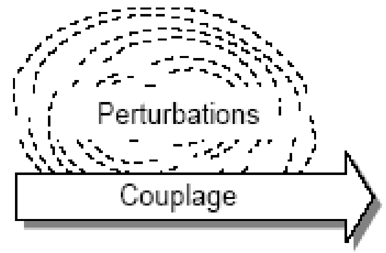
Coupling modes

Véronique Beauvois, Ir.
2020-2021

General problem in EMC = a trilogy

Parameters
• Amplitude
• Spectrum
•…



Source (disturbing) → Victim (disturbed)

Propagation
Coupling modes

• lightning
• electrostatic discharges
• motors, converters
• etc.

• conducted (I / U)
• radiated
(cables, slot, shielding defect,…)

• receivers
• sensors
• amplifiers
• μC
• etc.

General solution in EMC = a trilogy

Source (disturbing) → Victim (disturbed)

Propagation
Coupling mode

To act on the source
(not always possible)

To reduce the efficiency
of the coupling mode
= frequently only solution

To act on the victim
(increasing immunity –
reducing susceptibility)

or different combined solutions

Remark : reciprocity (improving emission frequently improving immunity)

1st step: to identify the disturbing elements

⇩

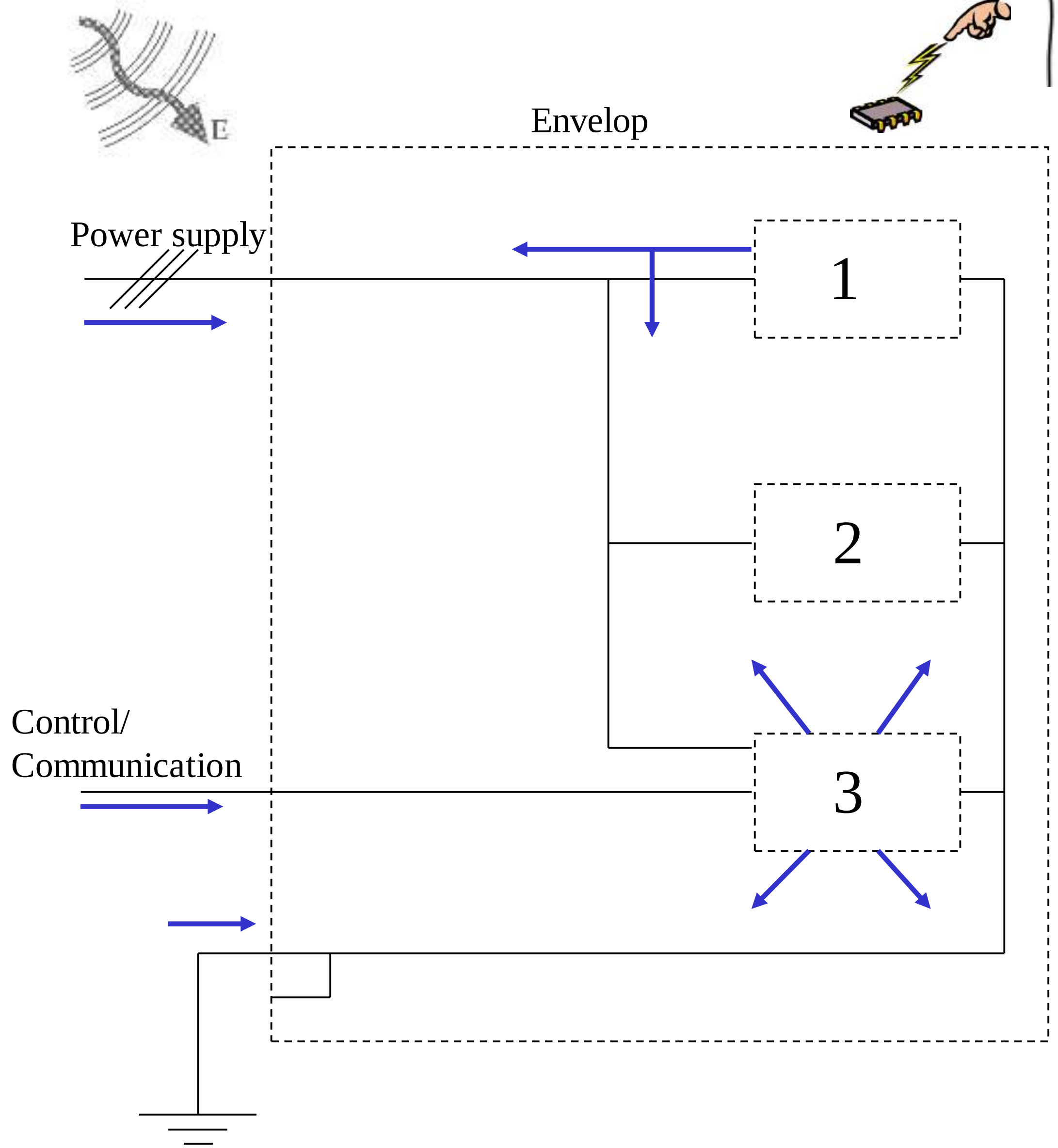
Protections

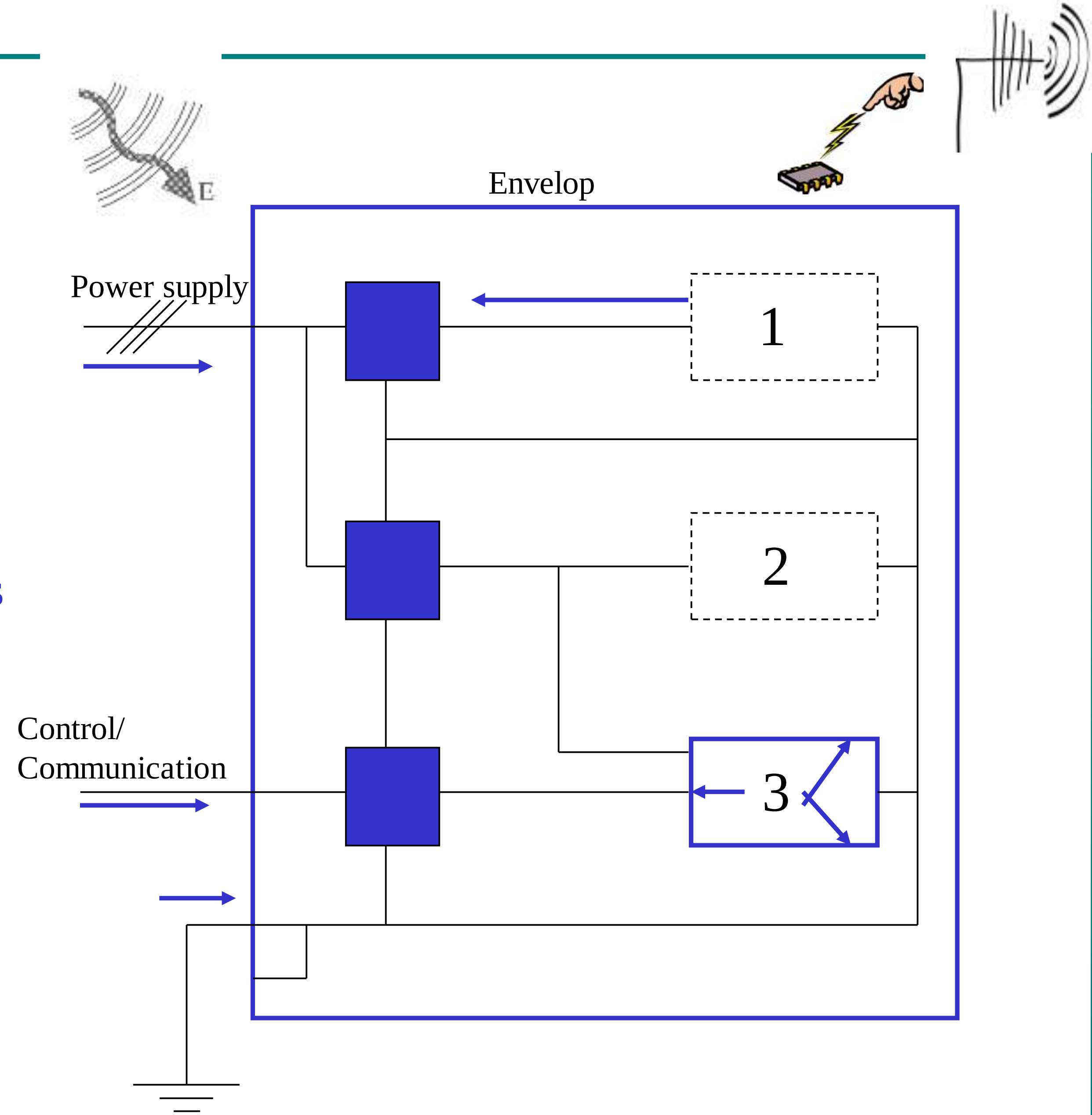
- ↳ for inter-system
- ↳ for intra-system

= source & victim
inside the same system

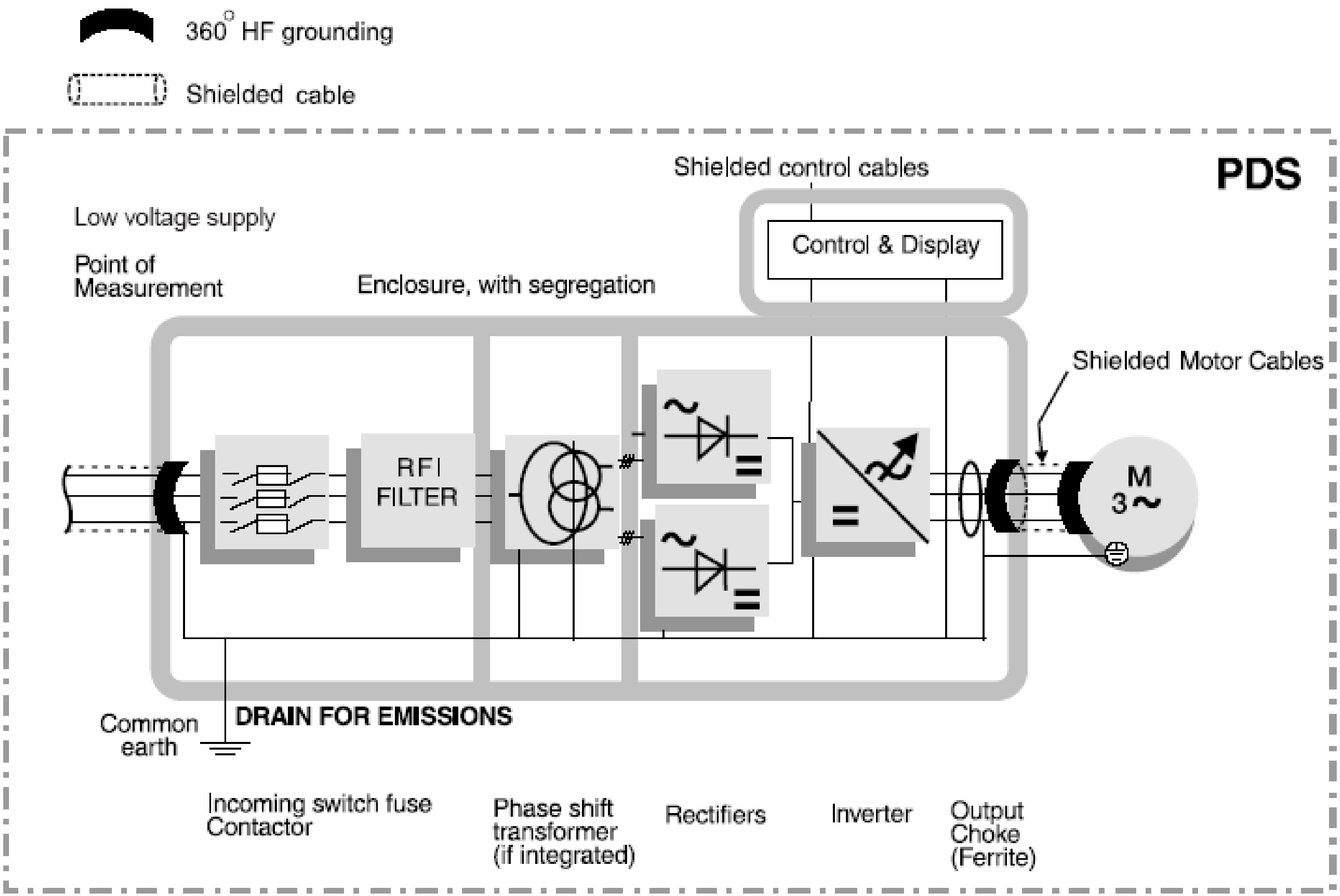
To identify the disturbing elements, the coupling paths,

…





To change the design
To add components
to reduce some effects

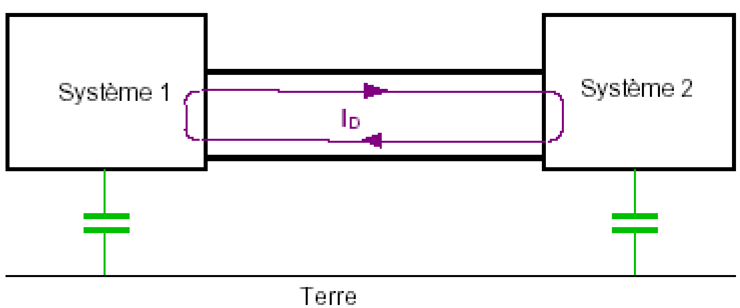

360° HF grounding
Shielded cable
Shielded control cables
PDS
Low voltage supply
Point of Measurement
Enclosure, with segregation
Control & Display
Shielded Motor Cables
RFI FILTER
M
3 ~
Common earth
DRAIN FOR EMISSIONS
Incoming switch fuse Contactor
Phase shift transformer (if integrated)
Rectifiers
Inverter
Output Choke (Ferrite)

© ABB Drives

Coupling modes (1)

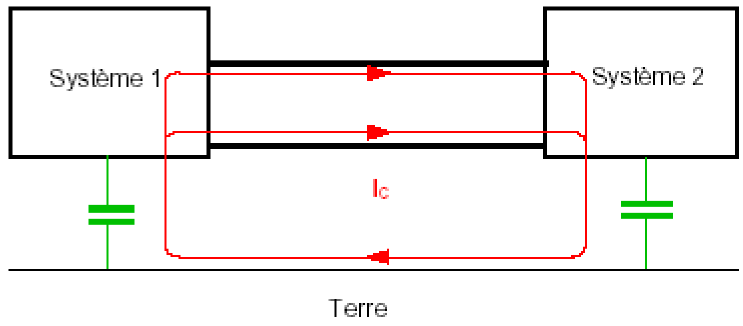
The coupling modes between source and victim could be classified according to:

- Common mode
- Differential mode



Differential mode (DM) (or symmetrical) : current is in one conductor in one direction and in phase opposition in the second conductor (e.g. power supply, RS-485, CAN, USB).

