$
	Valve	$1*10^{-1}$
Circuit-upset (affect)	Digital IC	$4*10^{-10}$
	Digital circuit (not integrated)	$1*10^{-9}$
	Memory unit	$3*10^{-9}$

2.4 How do interference signals get in?(Coupling paths)

There are four main ways of how the interfering signals can get into an electrical system:

1. Direct coupling (galvanic or conductive coupling).
2. Capacitive coupling (electric field interaction).
3. Inductive coupling (magnetic field interaction).
4. Electromagnetic field interaction or normal EM-radiation.

2.4.1 Direct coupling

The galvanic coupling is through direct, metal to metal, contact. This coupling is mainly causing severe problems due to its possibility to distribute low frequency EMI-signals like for example hum.

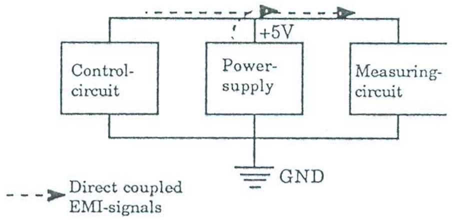


Figure 5. Example on direct (galvanic or metal to metal) coupling.

A special form of direct coupling is varying ground potential due to varying ground-currents through common ground impedances.

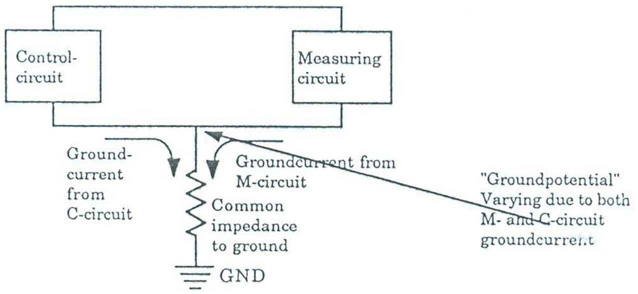


Figure 6. Ground-currents through common impedances.

The direct coupling also offers a path for DC-interference signals contrary to the capacitive or inductive coupling which only can distribute AC-interference signals. The reason is that the capacitive and inductive coupled interfering-signals are distributed by time varying induction- and radiation-fields and not by direct coupling.

2.4.2 Capacitive coupling

Capacitive coupling is an effect of electric field interaction between conductors. A conductor that has a certain time-varying voltage or potential is surrounded by an electric field. This field can affect electrons in another conductor in the vicinity, if it has a different potential. A good picture of this is that of an ordinary capacitor; charge on the two conductorplates affect each other through electric field interaction. The created current, i, is the flow of charge ($i=dQ/dt$), where Q is the amount of charge. In a capacitor is $Q=C*V$, where C is the capacitance and V the voltage across it. This means that $i=d(C*V)/dt=\underline{C*dV/dt}$ (or $V*dC/dt$). If we return to the conductor (e.g. a wire) with the vicinity conductor (e.g. another wire) we can look on these conductors as the two conductor plates in an ordinary capacitor and if there is a way for the electric field to couple we have capacitive coupling between these, or there is a stray or leak capacitance, C_{12}, between these, distributing time varying interference signals.

The impedance of a capacitor is $Z=1/j\omega C$, where $\omega=2\pi*$frequency. The model of the capacitive coupling can, due to the high impedance, be seen as an ideal current generator, where the interfering current it generates into the receiving system is $I_N=j\omega C_{12}V_1$,see figure 7.

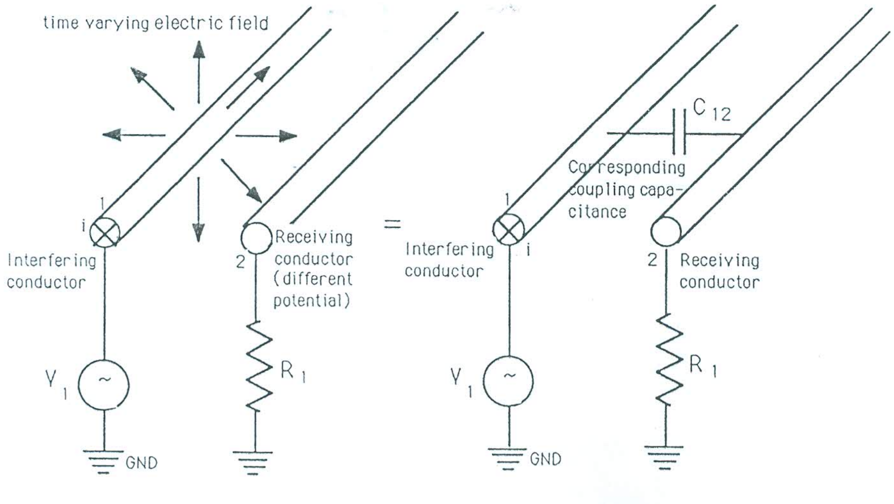


Figure 7. Capacitive coupling.

High impedance
source Z=1/ $j\omega C_{12}$
(e.g. C_{12} = 10pF,
f=50 Hz, Z≈300 MΩ
model: ideal
currentgenerator
(Note: I=V/Z)

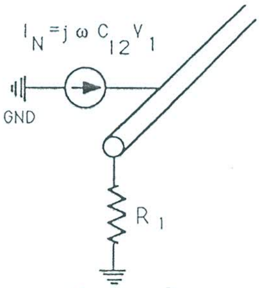


Figure 8. Model for capacitive coupling.

Calculations of capacitance between two parallel cables are summed up in figure 9.

$$C = \frac{\pi * \varepsilon_0 * L}{\ln(d/a)}$$

(d>>a)

$$C = \frac{\pi * \varepsilon_0 * L}{\ln \dfrac{2*h*d}{a*\sqrt{4*h^2 + d^2}}}$$

(d,h>>a)

Figure 9. Capacitances between two ideal conductors (cables) in vacuum.

Note that to achieve a minimum capacitive coupling between two cables the distance between them should be as large as possible. The parall length and the distance to ground as small as possible. Another way o decreasing the capacitive coupling between two cables is shielding and grounding the shield, thus preventing the inner information-carrying conductor from being affected by the interfering fields.

Note that the part of the inner conductor that extends the shield, which is almost always there to be able to connect it to something, should be as small as possible, otherwise the interfering signals can be coupled via that part. The important thing to keep in mind is to ground the shield, otherwise will the interfering signals that reach the shield also reach the inner conductor via the capacitance between the shield and the inner conductor. See figure 10.

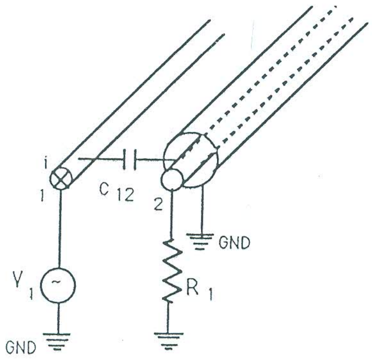


Figure 10. The shield should be grounded.

2.4.3 The Human being in an electrical environment

The reason for presenting a model for the human body in an electrical environment is that very often the body can cause a great deal of disturbances into systems. A model of the human body can be a perforated, due to pores in the skin, bag filled with salt water; A conductor with approximately 50-500 pF (normally ≈ 100 pF) capacitance to ground, depending on whether the shoes etc. are good insulators or not. This conductor has also ≈ 5-10 pF capacitance to surrounding wires. The presence of a human being in close proximity to a susceptible system is sometimes enough to inject interferences, because the interference-signals will find a more efficient path to affect the system via the human body.