Coupling modes (1)



Common Mode (CM)
(or asymmetrical or longitudinal) :
current on both conductors in the same direction.

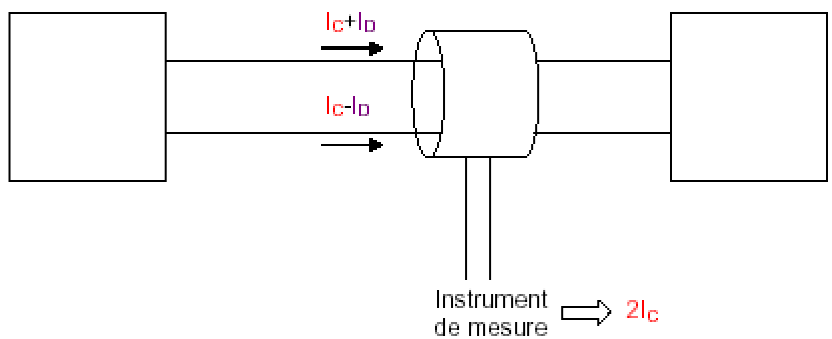
The EM disturbances are weakly coupled in DM as conductors are nearby. On the other hand, in CM, current could be induced by an external field.

> How to measure CM and DM?

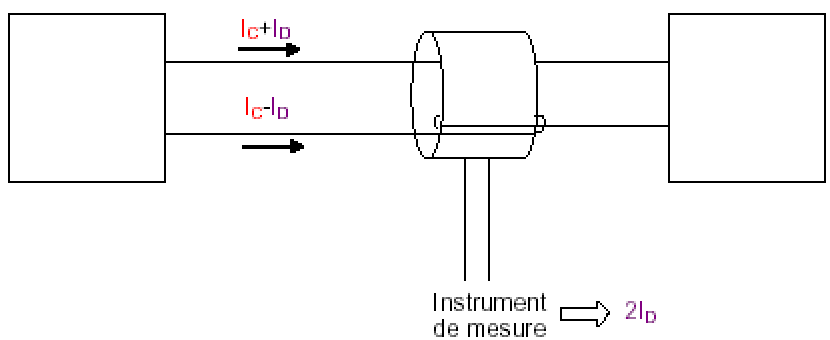
Coupling modes (1)

How to measure CM and DM?
With a current clamp

CM



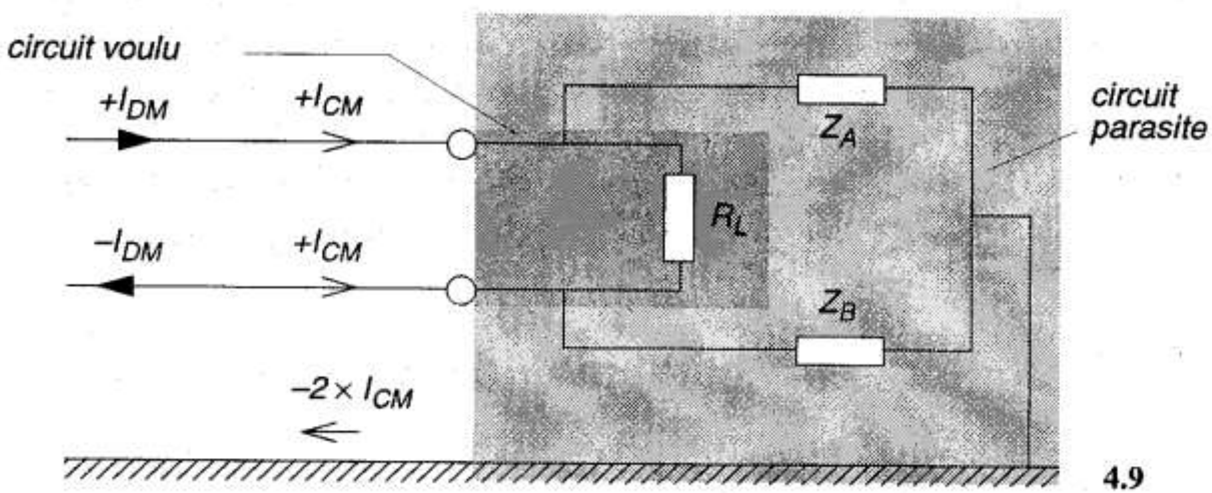
DM



Coupling modes (1)

Conversion between DM and CM?

Related to the parasitic impedances of different values



4.9

Origin? When 2 conductors have a different impedance regarding earth (e.g. parasitic capacitors)

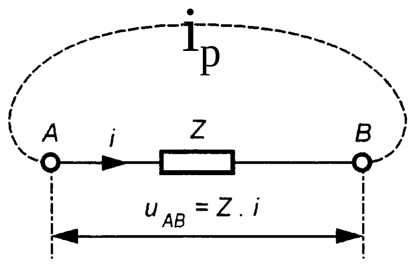
If $Z_A = Z_B$, there is no voltage across R_L due to I_{CM}

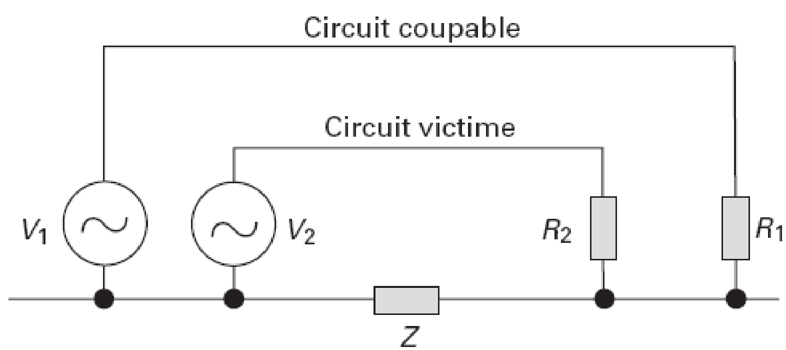
If $Z_A \neq Z_B$, $V_{Load(CM)} = I_{CM}.(Z_A - Z_B)$

Coupling modes (2)

A. Common impedance coupling (conducted coupling)
= common conductor

Considering a conductor AB, impedance Z(f) (≠0) :





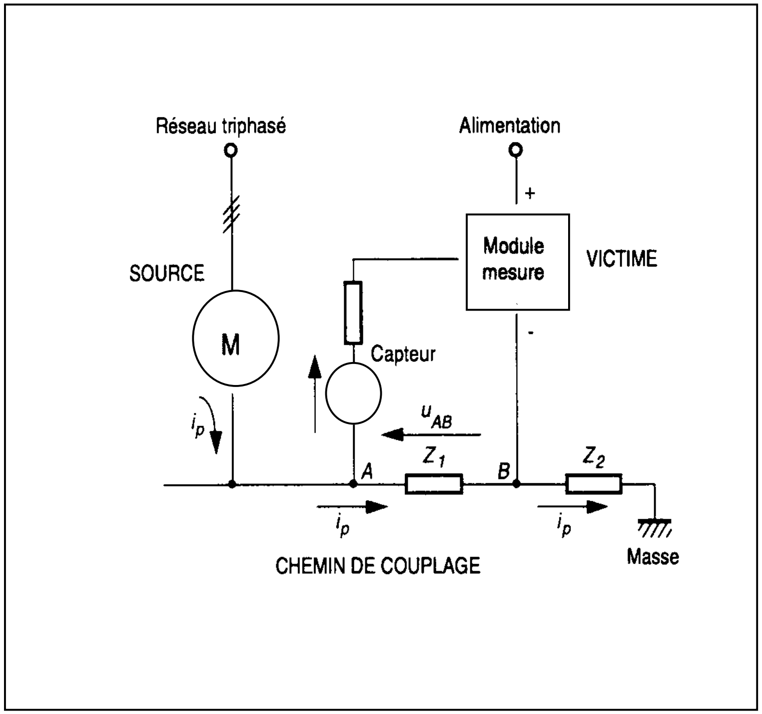
Z impédance commune aux deux circuits

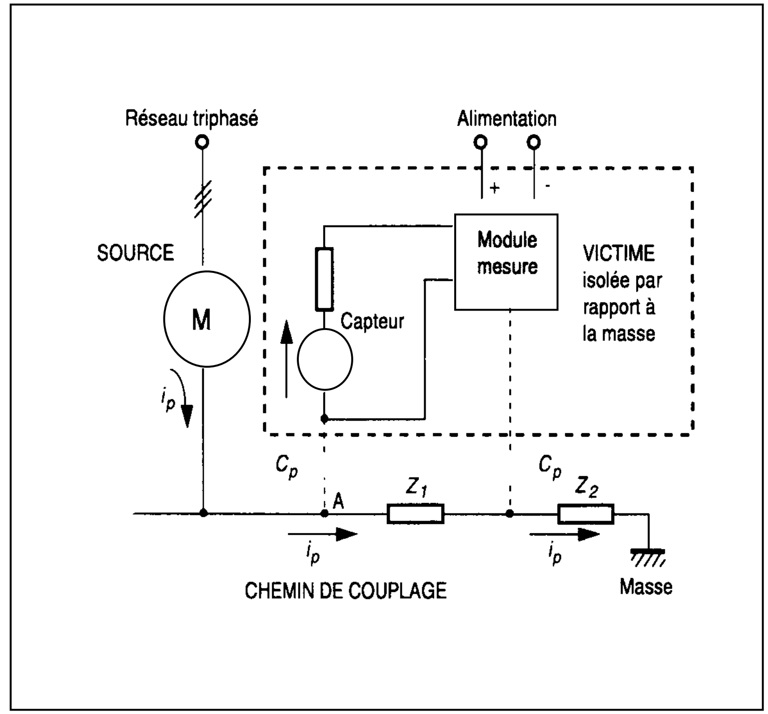
Solutions:

- to decrease Z (coupling)
- to decrease i_p (source)

Coupling modes (2)

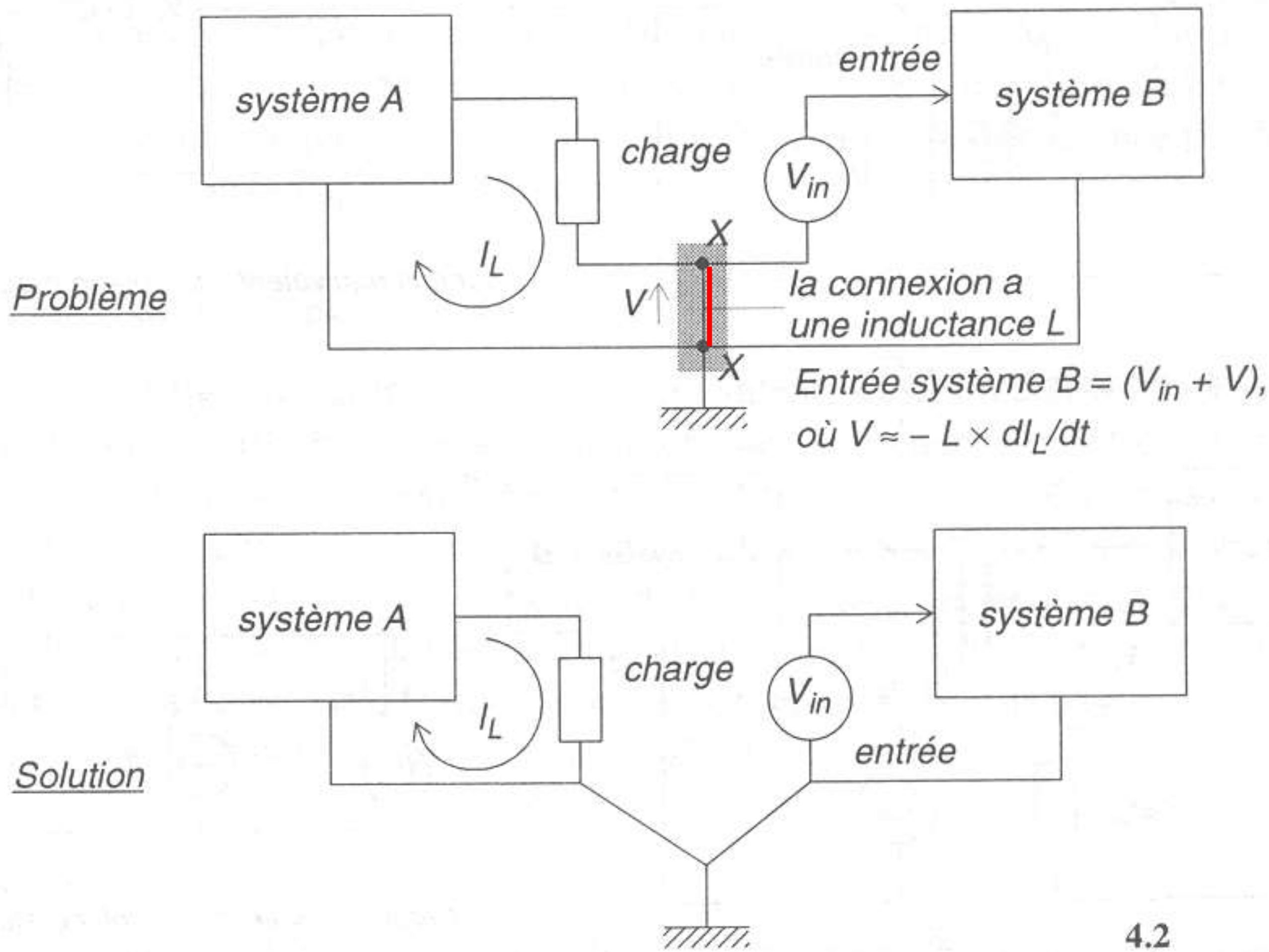
A. Common impedance coupling (conducted coupling) = common conductor





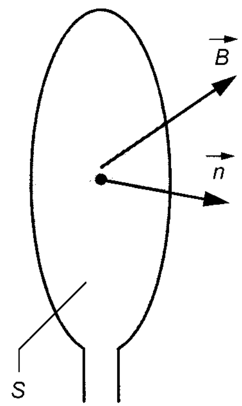
Coupling modes (2)

A. Common impedance coupling (conducted coupling) = common conductor



Coupling modes (2)

B. Inductive Coupling



The circulation of a current in a conductor creates a magnetic field, which could couple with a nearby circuit, and induced a voltage.

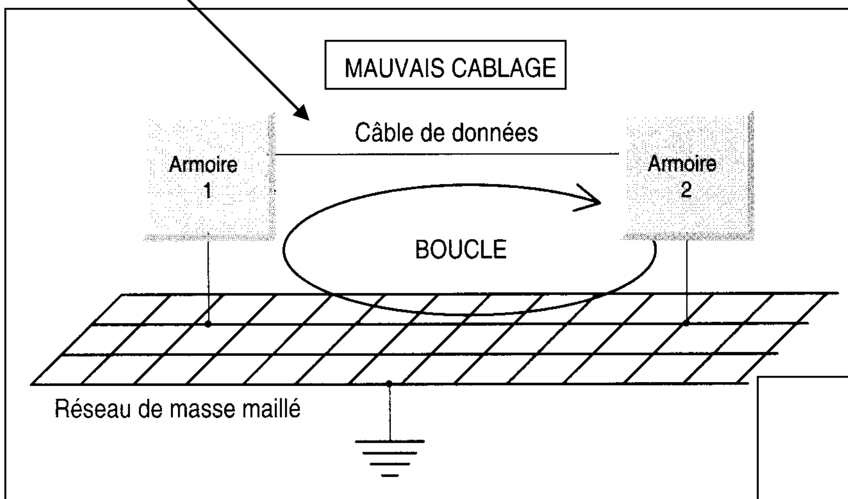
Solutions:

- source: to decrease dB/dt
- victim: to decrease S or modify orientation
  (n and B perpendicular, B // loop)
- coupling: to increase distance or add a magnetic screen

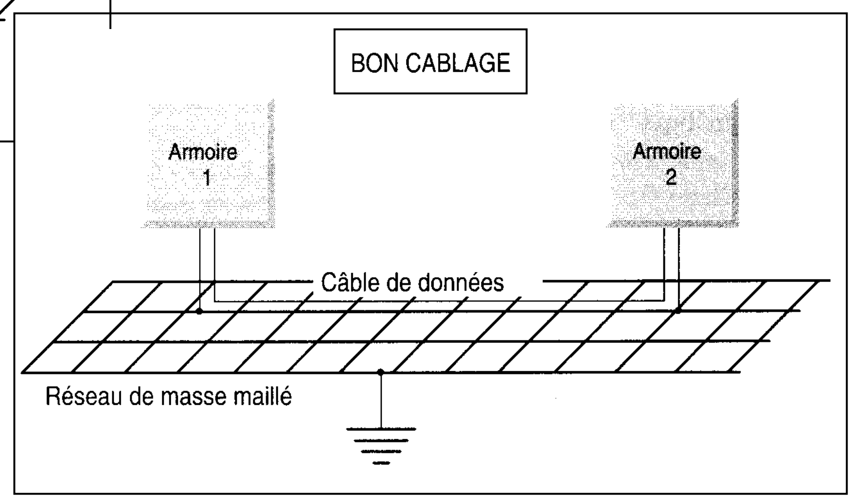
Coupling modes (2)

B. Inductive Coupling

External disturbance



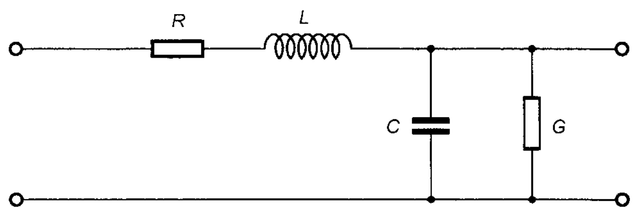
To reduce S loop

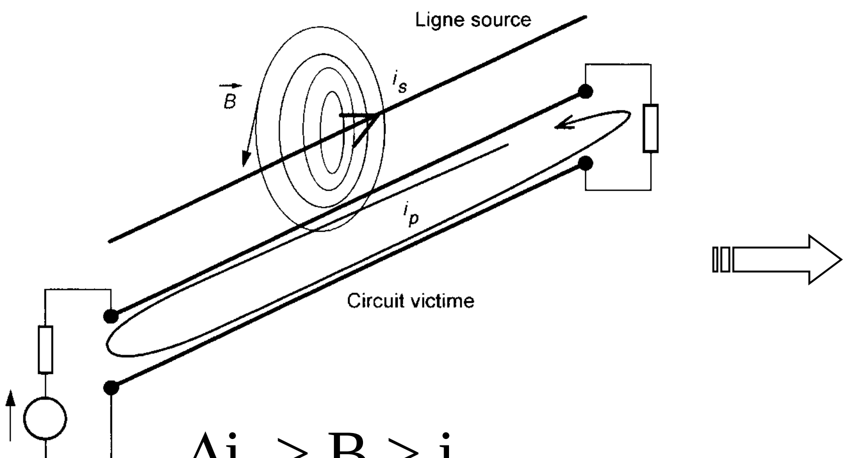


Coupling modes (2)

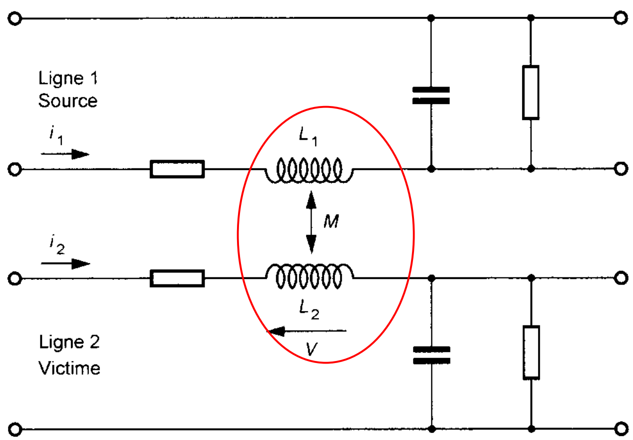
B. Inductive Coupling

Inductive diaphony





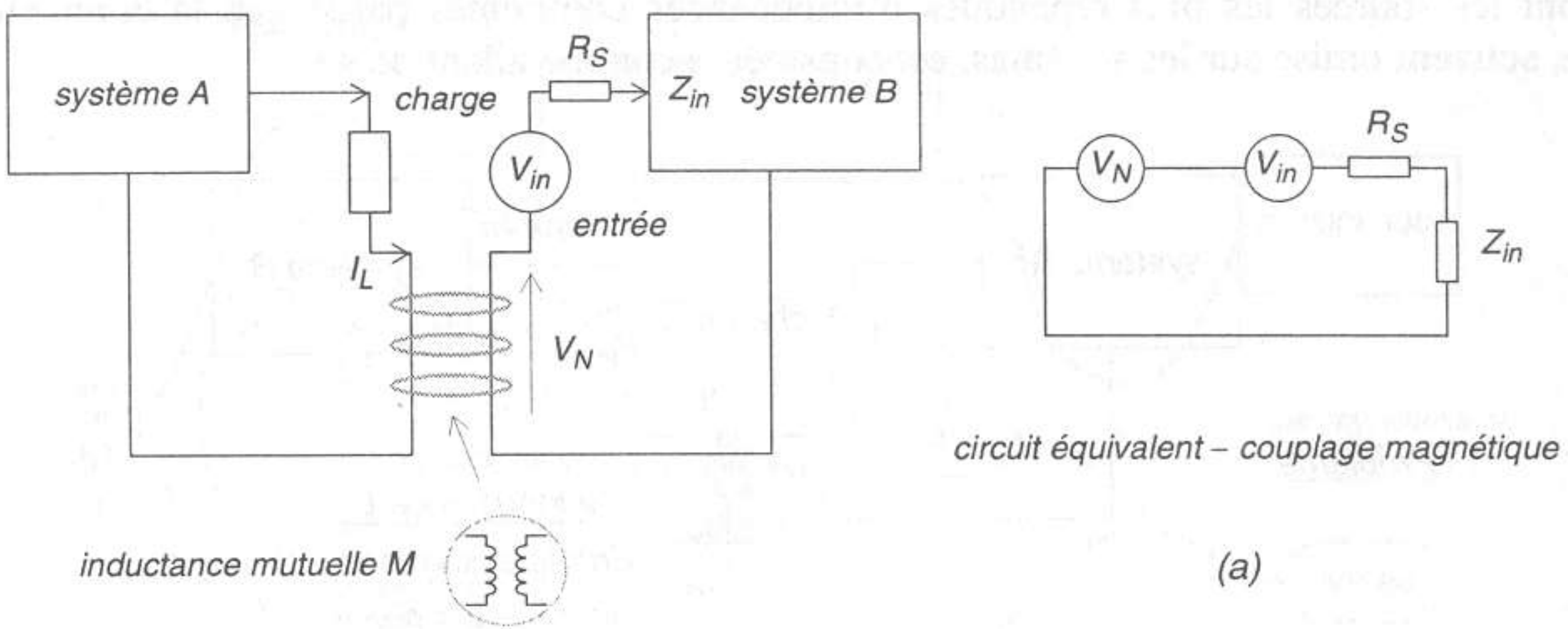
$\Delta i_s > B > i_p$



$V = L_2 di_2/dt + M di_1/dt$

Coupling modes (2)

B. Inductive Coupling

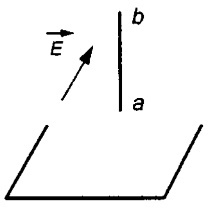


$$V_N = - M \times dI_L/dt$$

Coupling modes (2)

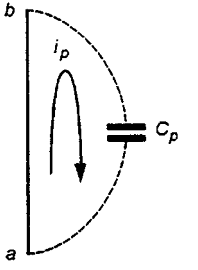
C. Capacitive Coupling

dU/dt > E electric field could couple with a nearby conductor and generate a voltage



Solutions:

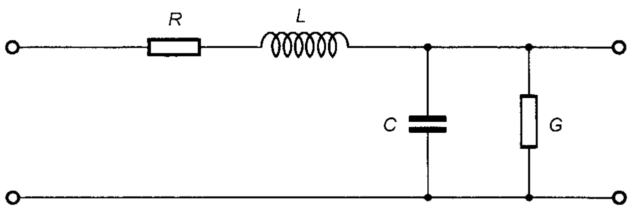
- source: to reduce dU/dt
- coupling: to increase distance

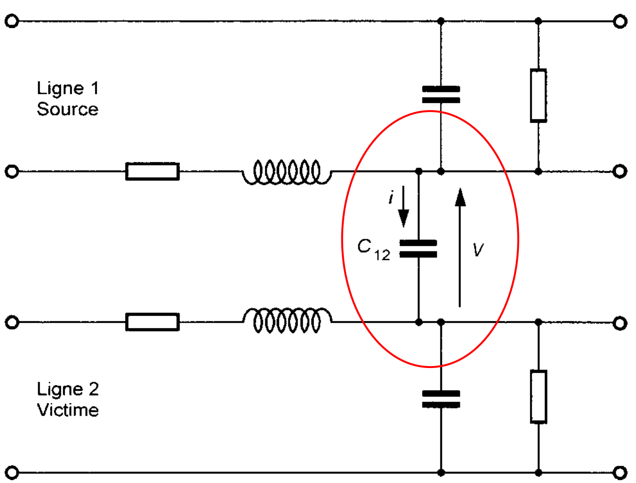


Coupling modes (2)

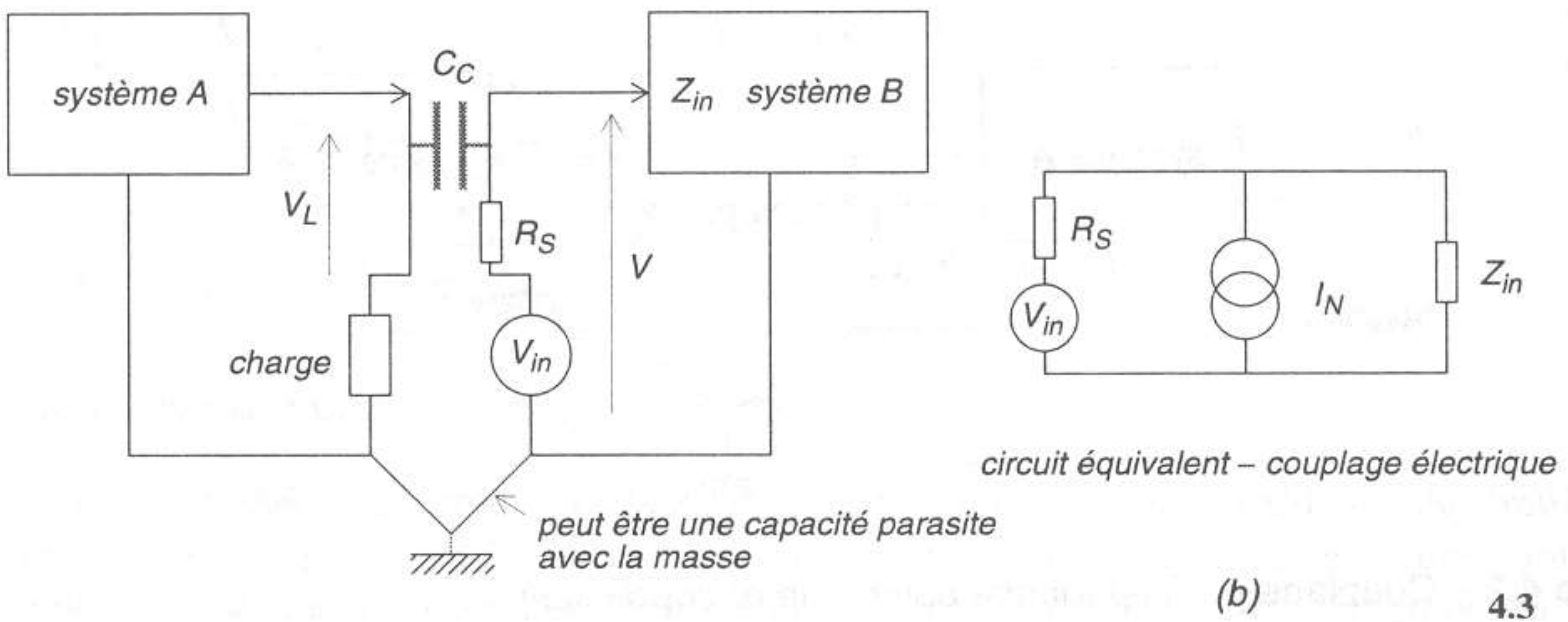
C. Capacitive Coupling

Capacitive diaphony





C. Capacitive Coupling

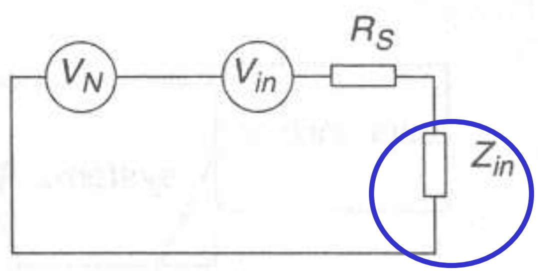


4.3

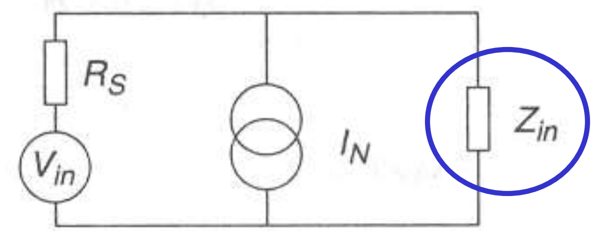
$$V = C_C \times dV_L/dt \times \underbrace{(Z_{in} // R_S)}_{\text{Impedance of victim circuit to ground}}$$

Coupling modes (2)

Input impedance?