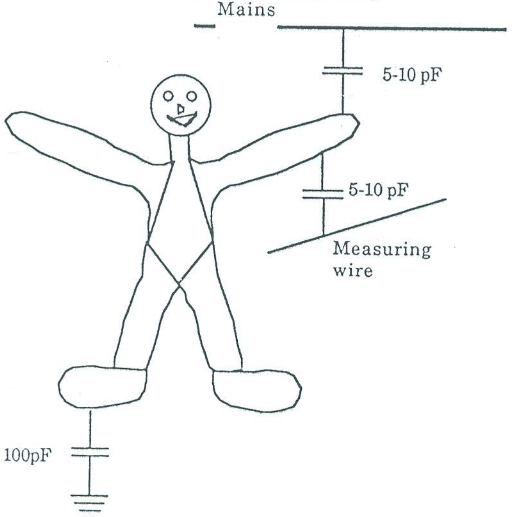


Figure 11. A human body model.

2.4.4 Inductive coupling

Inductive coupling is caused by magnetic field interaction. A conductor or wire-circuit in which a time-varying current,I_1, is floating is surrounded by an alternating magnetic field. If this field is acting more or less perpendicular on a closed loop circuit, with an area A, in the vicinity and the magnetic flow through this loop creates a signal in it, we can say that there is an inductive coupling, or a mutual inductance,M_{12} , between the two circuits. Mutual inductance is defined as the flow $Ø_2$ through the receiving circuit due to the current, I_1, floating in the source circuit, o $M_{12}=Ø_2/I_1$. The magnetic flow, $Ø_2$, can be calculated as $Ø_2 = B*A$. The induction law says that the interfering voltage,$V_N=A*dB/dt$, on this receiving circuit depends on B and A and how fast the magnetic field is varying; $V_N=j\omega M_{12}i_1$.

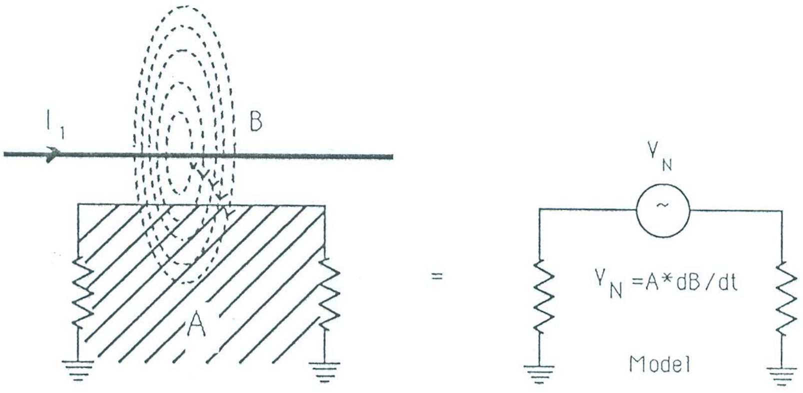
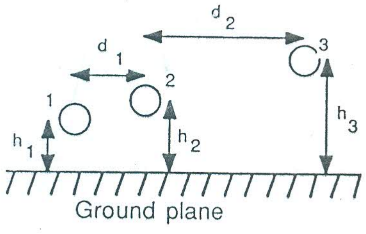


Figure 12. Inductive coupling and its model.

The impedance for an inductive coupling is $Z=j\omega M_{12}$. Z is normally very low (due to small M_{12}) and therefore can the inductive coupling-model be seen as an ideal voltage generator, acting in series with the receiving circuit.

Ideal parallell cable conductors. Length L.



$$M_{13} = \frac{\mu_0}{4\pi} \ln\left(\frac{(d_1+d_2)^2+(h_3+h_1)^2}{(d_1+d_2)^2+(h_3-h_1)^2}\right) * L$$

$$M_{23} = \frac{\mu_0}{4\pi} \ln\left(\frac{d_2^2+(h_3+h_2)^2}{d_2^2+(h_3-h_2)^2}\right) * L$$

1,2: Interfered cables
3: Interfering cable

Figure 14. Mutual inductances between parallel cables (in vacuum).

To achieve minimum inductive coupling the distance between the cables should be as large as possible and the distance to ground should be as small as possible.

A daily measuring situation is shown in figure 15, where two receiving loops for interfering magnetic fields (with areas A1 and A2) are a fact. The result of the interfering magnetic field, B, acting on the area A1 is a differential mode signal across the inputs. The same "B-field" acting on the area A2 results in a common mode signal across the inputs. See chapter 5 for definitions of the differential mode and common mode signals.

Minimizing these areas can be done as in figure 16 and even better in figure 17.

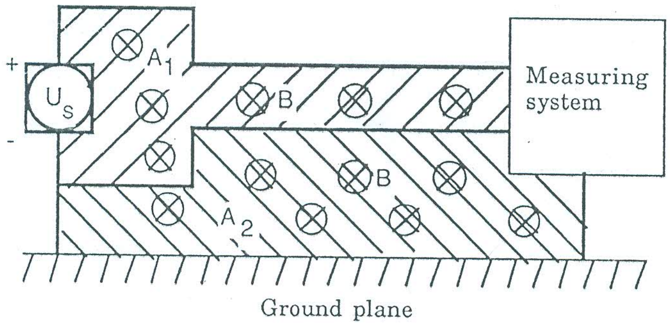
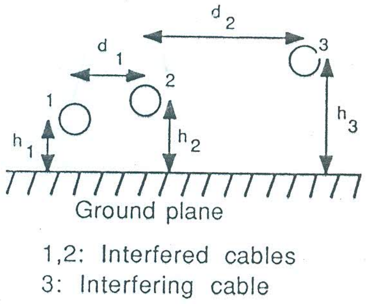


Figure 15. Normal situation. Large inductive coupling due to large areas A_1 and A_2.

Ideal parallell cable conductors. Length L.



$$M_{13} = \frac{\mu_0}{4\pi} \ln\left(\frac{(d_1+d_2)^2+(h_3+h_1)^2}{(d_1+d_2)^2+(h_3-h_1)^2}\right) \cdot L$$

$$M_{23} = \frac{\mu_0}{4\pi} \ln\left(\frac{d_2^2+(h_3+h_2)^2}{d_2^2+(h_3-h_2)^2}\right) \cdot L$$

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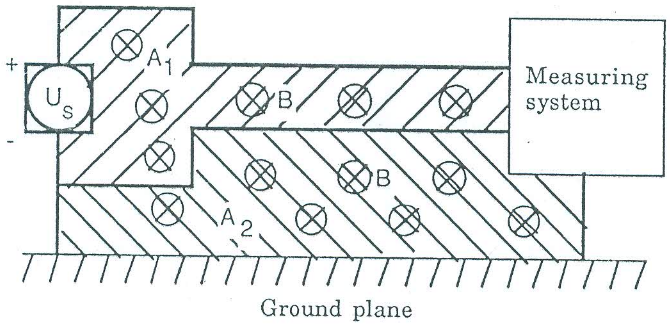


Figure 15. Normal situation. Large inductive coupling due to large areas A_1 and A_2.

By using a twisted pair cable the area A1 is minimized both physically (the projected area is smaller) and electrically (the induced interfering signal in each "small" loop (++) is in opposite phase with the one next to it (--), thus cancelling each other).

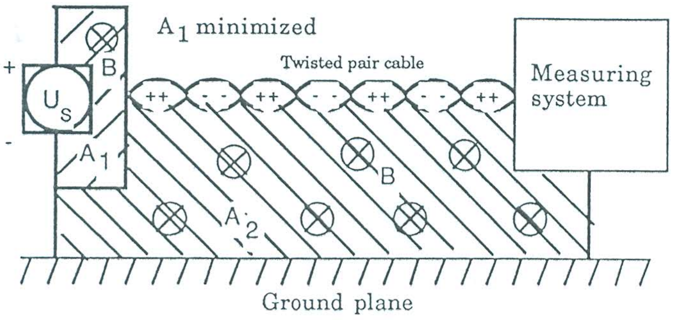


Figure 16. Area A_1 minimized due to usage of twisted pair cable.

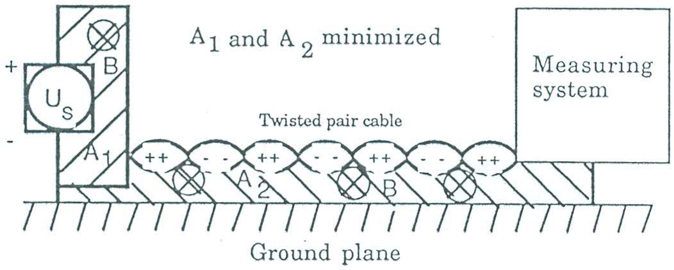


Figure 17. Both A1 and A2 minimized by laying twisted pair cable close to ground plane.

2.4.5 Test whether capacitive or inductive coupling

To decide whether the coupling is capacitive or inductive and if you have a circuit with decent impedance conditions, you can act as follows: decrease the impedance in one of the circuit-ends (R_2 in figure 18) while you are measuring the interference voltage, V_N, over the impedance in the other end (R_1). If V_N decreases then the coupling is capacitive, in the model the capacitive coupling can be seen as a current generator and V_N over R_1 is $V_N=I_N*R_1$). If V_N increases (due to different voltage divide relations) then the coupling is inductive.

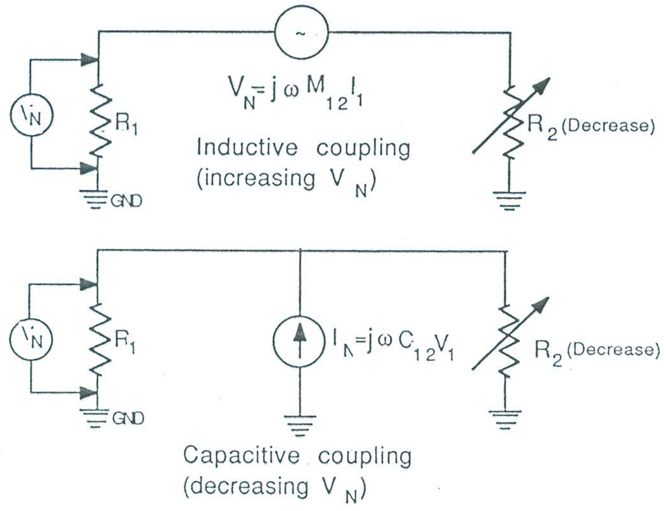


Figure 18. Test whether it is capacitive or inductive coupling.

3 Shielding

Shielding is a way to stop or attenuate the propagation of electric, magnetic or electromagnetic fields with a partition of metal.

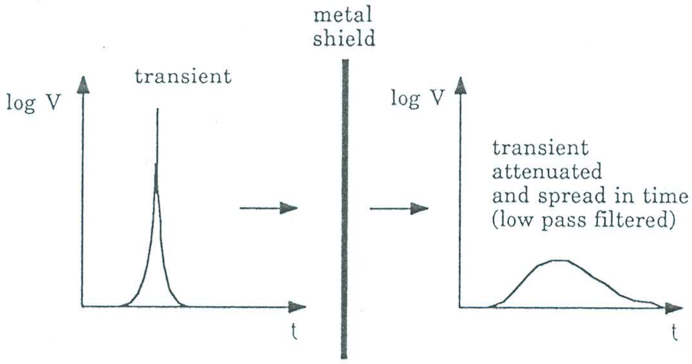


Figure 19. Transient outlook before and after partition.

A practical example on a shield is the metal "skin" around the inner conductor in a coaxial cable.

The shield attenuates the fields by reflection loss and absorption loss of the incoming fields. It can be used in two ways according to figure 20.

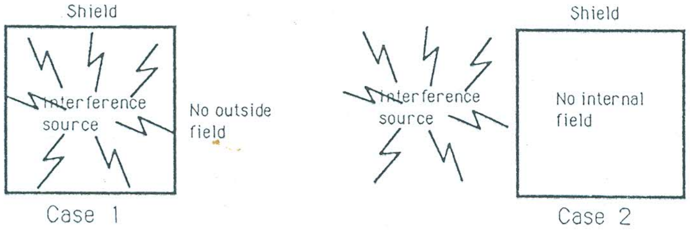


Figure 20. Shielding principles.

Shielding the source is the best way leaving the space outside without interfering fields. In many cases this can be difficult and expensive, e.g. if the source is some kind of natural phenomenon, and you have to consider shielding the receptors instead. Depending on whether the field is electric or magnetic, different techniques have to be used. The effect of multiple shields is better than a single, even if the total "thickness" is the same.

If the shield completely covers the source or the receptor it doesn't matter which potential it has, a Faradays cage. The shielding effect is as good if it is not connected to anything, floating, as if it is grounded. In reality the shield never totally encloses the source or receptor and the potentials inside the shield are often related to the outside, therefore it is a good idea to ground the shield, thus creating a shunt path to ground for EMI-signals as well as for dangerous high-power signals if there is an insulation fault.

3.1 Shielding electric fields

This is a quite simple case because a thin metallic shell keeps the electric field out. Even a metal net ("chickencage") is a good shield for electric fields. At low frequencies reflection losses are the primary shielding mechanism whereas at high frequencies absorption losses are primary.

3.2 Shielding magnetic fields

Shielding magnetic fields is much more difficult, especially at low frequencies. Thick shields made of expensive materials are often needed. There are three principle ways of shielding magnetic fields:

1. Ferromagnetic shields.
2. Eddy current shields.
3. Compensation with opposite fields.

The ferromagnetic shield is the most common one, often made of my-metal. Because of very low reluctance (low magnetic resistance) it draws the magnetic flow inside the shield and leads it past the protected region. If the field is strong enough this ferromagnetic shield can be saturated, which reduces its effect.

The eddy current shield has a completely different principle. It only works properly when the magnetic field is alternating with a frequency and fieldstrength high enough to create eddy currents in the shield. These eddy currents causes opposite magnetic fields that "pushes out" the outside interfering magnetic field. This shield requires that the path for the eddy currents to flow is free from obstacles. No bad contact in the joints e.g. between the walls and the cover of the shield. It has to be "waterproof".

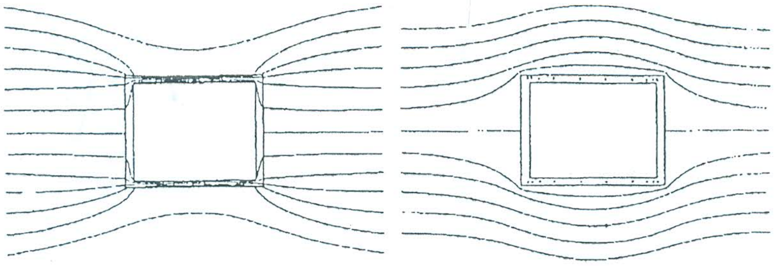


Figure 21. Fieldpictures from a ferromagnetic (left) and an eddy-current shield (right).

Compensation with an opposite field is normally done when the interfering magnetic field is static, e.g. the earth magnetic field (≈ 0.1 mT). Then compensation can be done with a pair of "Helmholtz coils", which are coils with radie, R, and placed at a distance R between them. This arrangement creates a very homogeneous static magnetic field in the centre ($\partial B/\partial z=0$, $\partial^2B/\partial z^2=0$), and the strength of this field is chosen by the current floating in the coils.

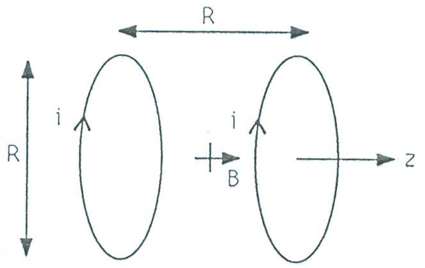


Figure 22. Helmholtz coils for compensation of static magnetic field.