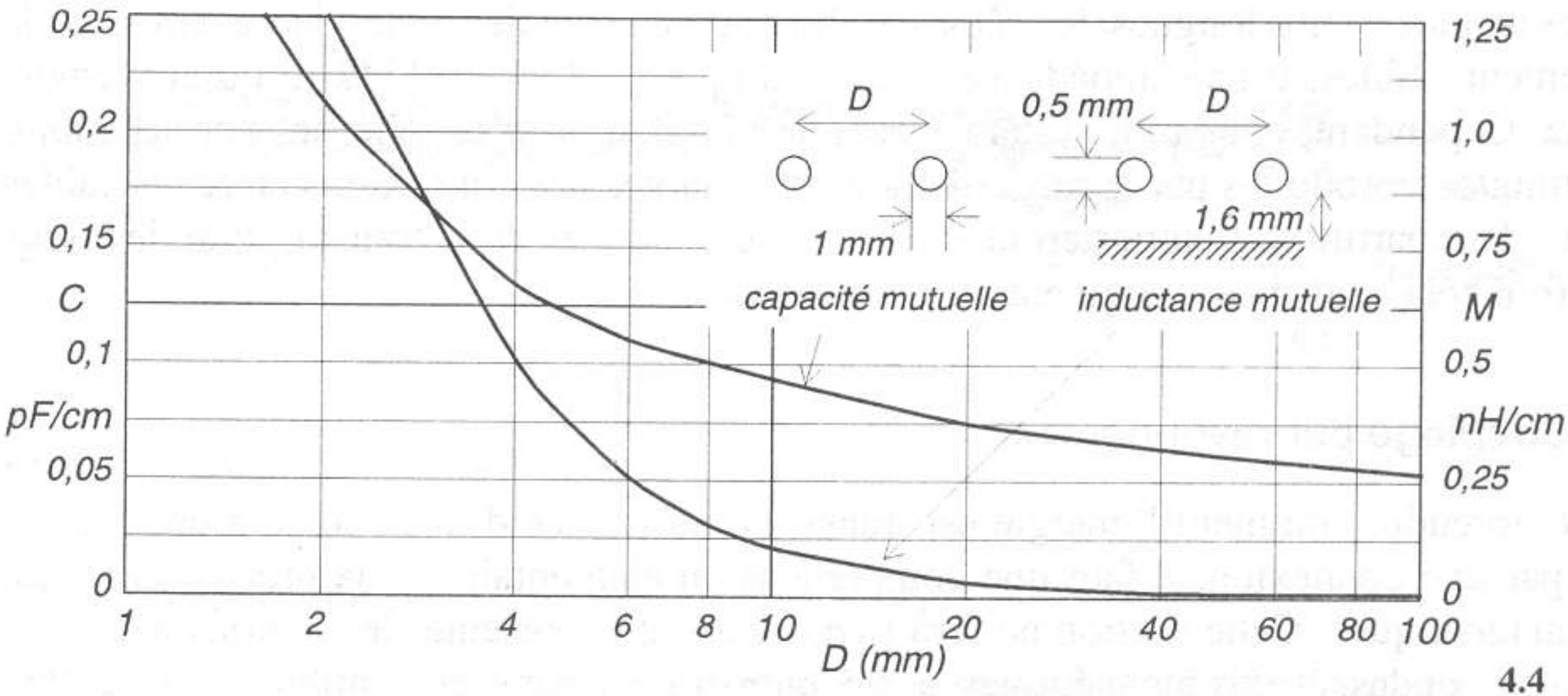
circuit équivalent – couplage magnétique



circuit équivalent – couplage électrique

Electric coupling *increases with* Z_{IN} growing whereas magnetic coupling *decreases*.
For the same reason, magnetic coupling is related to circuits with low input impedance as electric coupling to high input impedance.

Relationship distance - M and C



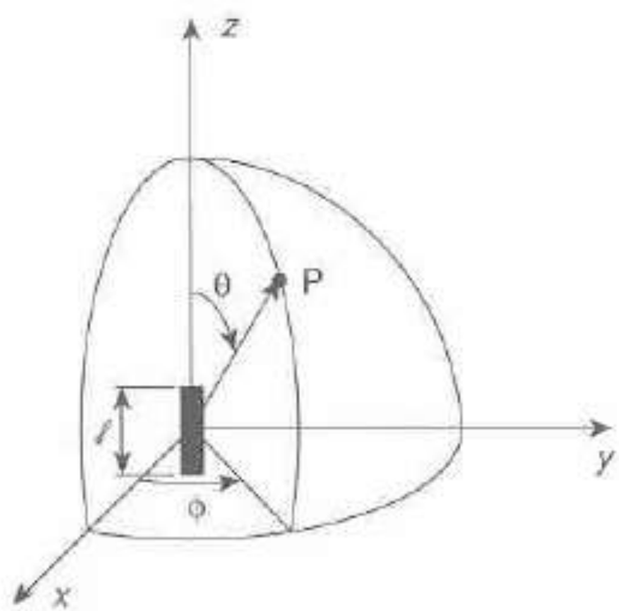
Coupling modes (2)

D. Radiated Coupling

- H-field (field to loop)
- E-field (field to conductor)

D. Radiated Coupling

1. Electromagnetic field of short electric dipole



Conductor length *l* with a current *I*o

l <<< λ of the field

So *I*o is constant on *l*

1. Electromagnetic field of short electric dipole

Electromagnetic fields (in spherical coordinates) is evaluated at an observation point P at a distance *r* from the origin:

$$E_r = \frac{Z_o}{2\pi}\frac{I_o l \cos\theta}{r^2}\left(1 + \frac{1}{jkr}\right)\exp(-jkr)$$

$$E_\theta = \frac{jZ_o k}{4\pi}\frac{I_o l \sin\theta}{r}\left(1 + \frac{1}{jkr} - \frac{1}{(kr)^2}\right)\exp(-jkr)$$

$$H_\phi = \frac{jk}{4\pi}\frac{I_o l \sin\theta}{r}\left(1 + \frac{1}{jkr}\right)\exp(-jkr)$$

où

$$k = 2\pi/\lambda = 2\pi f/c$$

$$Z_o = \sqrt{\mu/\varepsilon}$$

1. Electromagnetic field of short electric dipole

We have to consider 3 cases:

- $r \gg \lambda/(2\pi)$ or $kr \gg 1$

  far-field

- $r \ll \lambda/(2\pi)$ or $kr \ll 1$

  near-field

- $r \approx \lambda/(2\pi)$ or $kr \approx 1$

  intermediate zone

Far-field

For θ=0° , no electromagnetic wave,
consider θ=90° (maximum of radiation):

$$E_r = 0$$

$$E_\theta = \frac{jZ_o k}{4\pi} \frac{I_o l}{r} \exp(-jkr)$$

$$H_\phi = \frac{jk}{4\pi} \frac{I_o l}{r} \exp(-jkr)$$

Caracteristic Impedance

$$Z_w = \left| \frac{E_\theta}{H\phi} \right| = Z_o = \sqrt{\frac{\mu}{\varepsilon}}$$

Dans le vide,

$$Z_o = 120\pi \cong 377\ \Omega$$

1. Electromagnetic field of short electric dipole

Near-field

$$E_r = \frac{Z_o}{2\pi jk} \frac{I_o l \cos\theta}{r^3} \exp(-jkr)$$

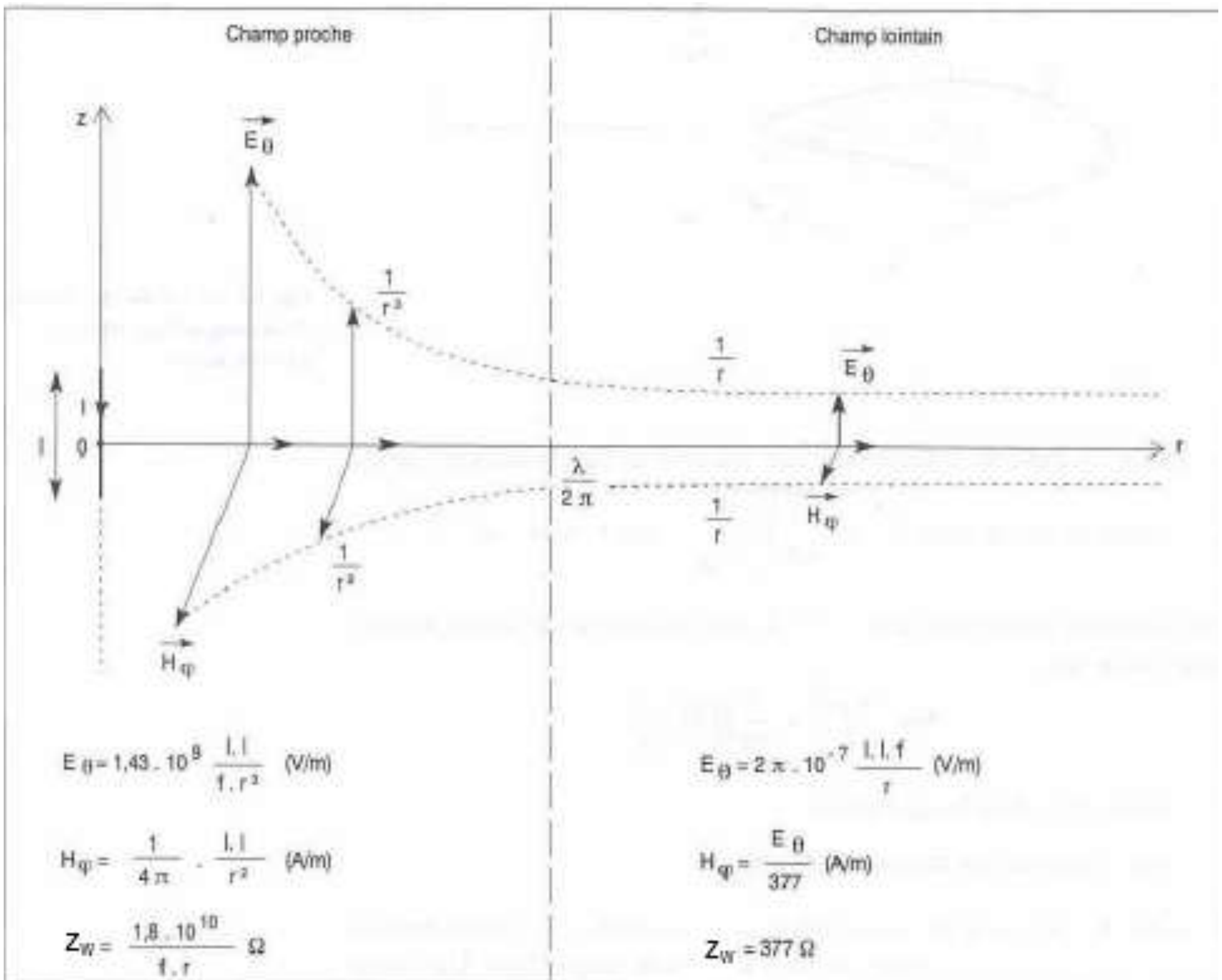
$$E_\theta = -\frac{jZ_o}{4\pi k} \frac{I_o l \sin\theta}{r^3} \exp(-jkr)$$

$$H_\phi = \frac{1}{4\pi} \frac{I_o l \sin\theta}{r^2} \exp(-jkr)$$

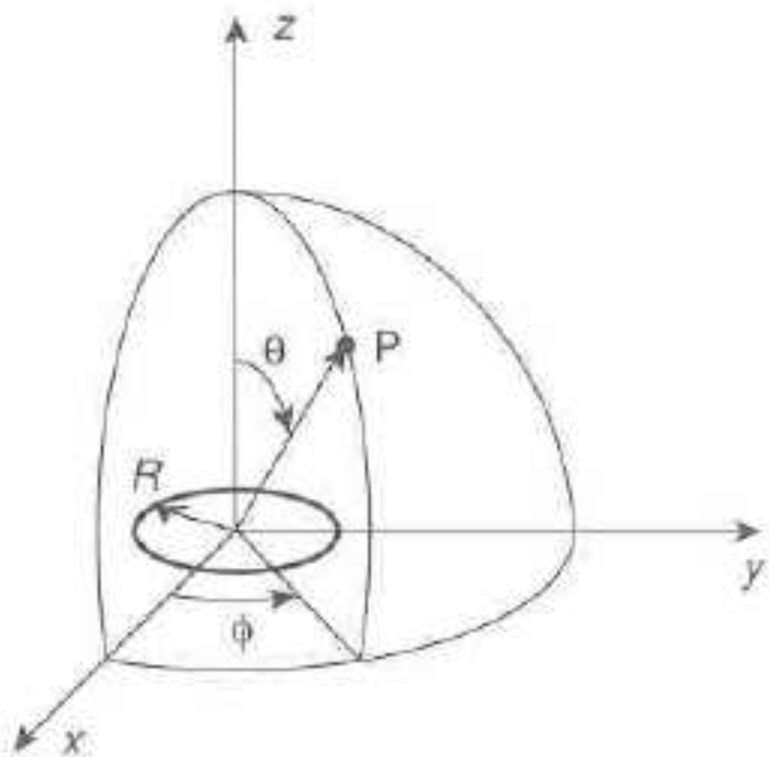
Caracteristic Impedance

$$Z_w = \left| \frac{E_\theta}{H_\phi} \right| = \frac{Z_o}{kr}$$

1. Electromagnetic field of short electric dipole



D. Radiated Coupling
2. Electromagnetic field of magnetic dipole



Consider a loop with *I*o

Electromagnetic fields (in spherical coordinates):

$$H_r = \frac{jk}{2\pi}\frac{\pi R^2 I_o \cos\theta}{r^2}\left(1+\frac{1}{jkr}\right)\exp(-jkr)$$

$$H_\theta = \frac{-k^2}{4\pi}\frac{\pi R^2 I_o \sin\theta}{r}\left(1+\frac{1}{jkr}-\frac{1}{(kr)^2}\right)\exp(-jkr)$$

$$E_\phi = \frac{Z_o k^2}{4\pi}\frac{\pi R^2 I_o \sin\theta}{r}\left(1+\frac{1}{jkr}\right)\exp(-jkr)$$

Far-field ($r >> \lambda/(2\pi)$)

For $\theta=90°$:

$$H_r = 0$$

$$H_\theta = \frac{-k^2}{4\pi}\frac{\pi R^2 I_o}{r}\exp(-jkr)$$

$$E_\phi = \frac{Z_o k^2}{4\pi}\frac{\pi R^2 I_o}{r}\exp(-jkr)$$

Caracteristic Impedance

$$Z_w = \left|\frac{E_\phi}{H_\theta}\right| = Z_o = \sqrt{\frac{\mu}{\varepsilon}}$$

Near-field ($r << \lambda/(2\pi)$)

$$H_r = \frac{1}{2\pi}\frac{\pi R^2 I_o \cos\theta}{r^3}\exp(-jkr)$$

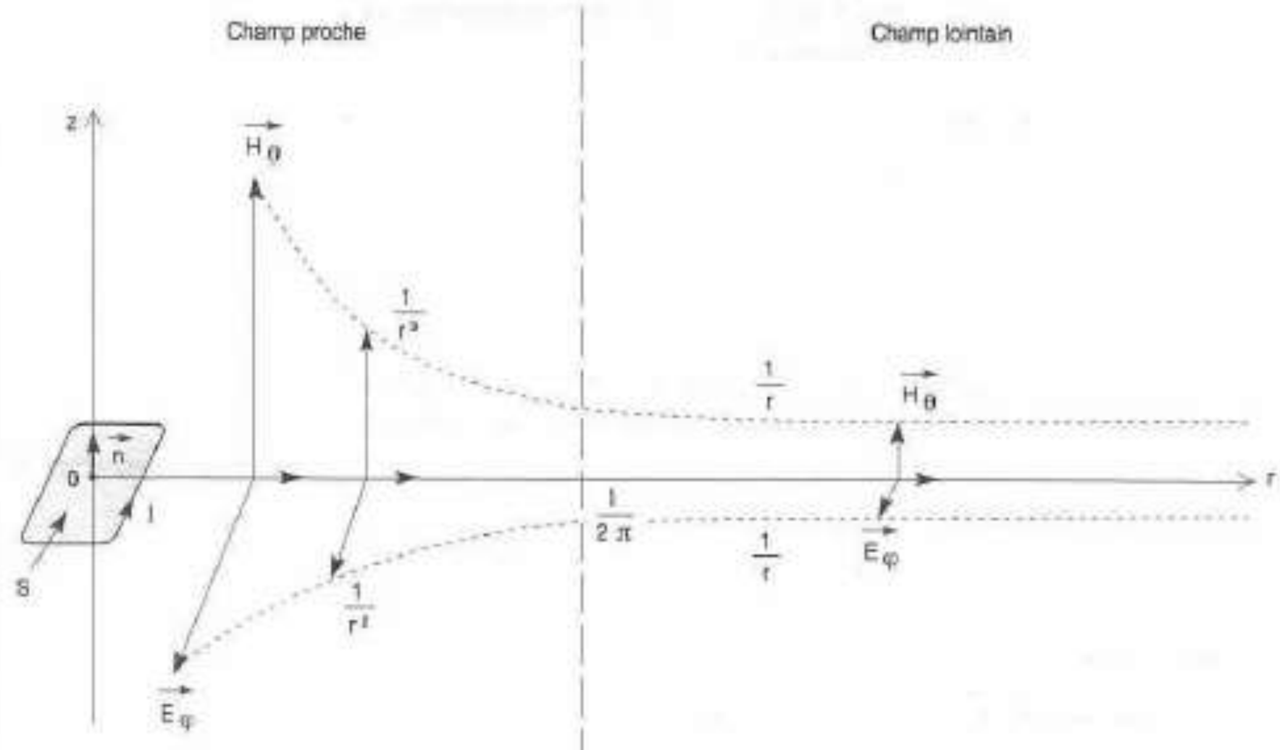
$$H_\theta = \frac{1}{4\pi}\frac{\pi R^2 I_o \sin\theta}{r^3}\exp(-jkr)$$

$$E_\phi = \frac{Z_o k}{4\pi}\frac{\pi R^2 I_o \sin\theta}{r^2}\exp(-jkr)$$

Caracteristic Impedance

$$Z_w = \left|\frac{E_\phi}{H_\theta}\right| = Z_o kr$$

2. Electromagnetic field of magnetic dipole



$$E_\varphi = 2\,\pi\,.10^{-7}\,\frac{I.S.f}{r^2}\ \text{(V/m)}$$

$$H_\theta = \frac{1}{4\pi}\cdot\frac{I.S}{r^3}\ \text{(A/m)}$$

$$Z_W = 7{,}89\,.\,10^{-6}.f.r$$

$$E_\varphi = 1{,}32\,.\,10^{-14}\,\frac{I.S.f^2}{r}\ \text{(V/m)}$$

$$H_\theta = \frac{E_\varphi}{377}\ \text{(A/m)}$$

$$Z_W = 377\ \Omega$$

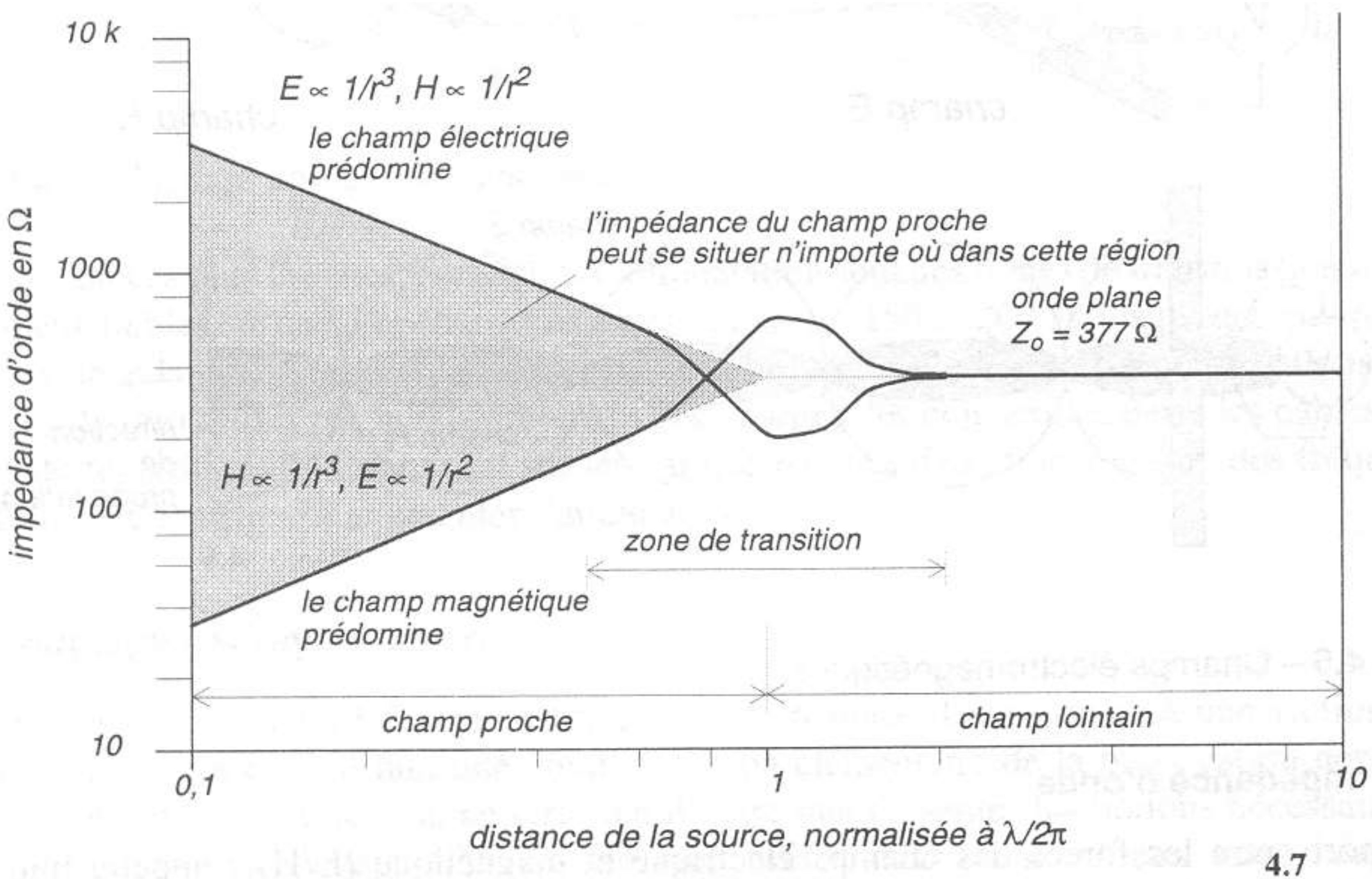
D. Radiated Coupling
Wave impedance of electromagnetic field

E/H is called wave impedance. It is an important parameter as it determines the coupling efficiency ot this wave with a structure, and the efficiency of a shielding structure.

In far-field ($r >> \lambda/2\pi$), plane wave, E and H are decreasing in the same proportion with distance.
Z is a constant and in air 377Ω.

In near-field ($r << \lambda/2\pi$), Z is determined by the characteristics of the source.

D. Radiated Coupling



D. Radiated Coupling
Far-field – near-field

Rayleigh criterion

This criterion is related to the radiating diagram of an antenna, too large to be considered as a ponctual source.
To consider a far-field condition as acceptable, it is needed that the phase shift of the components of the radiated field from the 2 ends of the antenna is small, regarding λ.
We have a criterion related to λ and maximum dimension D of antenna:

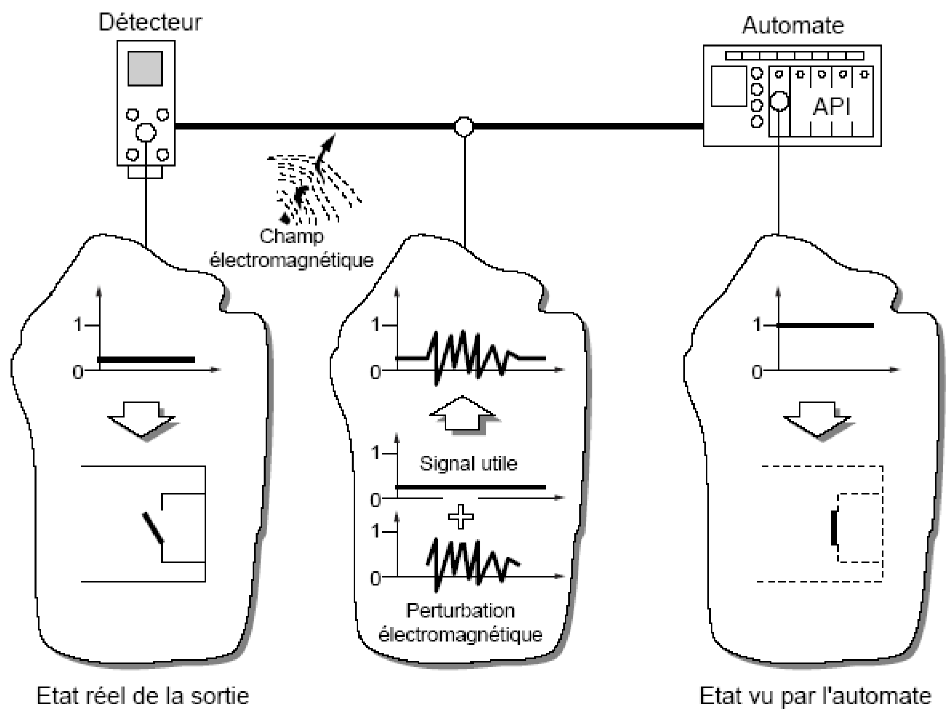
$$d >>> 2D^2/\lambda$$

Disturbances

Véronique Beauvois, Ir.
2020-2021

Definition of a disturbance

An electromagnetic phenomenon susceptible to degrade the performances of an apparatus or system.



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Types of disturbances - Classification

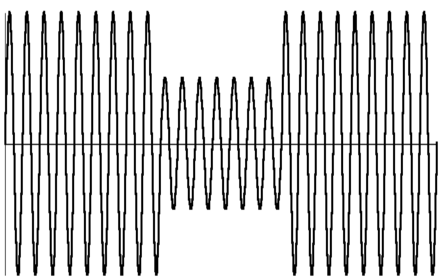
- frequency: L.F. / H.F.
- conducted / radiated
- narrowband / broadband
- duration (t): permanent, repetitive, transient, random
- common mode/differential mode

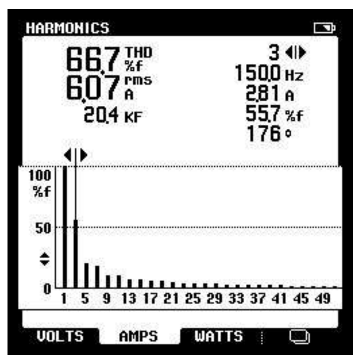
Types of disturbances - Classification

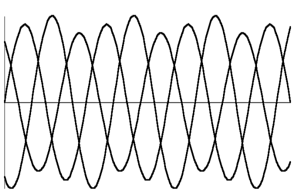
Frequency: L.F. / H.F.