3.3 Shielding effects

The total shielding effect is a combination of both reflection losses and absorption losses and it depends on the frequency, geometry of the shield, type, direction and polarization of the incoming field. The absorption loss in a shield is almost independent of whether it`s a near magnetic or electric field or a far electromagnetic field coming in. But it is strongly related to which frequency the incoming field has. On low frequencies the absorption loss is negligible raising with higher frequencies (see figure 23).

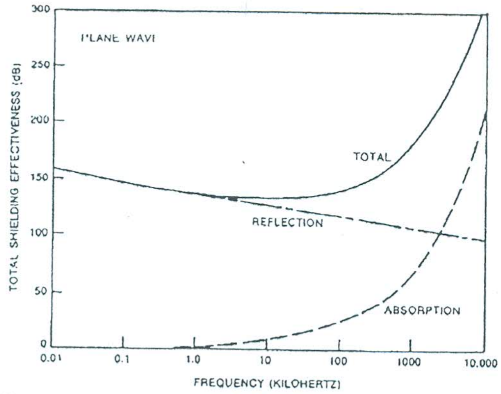


Figure 23. Reflection- and absorption-loss vs. frequency. (Ott)

The reflection loss however varies a lot with different kinds of fields. With low frequency *magnetic* fields the reflection losses is very small contrary to reflection losses of low frequency *electric* fields, which is quite large. Attenuate magnetic fields requires thick shields to reach the same effect as relatively thin shields, shielding electric fields.

The total shielding effect is summed up in figure 24. Note that it is difficult to shield out low frequency magnetic fields. The results in the figure is from an aluminium-shield experiment (from Ott:s book) and aluminium is a very bad shield for low frequency magnetic fields.

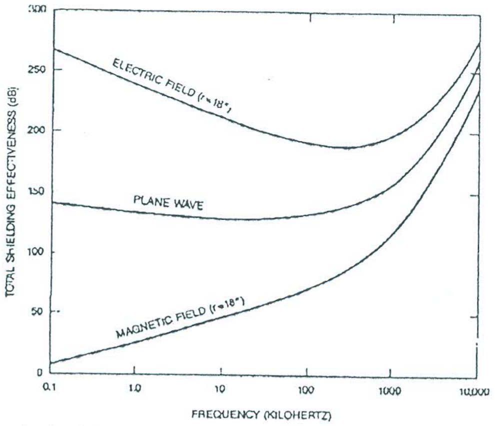


Figure 24. Total shielding effectiveness.

4 Grounding

A subject very often treated with a great disrespect is grounding. People do often not realize that ground is not always the well-defined potential we want it to be and this causes a great deal of problems. A definition closer to the truth than the "ideal well-defined earth-potential" of a ground should be: "a low impedance path for current to return to the source" (Ott).

4.1 Safety ground

One of the major functions for grounding an electrical system is safety. Using safety ground protects the people as well as the equipment from different kinds of electrical shocks from insulation faults and breakdown incidents inside and outside the equipment. For example if the mains-voltage cable is accidently in contact with the chassis of washing machine it could be deadly to touch that machine, but if the chassis is connected to safety ground the mains will be short-cut and the fuse will blow and disconnect the mains cable from the chassis (figure 25).

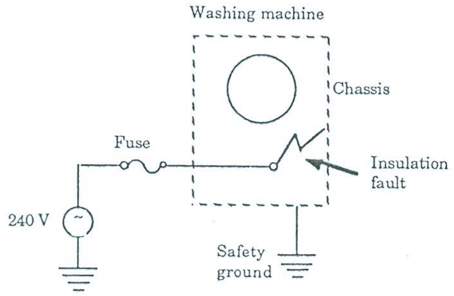


Figure 25. Safety ground prevents from electric shock.

Most power-distribution networks around the world has safety ground included in the mains. This wire is often connected to the neutral wire in the fuse box. From the fuse box to the transformer station the neutral and the safety ground is often the same wire. The safety ground is therefore contaminated with EMI-signals (also field-coupled EMI-signals may appear), mostly 50 Hz hum. This is a big problem because it makes it difficult to have both a safe system and a system with minimized EMI-conditions at the same time.

4.2 Signal ground

Signal ground is the reference-potential for the signal in an electrical system. It is not necessarily on earth-potential. But it should ideally have the same potential at every spot on the plane — equipotential-plane. This is not the case in reality, especially when large ground-currents and loops are floating in the ground-plane. Therefore a good idea is to ground the different circuits at the same spot — single point grounding (figure 26). Parallel connection is better than series connection but more expensive because the use of larger quantities of cable.

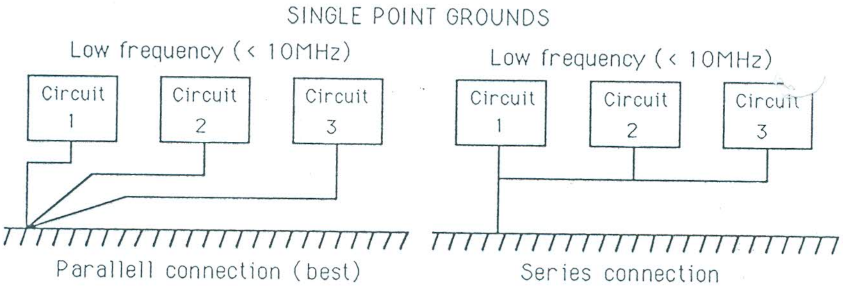


Figure 26. Single-point grounding is desirable for low frequencies.

If the frequency is high enough, the impedance due to the inductances in the ground-cables will increase and you will not have "a low impedance path for current to return to the source". The groundcable may also start to radiate if the length is greater than 1/20:th of the wavelength. Multiple point grounding (figure 27) is here a solution because you can keep the groundcables short.

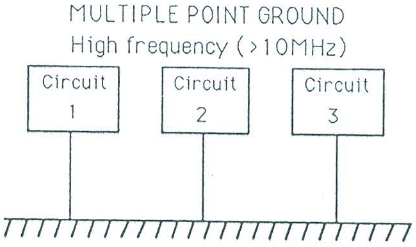


Figure 27. Multiple point grounding only for high frequencies.

4.3 Grounding principles

Many people are not aware of the large currents floating in ground-systems. These ground-currents through common impedances in ground-planes and electrical systems are often creating severe EMI-problems. A good ground should therefore be able to receive and deliver a lot of current without changing its potential, and that is definitely not always the case.

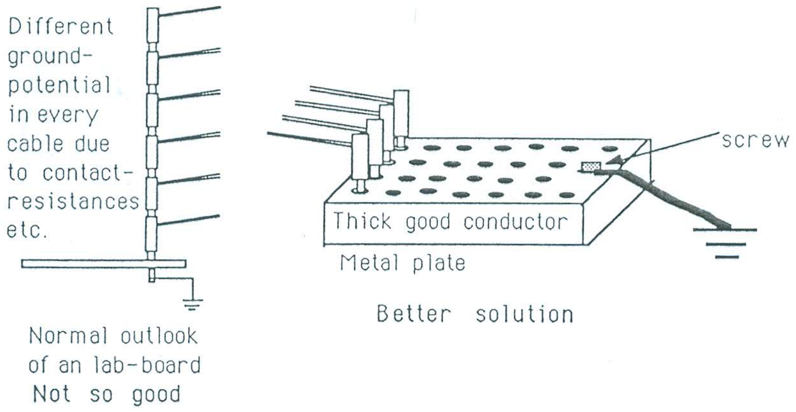


Figure 28. Use a thick metal plate with holes as ground reference instead of the "common impedance tower".

Another example on grounding without thinking is shown in figure 29, a circuit for measuring temperature combined with some logic circuit where low level analog signal ground is mixed with digital system ground. The result of the wrong groundpotential due to the current floating through the common impedance is an error of approx. 70°C.

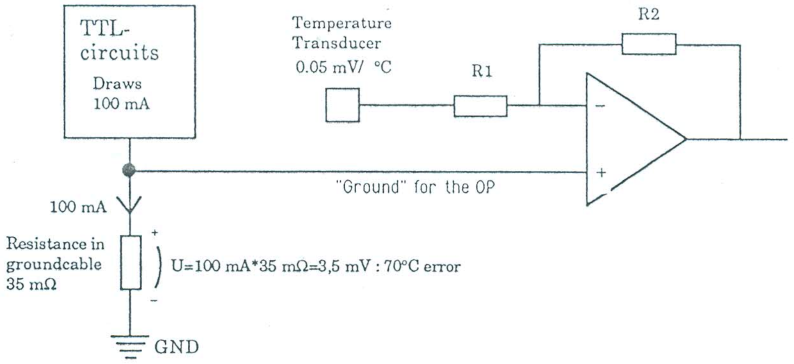


Figure 29. Example of incorrect grounding.

An electronic system contains often a lot of different parts; the power-supply, high power circuits, digital system, low-level analog part, high-level analog part. Mixing the grounds of every part together where currents from high-power system and low-level systems are floating through common impedances etc. may definitely be the same as asking for trouble.

Therefore a good solution is to separate the different grounds in a grounding tree (see figure 30).

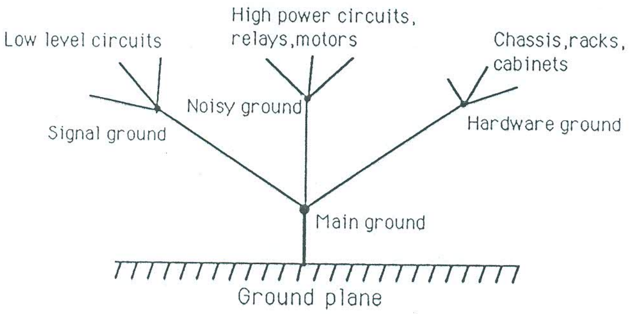


Figure 30. Grounding tree.

4.4 Ground-loops

A ground-loop with "vagabonding currents" is a fact when a system are grounded in two or more different grounding-places. These currents causes differences in potential between the grounding-points. This current is often very large, ≈ 5-10 A is normal. For example if the current is 10 A and the resistance between the grounding places is 10 mΩ, the difference in ground-potential will be 100 mV, a large potential-difference for low-level systems.

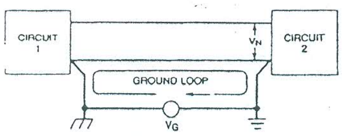


Figure 31. Ground-loop occurs if grounding at two different places.

Avoiding ground-loops can be done as grounding only in one point. This can sometimes be impossible in practical situations, e.g. if you are using two individually grounded instruments. Instead you can break the loop by using some kind of insulation (figure 32): transformers (figure 32 top), Common-mode choke (32 middle), opto-couplers (32 bottom) etc.

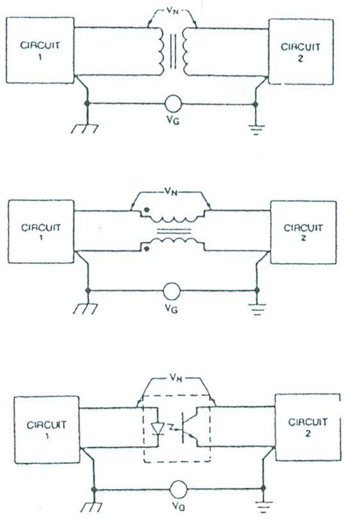


Figure 32. Breaking the ground-loop.

Another way to reduce the ground-loop current and the interfering voltage V_G is to introduce a large impedance in the ground loop (figure 33 and 34).

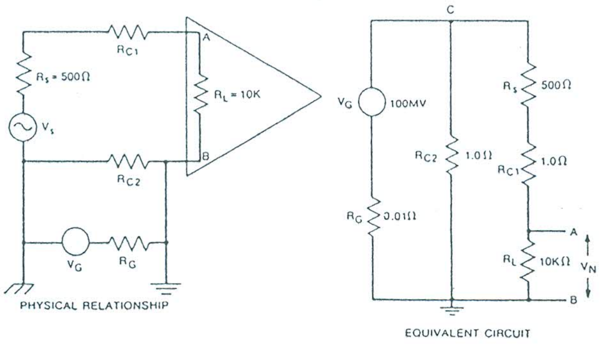


Figure 33. Ground-voltage V_G will interfere with V_S.

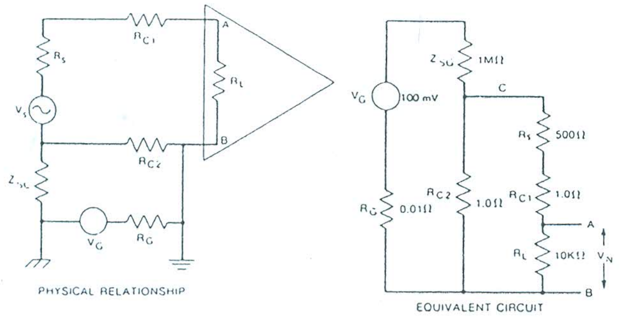


Figure 34. Ground-loop current reduced by Z_{SG}.

4.5 Grounding shielded cables

An important part in the area of reducing interfering signals when distributing electric signals is the usage of shielded cables and how to ground the shield.

As told in chapter 2.4 it is necessary to ground this shield to shunt the interfering signals to ground instead of being coupled once again via the capacitances and inductances between the shield and the inner conductor(s). Here comes an analyze about the best grounding-places for the cable-shield:

NOTE that this analyze only treats the low-frequency case. For HF-analysis you can consult the recommended books in the reference list.

Three different cases can be distinguished:

1. Ungrounded source, e.g. a transducer, and grounded receptor, e.g. an amplifier.

2. Grounded source and ungrounded receptor.

3. Both grounded.

The analyze for the first and second case, with models for different grounding-places, are done in figure 35 and 36. Study these two figures carefully. C1 and C3 in the figure are leak-capacitances between the shield and the inner conductors. C2 is leak-capacitance between the pair-cables.

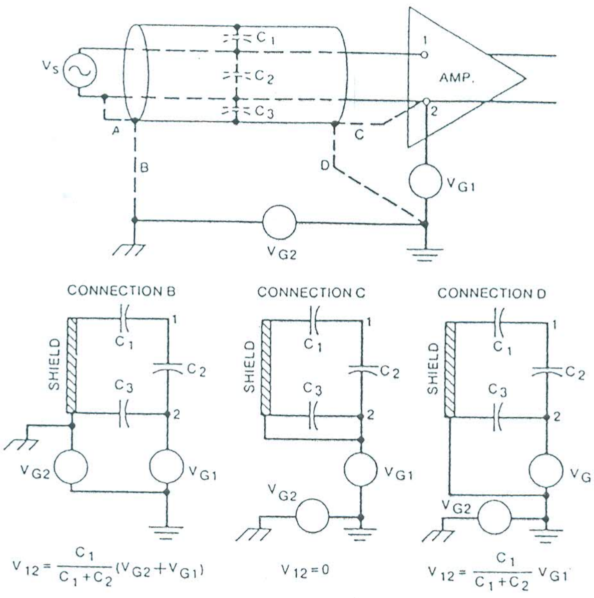


Figure 35. Ungrounded source and grounded receptor. Which grounding place is best (A-D)?

The analyze in figure 35 gives: for a circuit with ungrounded transducer and grounded amplifier the shield should be connected to the amplifier common terminal (or low) input, even if this place is not at earth-potential.