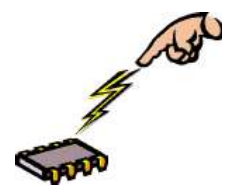
- 0≤f ≤…1 MHz
- conducted

- f > 30MHz
- radiated









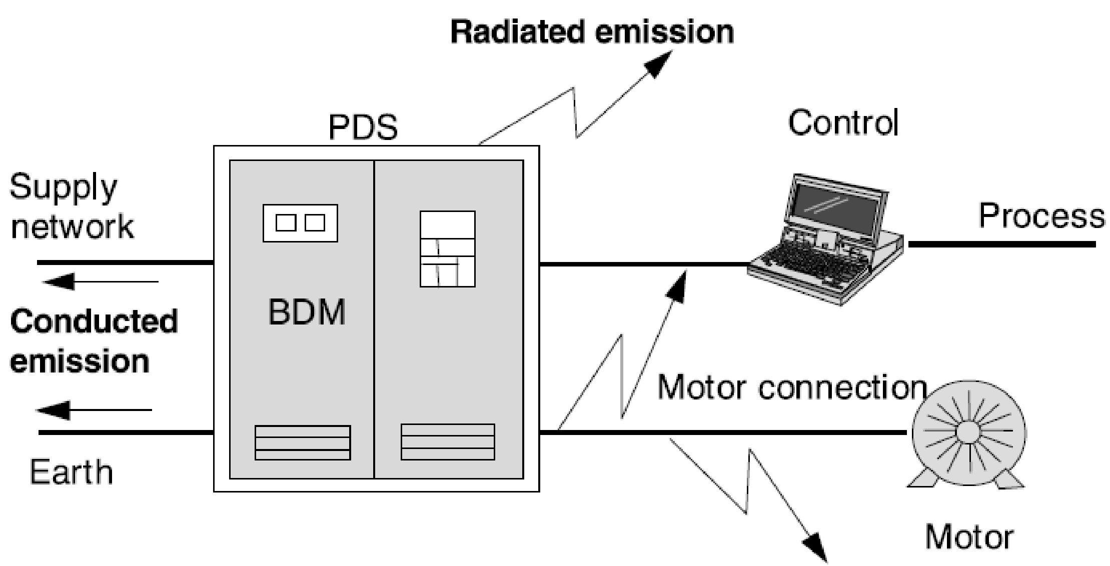
Types of disturbances - Classification

Conducted

Voltage/current

Radiated

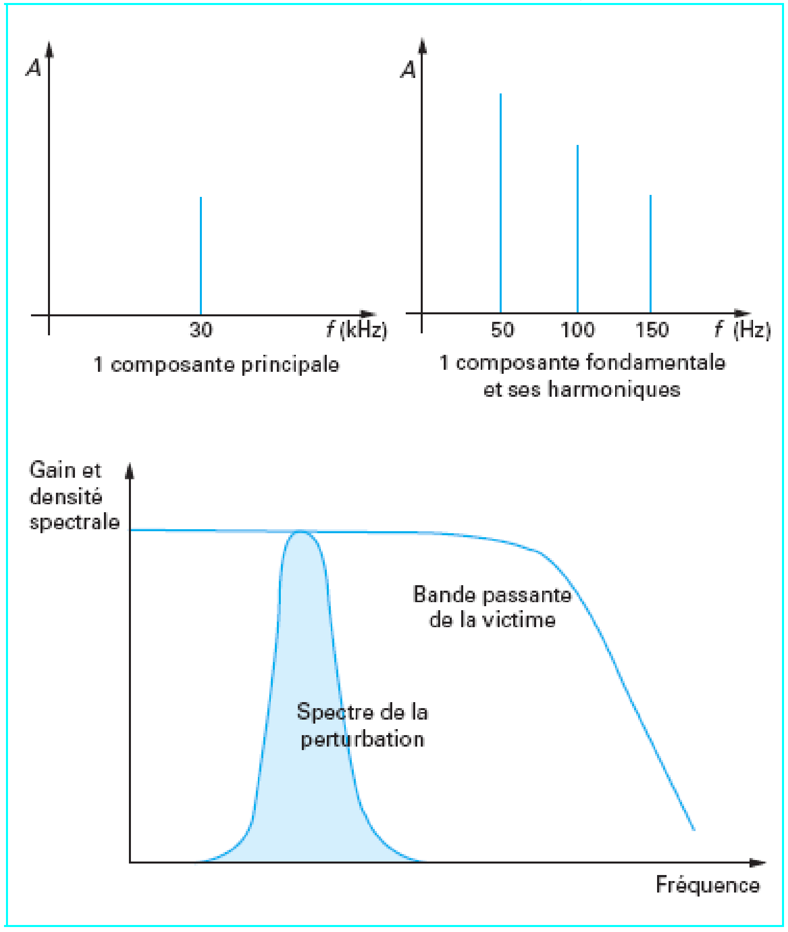
Electric/Magnetic fields

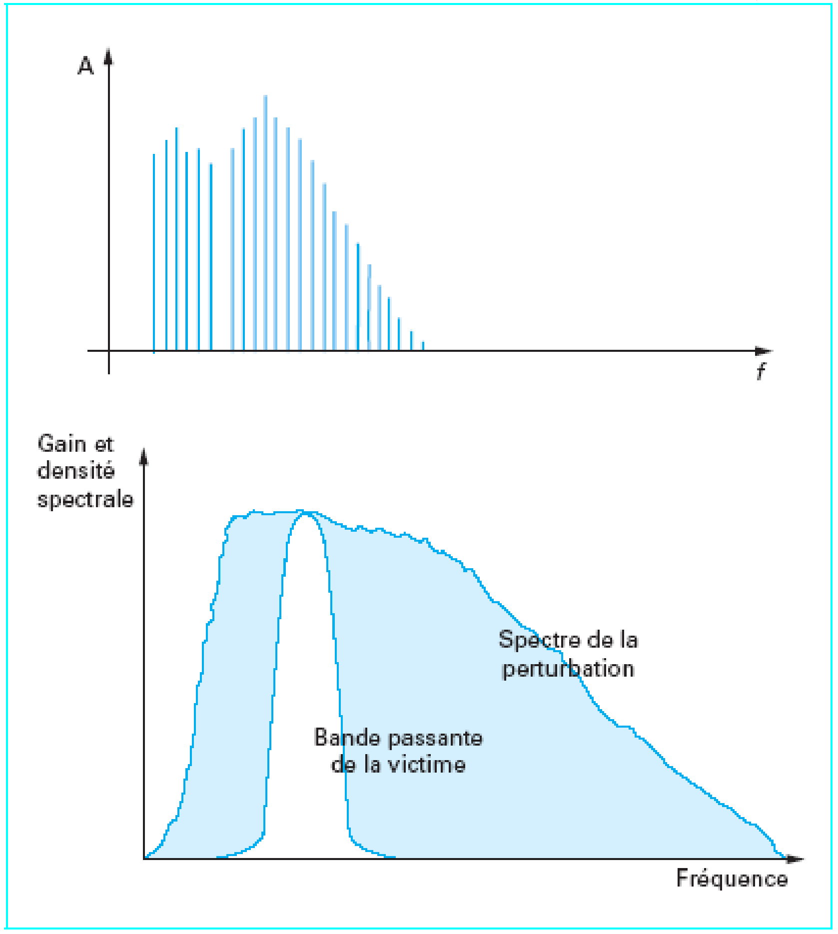


Types of disturbances - Classification

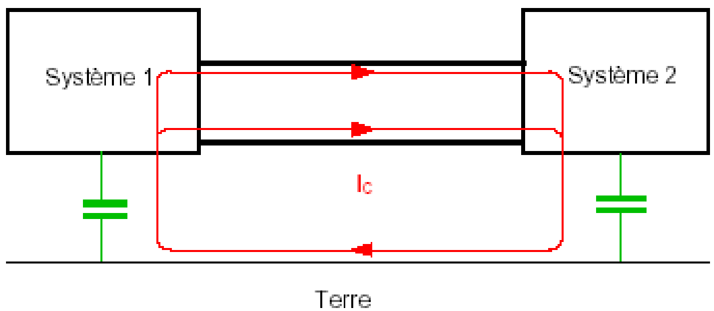
Narrowband (disturbance bandwidth < receiver's one)

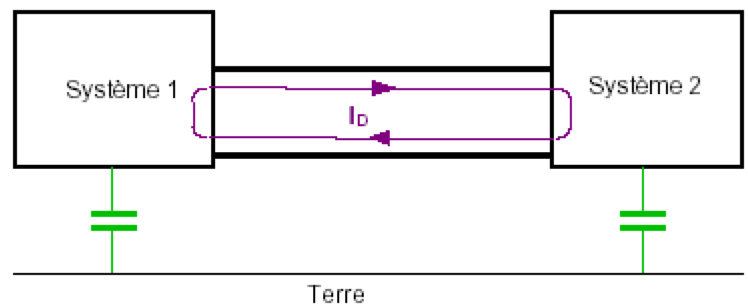
Broadband (disturbance bandwidth > receiver's one)





Common Mode – Differential Mode





Types of disturbances

- L.F. / conducted

  continuous:

  - quick variation of voltage (flicker)
  - (frequency variation)
  - harmonics
  - (interharmonics)

  transient:

  - voltage variations
  - dips and interruptions
  - slow overvoltages
  - lightning

Flicker

Power-line flicker is a visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply. The voltage drop is generated over the source impedance of the grid by the changing load current of an equipment (frequent starting of an elevator motor, air conditioning systems, arc furnaces, welding machines, …).

Effects in the band 0.5-25Hz.

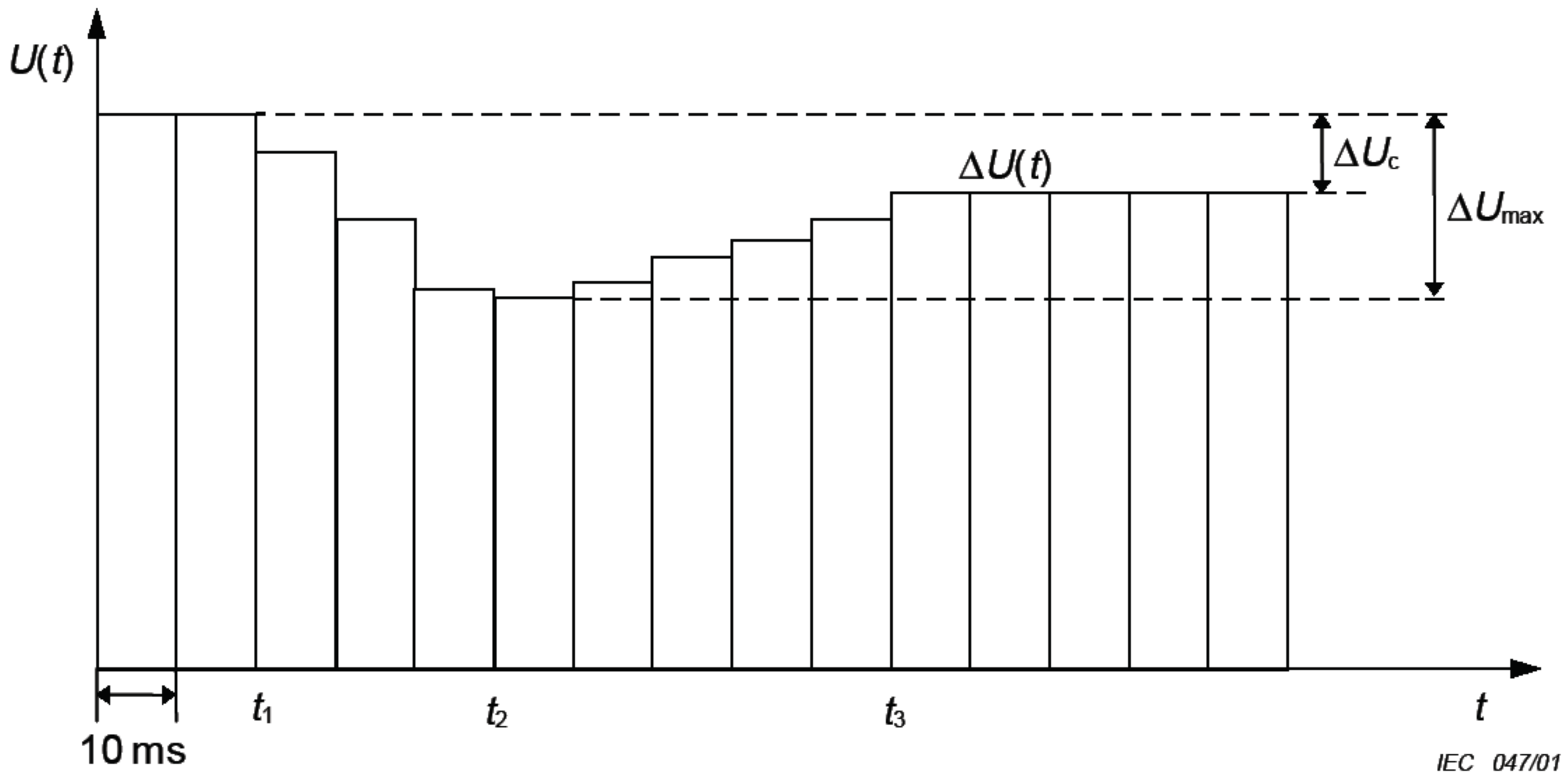
Major consequences on lamps.

Standards

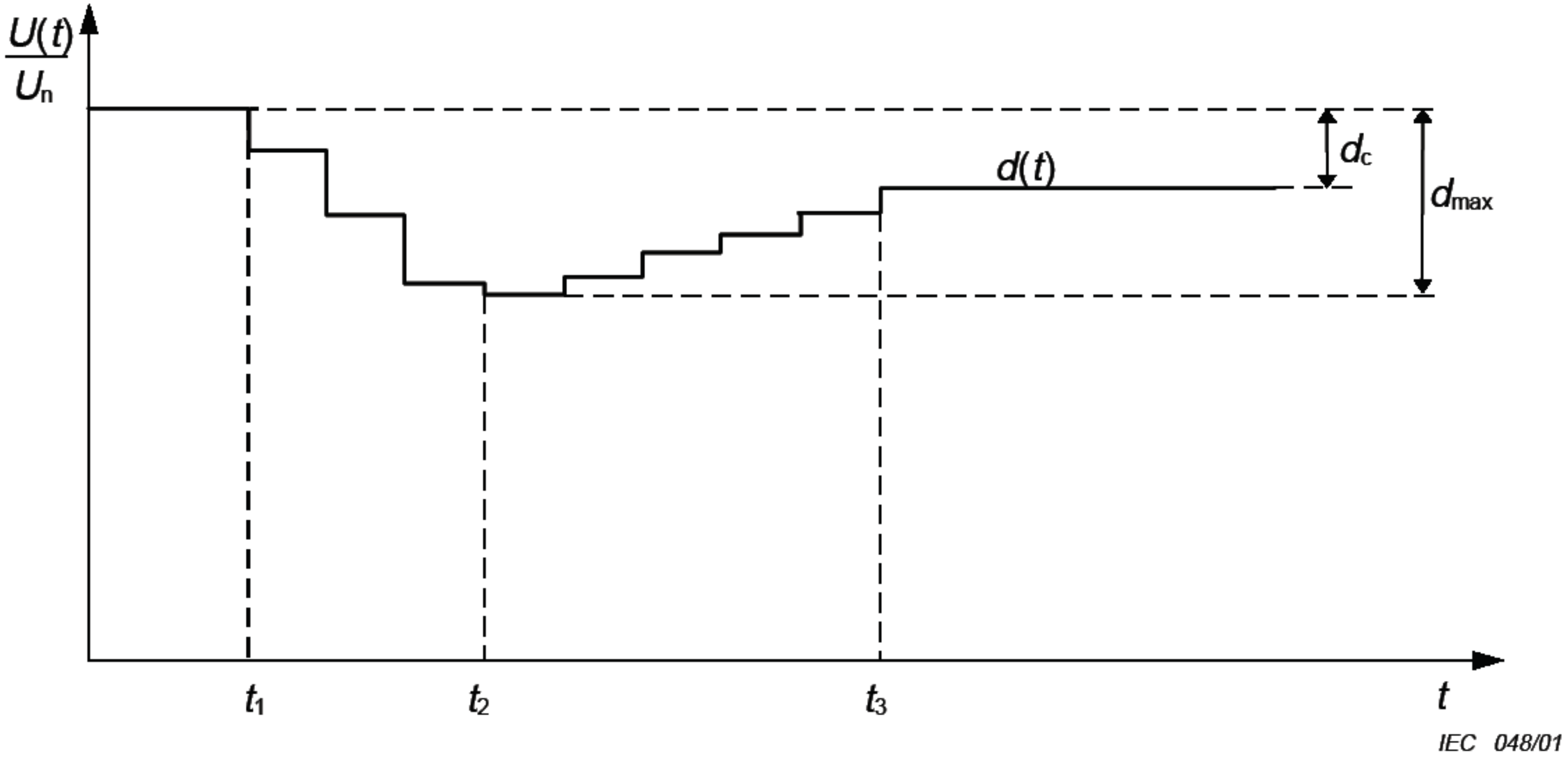
IEC/EN 61000-3-3 (I < 16A)