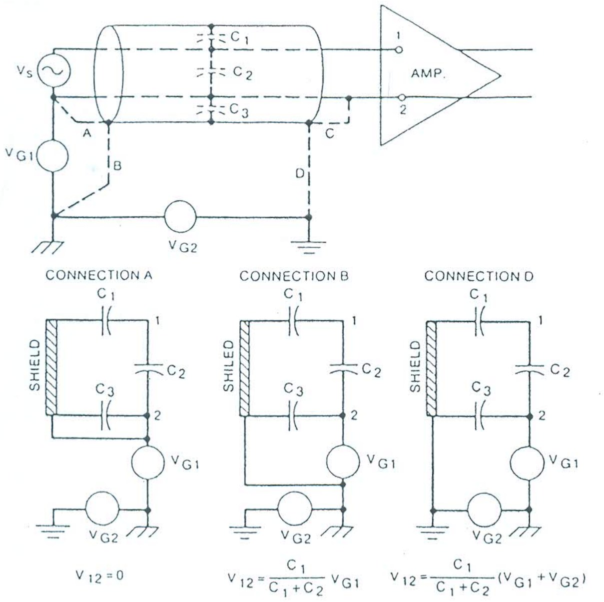


Figure 36. Grounded source and ungrounded receptor.

The analyze in figure 36 gives: For a circuit with grounded receptor and ungrounded amplifier the shield should be connected to the source common terminal, even if this place is not at earth-potential.

Another case are when both sides, source and receptor are connected to ground. This is, from an EMI-protecting point of view, not very good (ground-loops!). To avoid having to much ground-loop current floating in the inner information-carrying conductor(s) the shield should be grounded at both ends so that some ground-loop current will return via the shield instead (see figure 37 E-F). Of course can here also the different techniques for breaking the loop presented in chapter 4.4 be considered.

The recommended ways to ground cable-shields in different situations are summed up in figure 37, A and C shows case 1, and B and D case 2.

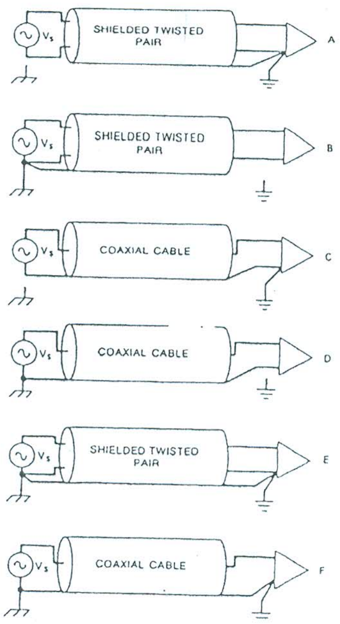


Figure 37. Grounding cable-shields in different situations.

Ribbon cables are nowadays popular and often used with both low-level analog signals as well as high-level digital signals (+-12V) in the same ribbon. Problems like cross-talk between the wires, and other kinds of interference may sometimes occur. Some shielding effect can be achieved by putting one or more grounded wires in between the interfering wires. This technique can also be used with multi-pin contacts.

Figure 38. Put some ground wires between interfering wires in a ribbon cable.

5 Common mode and Differential mode signals

Interference signals can appear both as DC or AC signals, superimposed with the information signal. Two principle kinds of of signals can be distinguished: the differential mode (or normal mode) signals and the common mode signals.

5.1 CM- and DM-signals – Definitions

The differential mode (DM or NM) voltage is defined as a voltage between the two sides in a circuit (e.g. A and B in figure 39).

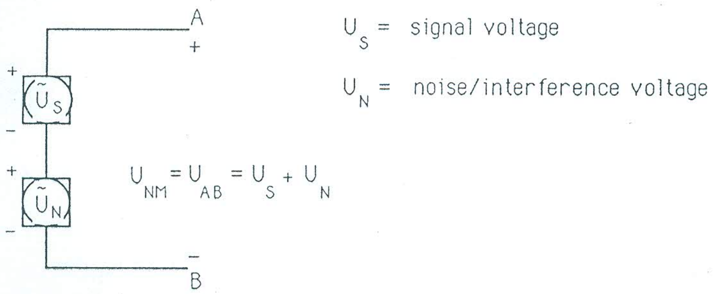


Figure 39. Definition of NM voltage.

The voltage between A and B is a NM voltage $U_{NM}=U_S+U_N$. The potential of this circuit related to ground is not significant for this definition.

The common mode (CM) voltage is defined as the average voltage of the two sides related to ground.

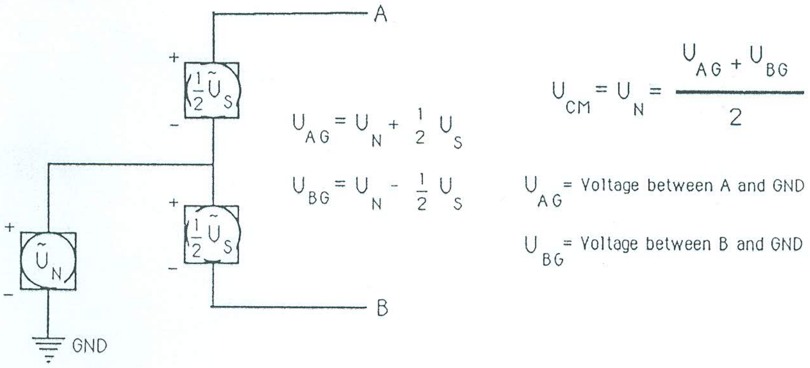


Figure 40. Definition of CM voltage

The CM voltage is here according to the definition $(U_{AG}+U_{BG})/2 = U_N$.

If U_N is much larger than U_S (which is quite common), the definition can be simplified as:

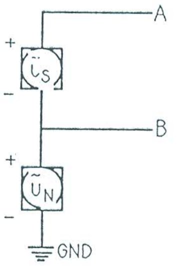
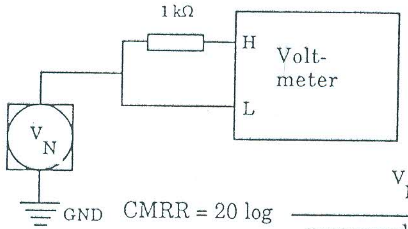


Figure 41. Definition of CM voltage when $U_N >> U_S$.

5.2 CMRR—common mode rejection ratio

The common mode (CM) interference signal is very often present, e.g. since the two wires in a two wire leader is laying next to each other , or the two inputs (+ and -) of an OP amplifier is placed next to each other, they may look similar for the interference fields in the vicinity and that will cause the same amount of interference coupling into both wires: a common mode interfering signal will appear on them. Therefore, in many input stages, special consideration has been taken to eliminate or at least attenuate these CM-signals. A parameter often used to tell how much a system suppresses CM-signals is the common mode rejection ratio (CMRR), for which the unit often is decibels (dB).

Measuring the CMRR-value of, for example, an ordinary voltmeter can practically be done as: Simulate an interference-source with an ordinary signal generator. Unbalance one of the two inputs with a 1 kΩ resistance. Connect as in the figure and read the maximum appearing voltage on the voltmeter display. The volt-meter should be set on DC-voltage. Calculate the CMRR-value according to figure 42:



$$\text{CMRR} = 20 \log \frac{V_N}{\text{measured voltage-error}}$$

Figure 42. CMRR- measurement.

5.3 NMRR—normal mode rejection ratio

Suppression of normal mode signals superimposed on the information signal is called normal mode rejection (NMR) and the parameter NMRR. The NMRR parameter is normally frequency-dependent. Since the mains signal (240 V, 50 Hz) is the most frequent occuring interference signal, systems are often constructed to have the highest attenuation-ability (NMRR) at 50 Hz and its harmonics (100,150, 200 Hz etc.). Digital voltmeters are often constructed with some integrating A/D-converter, e.g. dual slope type, to attenuate NM-signals. These are quite slow, measuring approx. 3-10 times a second. When the integration-time is one or an integer number of periods of the interfering NM-signal (n*20ms for 50 Hz), the NM-signal will be integrated away and only the wanted DC-level will be left, figure 43. In figure 43 there is also a small high-frequency component present, which will of course also disappear after integration.

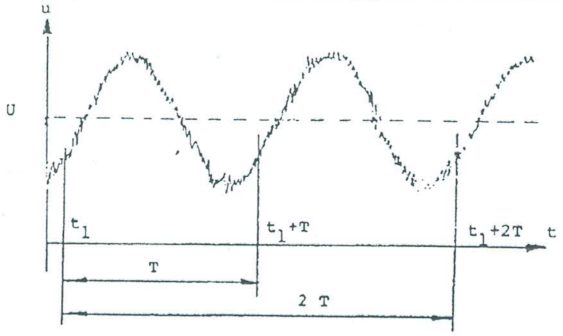


Figure 43. DC-level with superimposed low- and high-frequency components.

Since the NMRR-parameter is better for those frequencies at which the integration-time corresponds with an integer number of NM-signal periods, it will have a quite "spiky" outlook. The typical outlook of a NMRR vs. frequency diagram is showed in figure 44. Note that the frequency integrating-time product is showed instead of frequency.

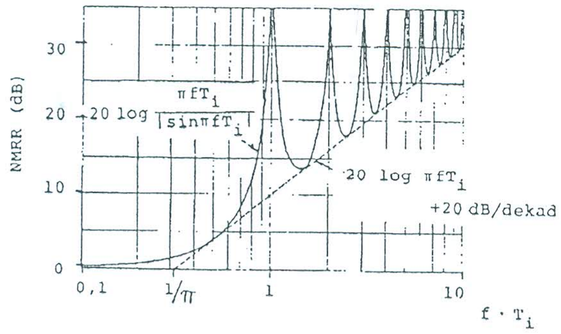
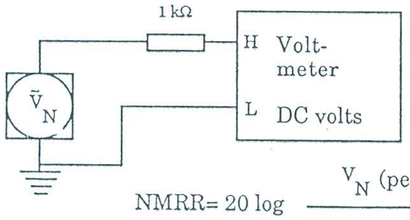


Figure 44. NMRR for a "slow" integrating (dual slope) voltmeter.

Other kinds of voltmeters may have some filters instead to reduce the effect of NM-signals. These ones are often momentary measuring and faster than the dual-slope kind.

NMRR can be measured in a similar way as that of the CMRR measurement.(see figure 45).



$$\text{NMRR} = 20\log\frac{V_N\ \text{(peak value)}}{\text{measured error voltage}}$$

Figure 45. NMRR measurement.

6 Filtering and balancing

6.1 Filtering

Interference signals can sometimes entirely or partly have a frequency-content that differs from that of the information signal being used. Eliminating or attenuating this interference signal can therefore be done with filtering techniques. Any of the different types of active or passive filters can be considered; low pass, high pass, band pass or stop band.

High and low frequency interference signals (e.g. noise and hum) can be eliminated by limiting the systembandwidth to what's needed in the actual system. By introducing a band (or low and high) pass filter somewhere in the system or use cables with just sufficient bandwidth, signals above the maximum and below the minimum system-frequency will be cut off.

6.2 Decoupling

Decoupling techniques are a very easy way of avoiding interference troubles, especially concerning power-supplies and digital circuits. A decoupling capacitor can be an effective shunt path to ground for the high frequency components, e.g. for transients. The impedance is very low at high frequencies, $Z=1/\omega C$. Note that these capacitors have designated for high frequencies. Normal capacitors becomes inductive at high frequencies!

By introducing a decoupling capacitor over the DC power-supply (between + and -), its non-ideal behaviours due to varying load conditions can be avoided. Decoupling capacitors in digital circuitry across each digital circuit or each group of circuits to minimizes the interference coupling between them.

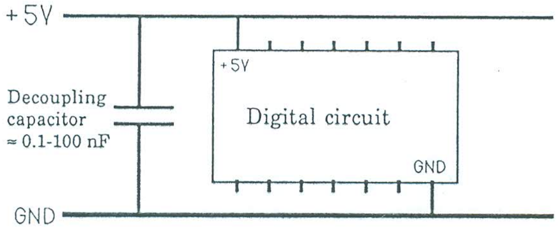


Figure 46. Decoupling capacitor across digital circuit.

6.3 Balancing

Balancing is a common EMI-suppressing technique. This technique is often used by telephone and telecommunication companies around the world to distribute telecommunication-signals on a cheap unshielded twisted pair two-wire circuit. In a balanced circuit both conductors and all circuits connected to them have the same impedance to ground, which makes the interference-pick-up equal in both wires; a common mode signal appears on them and the interference voltage over R_{L1} has opposite polarity to that over R_{L2}, therefore when summing the total voltage over the load (between 1 and 2) these interference voltages will cancel each other.

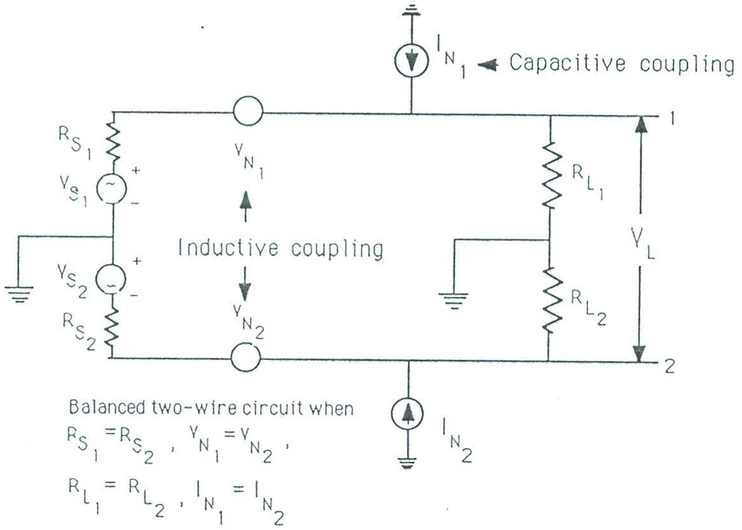


Figure 47. Definition of a two-conductor balanced circuit.

Combined with shielding, balancing is an even better choice due to the fact that achieving perfect balance conditions is difficult in the real world.

The CMRR-parameter can be used to tell how well balanced the circuit is.

7 Contacts and relays.

Almost certainly everybody has caused a small "spark" in a radio-program when switching on or off a lamp, maybe considering this contact switch as poorly designed. Switching on or off a contact always includes more or less fast changes in voltage- and current- conditions. In most industrial processes a lot of different kinds of electromechanical contacts and switches, e.g. relays, triacs, tyristors etc., are used and if these are poorly designed the interference environment will be very "dirty", causing big problems when installing new electronic equipment.

A normal relay in an electrical system represents partly an inductive load and partly a contact. Both components causes interference signals as high voltage transients and discharge sparks. A common interference-case is when a relay controls another inductive load. To be able to reduce interference-problems with relays we will analyze its both components starting with the contact:

7.1 Discharge-phenomena in a contact

Discharge-phenomena occurs when the electrostatic fieldstrength (Volts/meter) exceed its breakdown limit, i.e. when the voltage across the contactparts is high enough and/or the distance between it is small enough. This discharge transports charge and will continue until the contact-parts are closed and touching each other (if closing) or until the fieldstrength cannot support the discharge conditions any more (if opening). As in every discharge-case electromagnetic radiation will be emitted and the discharge will act as an interference-source.