IEC/EN 61000-3-11 (16A < I < 75A)

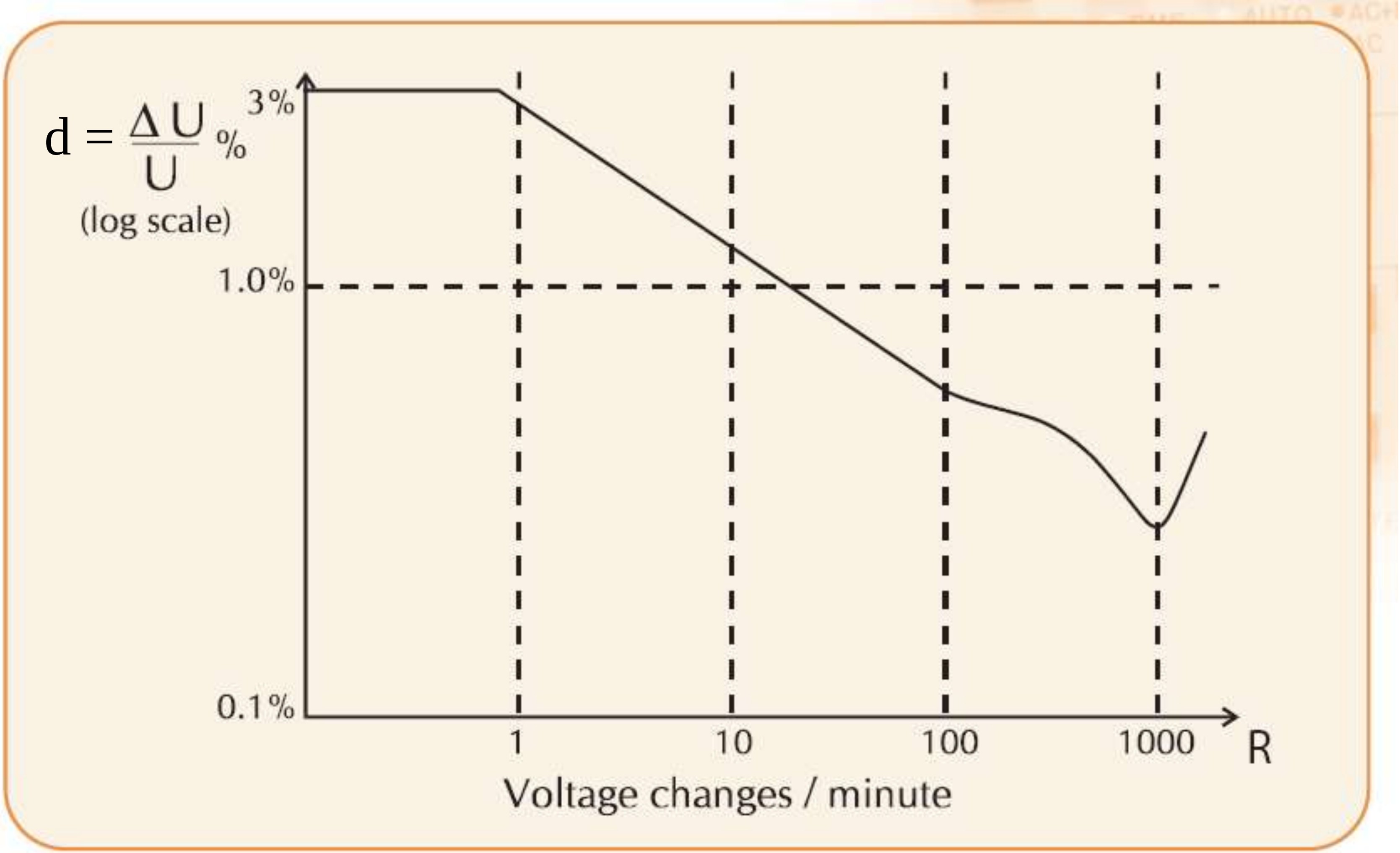
Flicker



Flicker



Flicker



$d = \frac{\Delta U}{U}$ %
(log scale)
3%
1.0%
0.1%
1
10
100
1000
R
Voltage changes / minute

Types of disturbances

- L.F. / conducted

  continuous:

  - quick variation of voltage (flicker)
  - (frequency variation)
  - harmonics
  - (interharmonics)

Rare with the network meshing

The origin of the phenomenon is related to the production of electric energy by a generating set with a not well regulated frequency, especially if the load changes frequently.
Electronic equipment shall support a frequency variations of +/- 4% measured during 10 minutes.
As the European grid is well meshed, its power is almost infinite, and frequency error is around 0.1%.

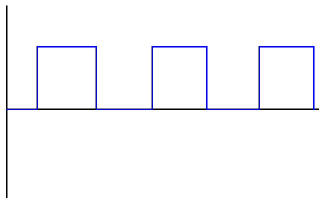
Types of disturbances

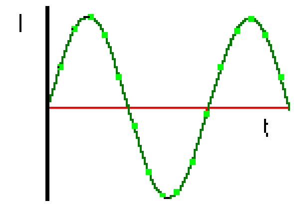
- L.F. / conducted

  continuous:

  - quick variation of voltage (flicker)
  - (frequency variations)
  - harmonics
  - (interharmonics)

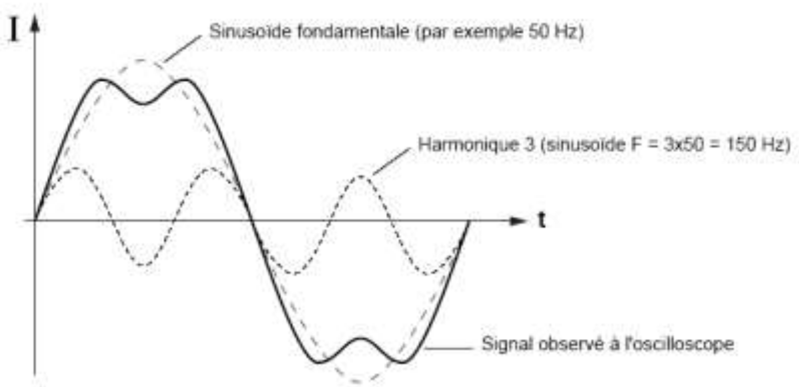
Harmonics

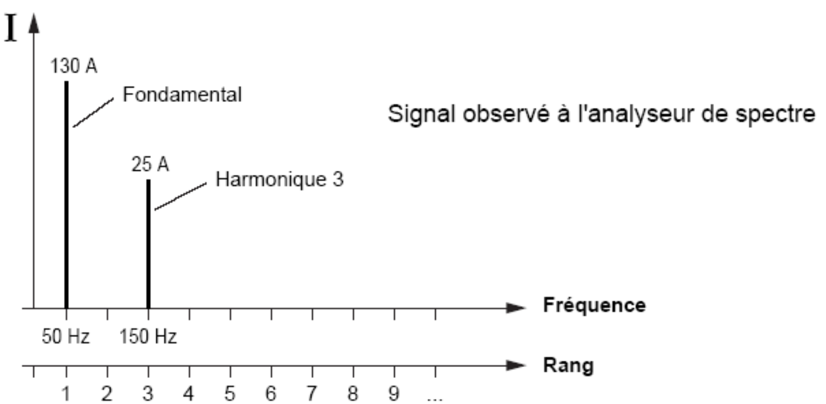




We have seen that a periodic signal could be represented by a sum of sinus with different amplitudes and phases, with frequency multiple integer of fundamental (frequency f).

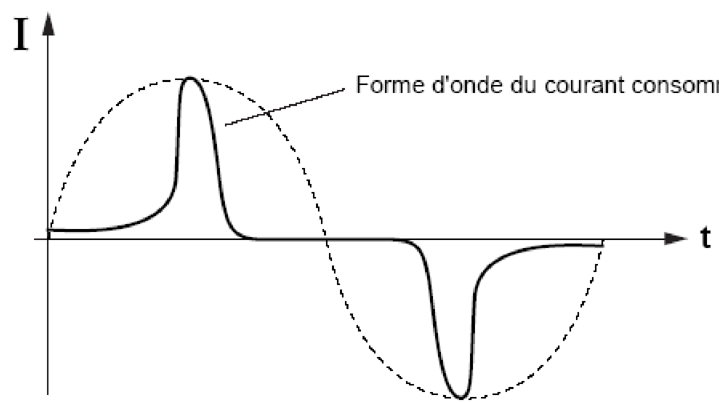
Harmonics.





Origin?

All non linear loads are associated with a non sinusoidal current and generates harmonics



Courant consommé par un tube fluorescent

Sources?

All non linear loads

- inverters, choppers, dc-dc converters
- rectifiers
- speed controllers
- frequency converters
- dimmers
- lighting
- Induction heating systems
- Saturated magnetic circuits
- …

Consequences?

Heating
Losses
Saturation
Additional torque components
Resonance (Q compensation capacitors)
Homopolar compenents (H3)
…

Types of disturbances

- L.F. / conducted

  continuous:

  - quick variation of voltage (flicker)
  - (frequency variation)
  - harmonics
  - (interharmonics)

Non integer multiples of the mains frequency.
Sources: static frequency converters for low speed applications, cycloconverters, ...
(e.g. cement crushers).
Harmonics $K.f_r \pm k.f_o$ (f_r mains frequency and f_o output frequency).

Types of disturbances

- L.F. / conducted
  transient:
  - voltage variations
  - dips and short interruptions
  - slow overvoltages
  - sinusoidal damped overvoltages
  - burst, lightning

Voltage variations: +6 to -10% with load variations (e.g. starting of powerful motors, arc furnaces, ...).
Dips: consequence of a network problem as a short-circuit. Parameters: voltage reduction in % of Un and duration (ms).
Short interruptions: interruptions with a duration less than 10 ms (half period).

Types of disturbances

- L.F. / conducted
  - transient:
    - voltage variations
    - dips and short interruptions
    - slow overvoltages
    - sinusoidal damped overvoltages
    - burst, lightning

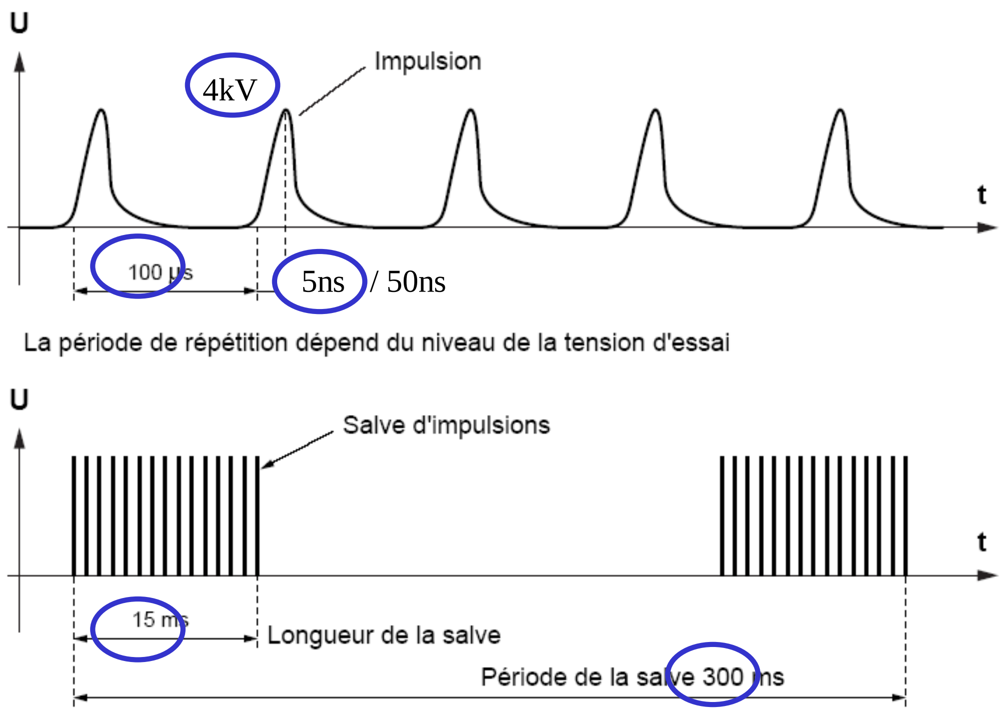
Slow overvoltages*: overvoltages dues to capacitors banks start up (Q reactive power compensation) or a fuse fusion.*

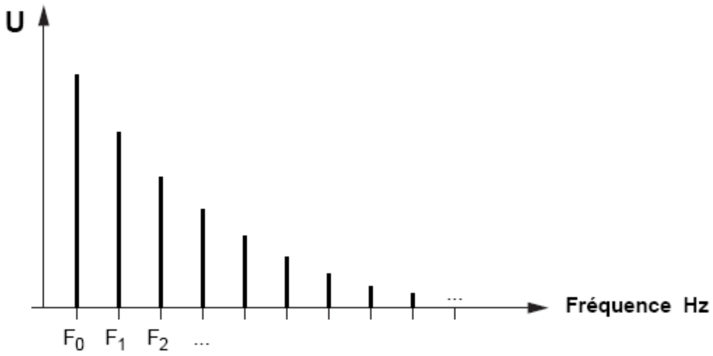
Sinusoidal damped overvoltages*: some maneuvers on the medium voltage network as an opening or closing of breakers, switches, isconnecting switches, … may cause a volatge variation which excites the line with a very short pulse with a short rise time and the consequence is a damped sinus (frequency between 10 kHz and 1 MHz).*

Types of disturbances

- en L.F. / conducted
  - transient:
    - voltage variations
    - dips and short interruptions
    - slow overvoltages
    - sinusoidal damped overvolatges
    - burst, lightning

Burst





0…200MHz…

Transient - Lightning

Lightning is a powerful sudden flow of electricity that occurs during an electric storm. The discharge will travel between the electrically charged regions within a thundercloud, or between a cloud and a cloud, or between a cloud and the surface of the planet. The charged regions within the atmosphere temporarily equalize themselves through a lightning flash, commonly referred to as a strike if it hits an object on the ground.
There are three primary types of lightning: from a cloud to itself (intra-cloud), from one cloud to another cloud and between a cloud and the ground.
Parameters: distance, current value, discharge shape.