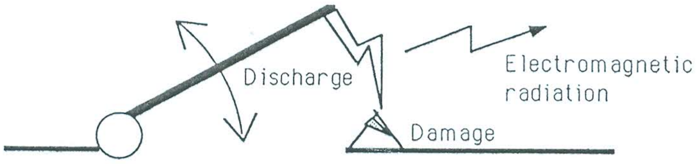


Figure 48. Contact discharge.

There are two kinds of discharges: Glow-discharge and Arc-discharge.

Glow-discharge occurs when the electrostatic fieldstrength ionizes the gas, e.g. air, between the contacts. It is characterized by relatively high voltage and low current. The voltage across the contacts needed for this phenomenon must be above approx. 300 V, so it is possible to avoid it by keeping the voltage below 300V.

Arc-discharge is a electron-emission phenomenon. Electrons are emitted form the cathode and transported to the anode. The conditions for Arc-discharge is characterized by low voltage and high current, but they are strongly dependent on what contact material is being used (good electron-emitter or not) and on the surface outlook. This discharge often damages the contacts due to local heating.

The arc-discharge conditions, low voltage and high current, are much easier to achieve than those for glow-discharge, high voltage and low current. The behaviour of discharges can sometimes be quite complex and difficult to predict. For example the concept "contact-bouncing" is not what everybody thinks it is, metal bouncing against metal, but instead it is an alternating discharge phenomena.

7.2 Inductive loads

An inductor is current-inert, i.e. it wants to conserve the magnetic flow (due to the current) flowing through it. The voltage across a coil is V=L*di/dt, where L is the inductance and i the current. When the current is suddenly cut, the di/dt term gets very large and negative, and a large negative voltage across the inductance will appear trying to maintain the magnetic flow through it. This "inductive kick" may cause interference in the circuit as well as the contact controlling it will "glue" when opening and be damaged.

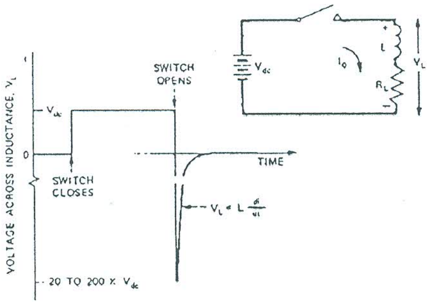


Figure 49. Transient over inductive load (from Ott:s book).

7.3 Protection networks across contacts and inductive loads

The discharge-phenomena across a contact is especially a severe problem when the contact controls an inductive or a capacitive load. Inductive loads causes a big transient when the contact opens and the capacitive load causes a big transient when the contact is being closed. To avoid discharge-phenomena and protect the contact and minimize transients in the circuit some protection networks should be used, across the contact and/or across the load. Of course should the ordinary EMI-suppressing techniques like shielding and grounding not be forgotten here.

Figure 50 and 51 presents some protection networks. Choosing the component-values for these networks can be quite complex with a lot of analysis to avoid deteriorating the performance of the switch-circuit (switching-speed etc.). In most normal cases it is enough to use some rules of thumb:

All the used passive components must manage to cope with at least ≈ 20times the used supply-voltage, due to high-voltage transients. The capacitor C should be typically 0.1 to 1 µF. The resistor should have about the same value as the load resistance if there is no diode in the network and if there is a diode it should preferably be larger (≈100 Ω to a few kΩ). The diode should have a peak inverse voltage (PIV) larger than the maximum transient voltage (to avoid breakdown). For deeper analysis consult the recommended books in the reference list.

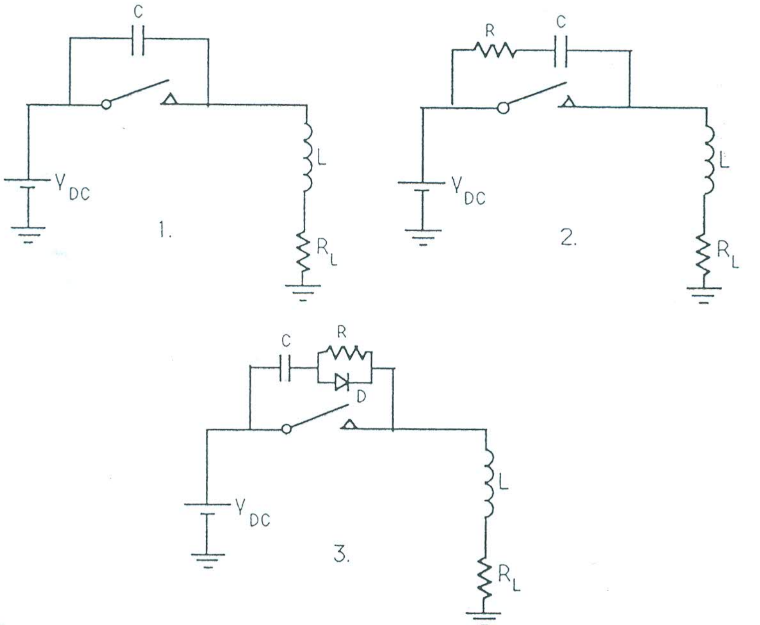


Figure 50. Networks for contact protection (inductive loads).

In figure 50 number 3 is best and number 2 is the most widespread.

If the "dirty" industrial process you are going to treat contains a lot of contacts controlling a few inductive loads it would be cheaper to equip the loads instead of the contacts with protection-networks. Some different networks for suppressing the transient over the inductive load are presented in figure 53.

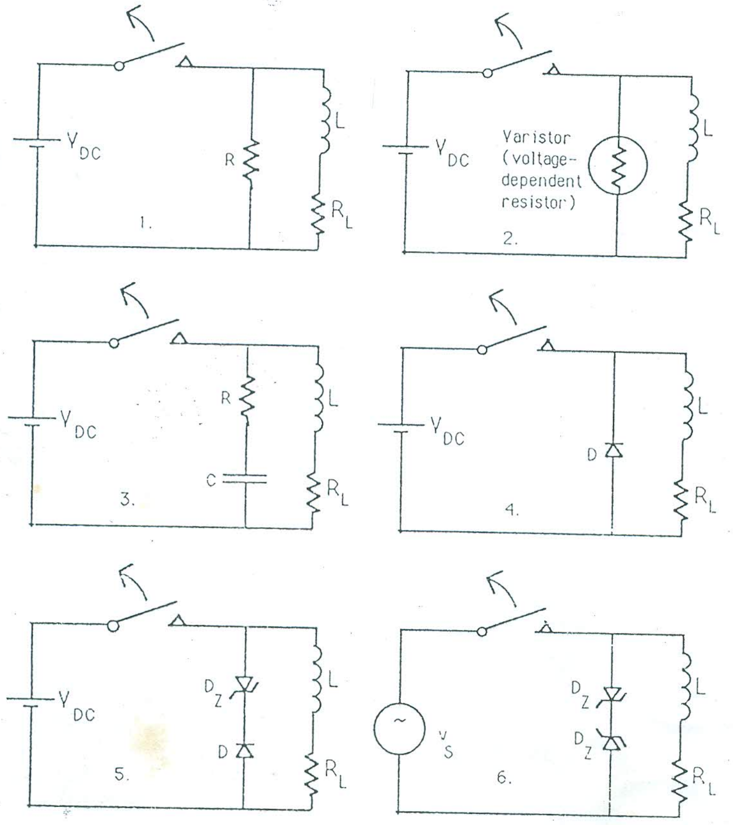


Figure 51. Networks for minimizing transients across inductive load.

It is more difficult to rank these networks. No. 3 is better than 1 but it requires at least a few ohms load resistance. No. 4 to 6 are also efficient often used networks and no. 6 can also handle AC-supply.

8 References

1. H.W. Ott: Noise reduction techniques in electronic systems. 2nd edition, New York, 1988, ISBN 0-471-85068-3

2. J.L.N. Violette, D.R.J. White, M.F. Violette: Electromagnetic compatibility handbook. 1987, ISBN 0-442-28903-0