Transient - Lightning

<u>Direct lightning</u>

If lightning current flows directly in the electrical circuit, creating voltages (according impedance of the circuits).

Consequences: insulation disruption (voltage), thermal destruction (current).

Not disturbances but destructive phenomena (dangerous for materials and human beings).

Protection: lightning arresters, shielding, overhead ground wires (the aim is to connect surge current to ground).

Transient - Lightning

Indirect phenomena

Even with protections to direct phanomena, some currents are flowing in electrical circuits > overvoltages (parameters: distance, di/dt, geometry of circuits)

Discharge shape

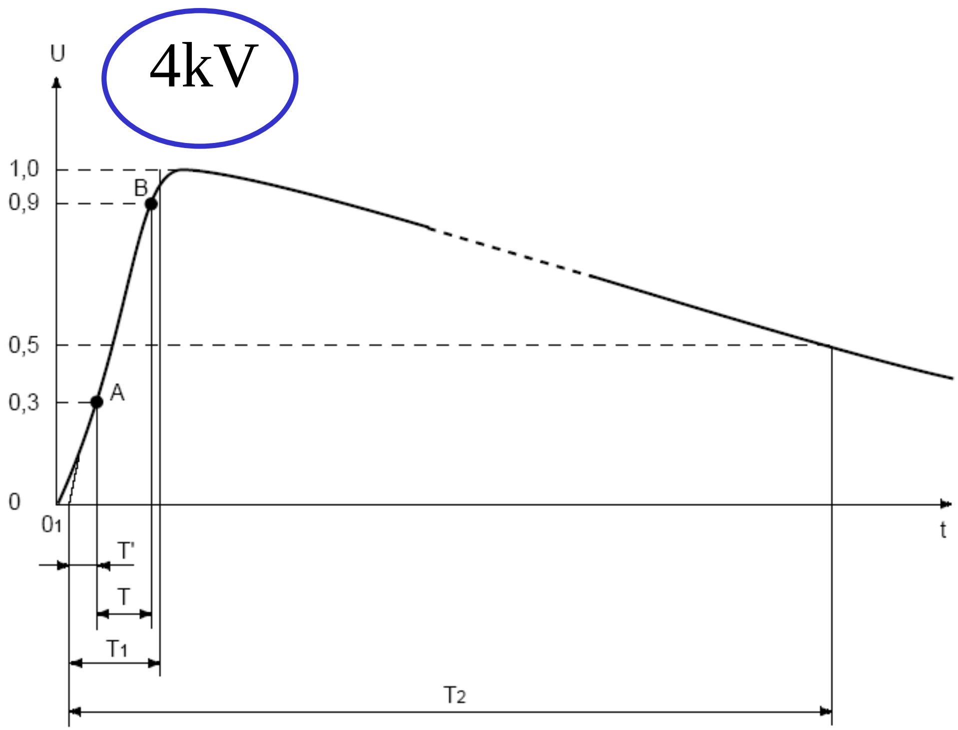
Unidirectional pulse, with very short rise time for negative discharges (10 to 20µs for the first, less than 1µs for the following ones) and a bit longer for positive discharges (around 20 - 50µs). Duration 10^2µs for negative discharges and 1000 to 2000µs for positive discharges.

Surge current: +/- 30kA for first arcing and 12kA for the followers.

Induced phenomena: vairable amplitude & shapes according to coupling modes, protection elements, capacitors, varistors, surge arrestors.

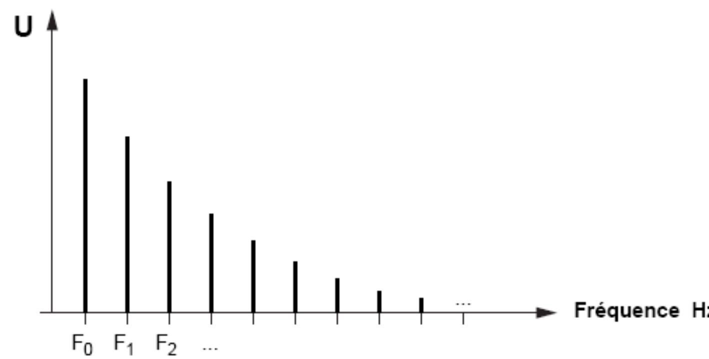
Transient - Lightning

Normalized waveshape
Voltage 1,2/50µs
Current 8/20µs



$T_1 = 1,67\ T$
$T' = 0,3\ T_1 = 0,5\ T$

$T_1 = 1,2\ \mu s$ $T_2 = 50\ \mu s$



0…100MHz…

Types of disturbances

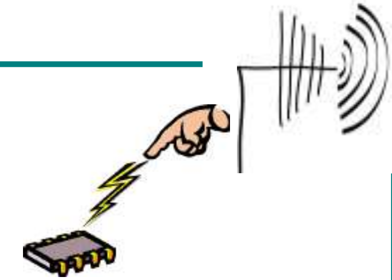
- H.F. / **conducted**

  continuous

  - Common mode current of static converters
  - Power line communications

  transient

  - inductive circuits commutation
  - lightning
  - electrostatic discharges



Origin?

<u>Static electricity</u>

Electricity comes from *elektron* which means *amber*, which charge by friction.

In nature: atoms = electrons + protons + neutrons = electrically neutrals.

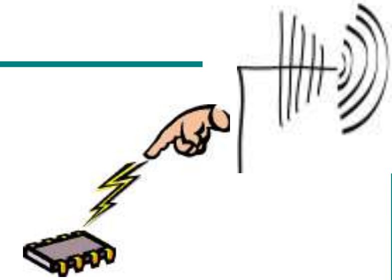
When you rub certain materials together, superficial electrons are pull out (e.g. silk on a glass tube, a balloon on your hair).

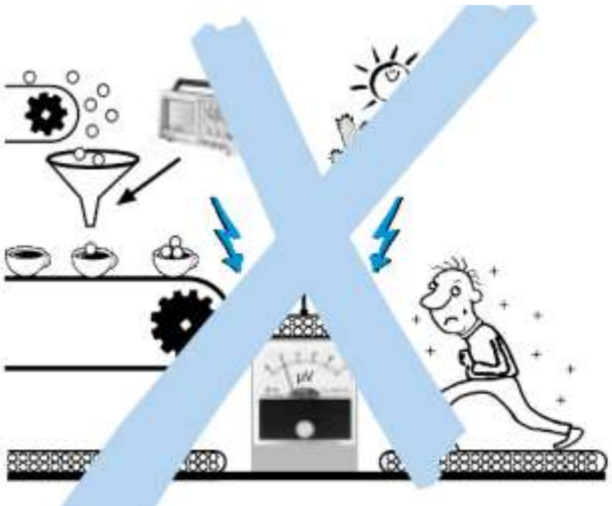
Accumulation of charges by *triboelectricity*.

Static electricity: the charges could not move, they are trapped in the insulating materials.

- Positive effects: some industrial applications as painting deposits on a material
- Negative effects: Hindenburg dirigible (1937).

Electrostatic Discharges





Sources?

- a person walking on a synthetic floor (carpet)
- paper on band
- belt conveyor
- liquid or gas in an isolated tube (nozzle e.g.)

With accumulation, a difference of potential exists between a loaded body adn the nearby ground.
Neutralisation happens with :
-either through a slow and dissipative flow,
-either through a quick arcing, called electrostatic discharge.

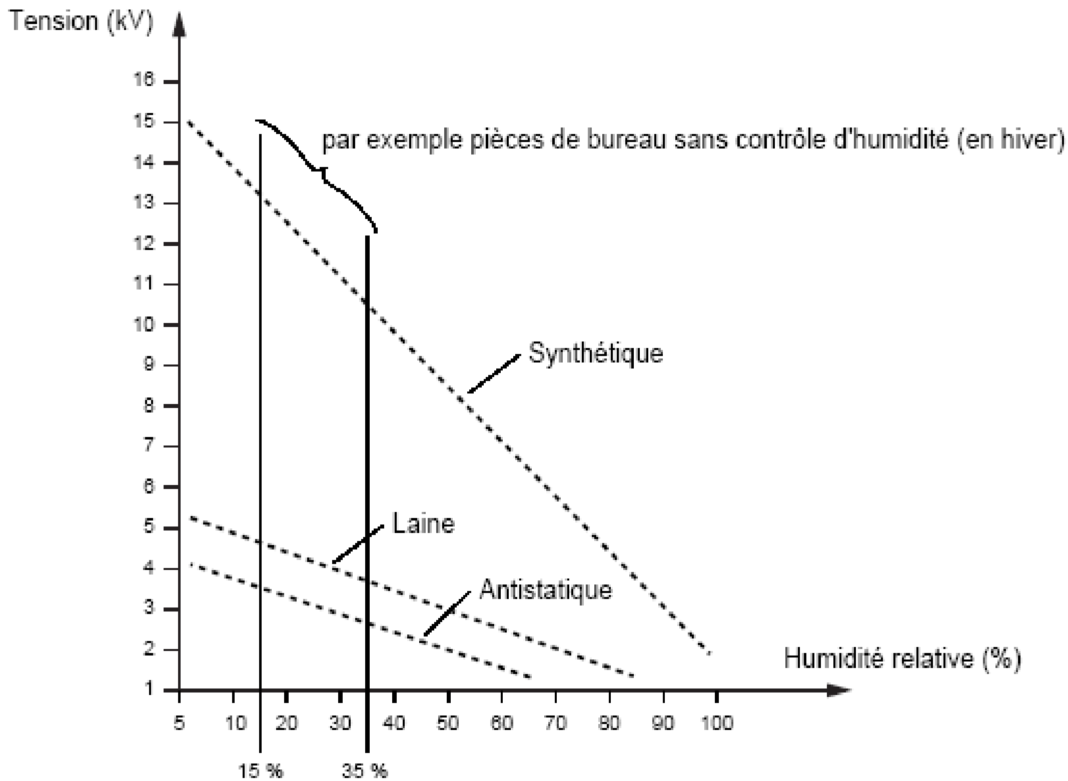
Electrostatic Discharges

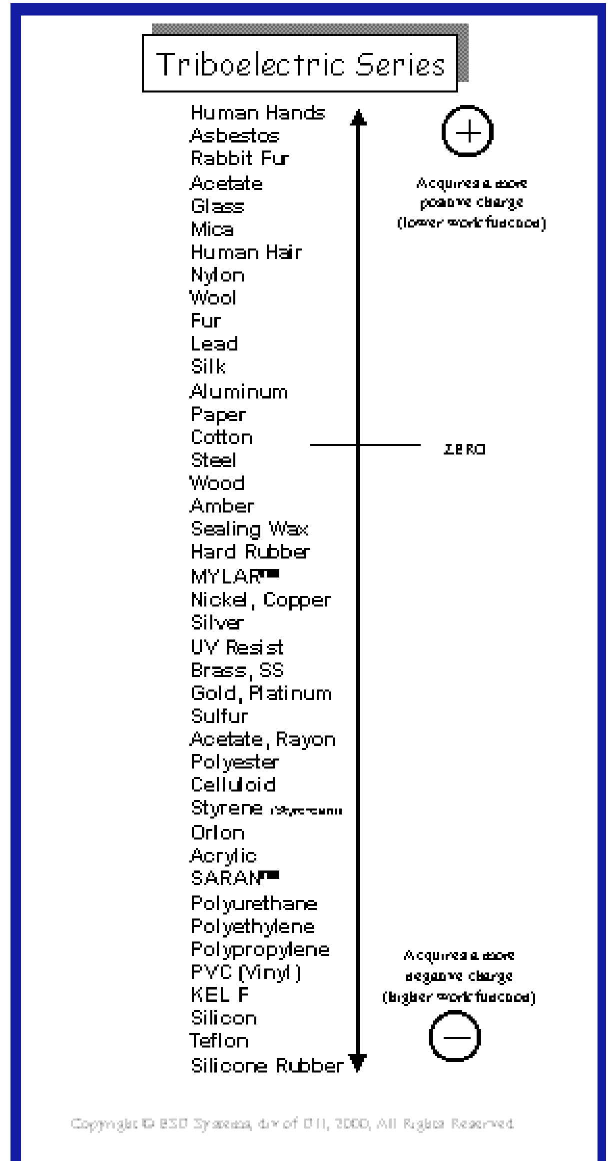
Important parameters?

• nature of the material (triboelectric series)

• relative humidity

• temperature

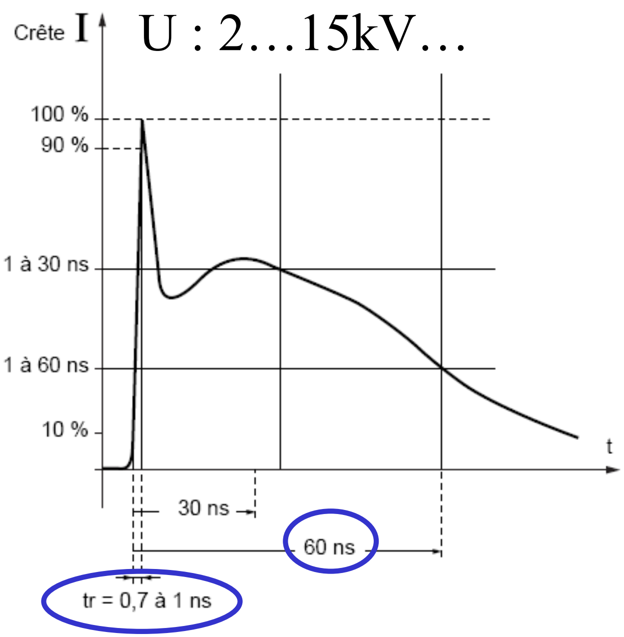


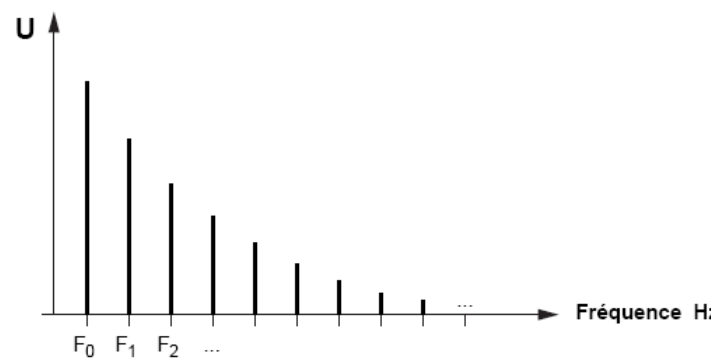


Electrostatic Discharges

Current pulse through an object, with a (direct or indurect) contact of this object to the ground, with another object at a high level electrical potential regarding the ground.

U : 2…15kV…





0…1000MHz…