

Conducted Emissions and Susceptibility

Prof. Victoria Shao

Outline

- Measurement of conducted emission
 - The line impedance stabilization network(LISN)
 - Common and Differential-Mode Currents
- Power supply filters
- A Generic Power Supply Filter Topology
 - Differential mode and common mode
- Conducted Emission: Line Filter Design
- Power Supplies
- Conducted Immunity



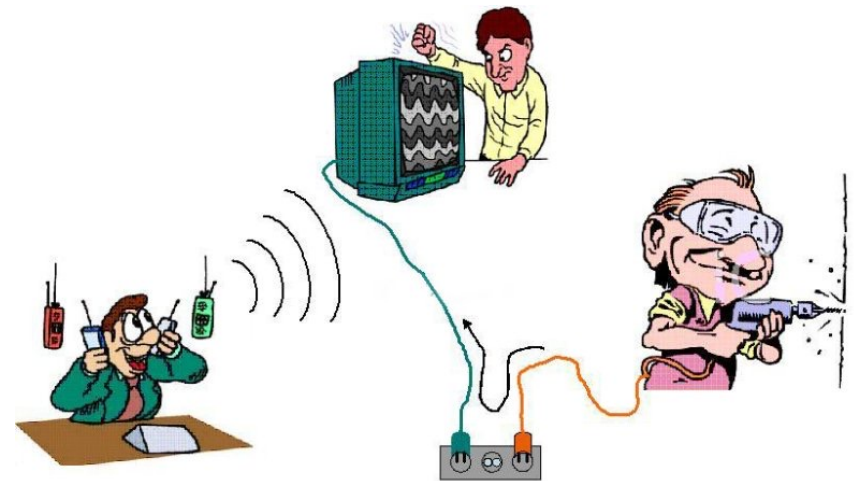
Conducted Emissions and Susceptibility

Conducted Emission

Conducted emissions are electromagnetic emissions propagated along a power or signal conductor, creating noise. The noise is subsequently transferred to the equipment.

Conducted Susceptibility

The conducted susceptibility is performed to determine a device's ability to operate in the presence of an external interference signal propagated via a conductor



- ❖ Susceptibility = A product must be reasonably insensitive to disturbances that are present on the power system net in order to insure reliable operation of the product.

Poll

Conducted interference CAN'T enter electronic devices primarily through which?

- A. Input Signal lines
- B. Overhead lighting
- C. Output signal lines
- D. Electrical power cords



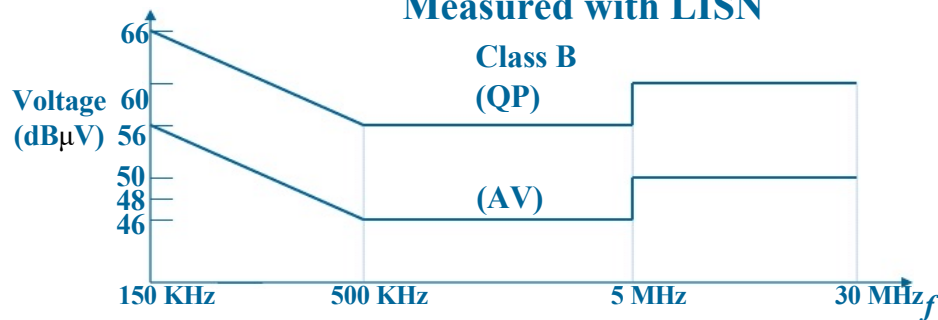
6.1 Measurement of conducted emission

FCC Part 15 150KHz ~ 30MHz United States
CISPR 22 150KHz ~ 30MHz EU countries

Conducted Emission: Regulation

FCC and CISPR 22 conducted emission limits

Measured with LISN

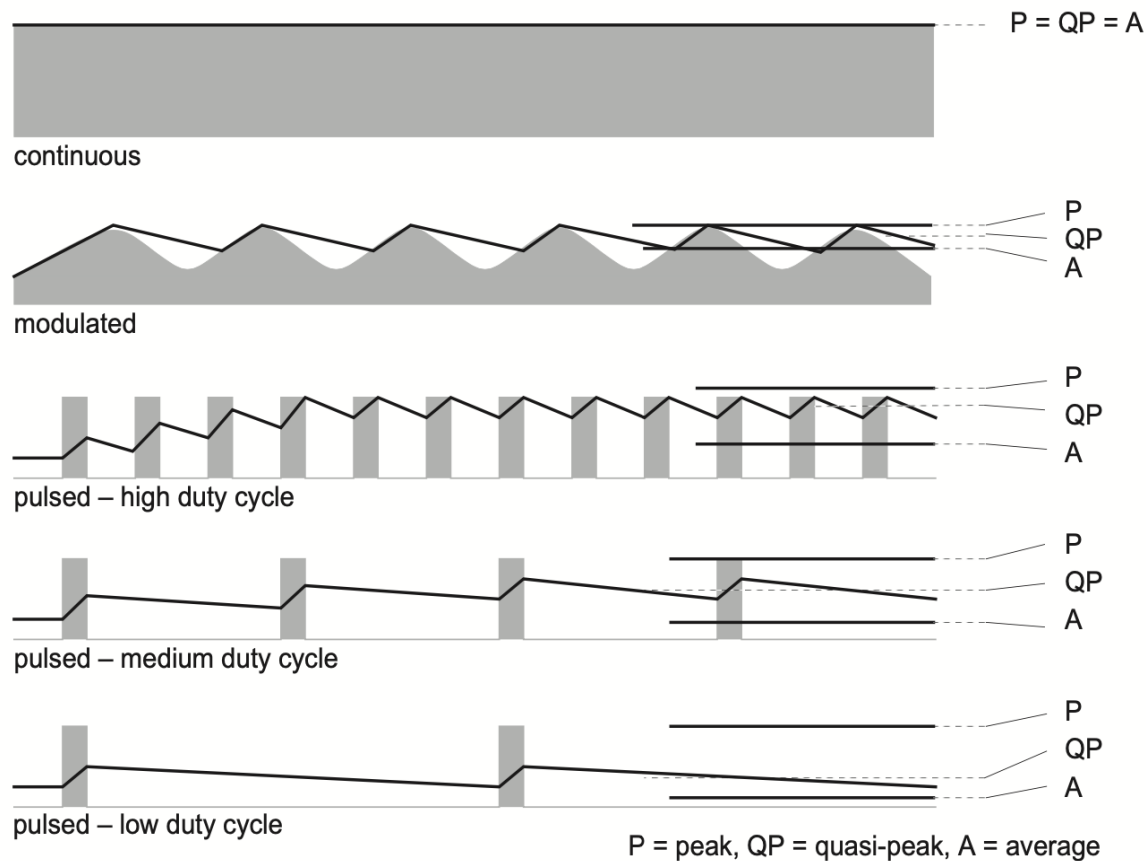


QP: Quasi – peak
AV: Average

Field strength limits for conducted emissions per FCC Part 15 regulation and CISPR 22 regulation

FCC Class B Conducted EMI Limit CISPR Class B Conducted EMI Limit for LTE products		
Frequency range MHz	Limits	
	Quasi – peak Limits (dBμV)	Average Limit (dBμV)
0.15 to 0.5	66 to 56 *	56 to 46*
0.5 to 5	56	46
5 to 30	60	50
* The limit decreases linearly with the logarithm of the frequency in the range 150 kHz to 0.5 MHz		

EMI emission testing: Peak, Quasi-peak, and average measurement



Poll

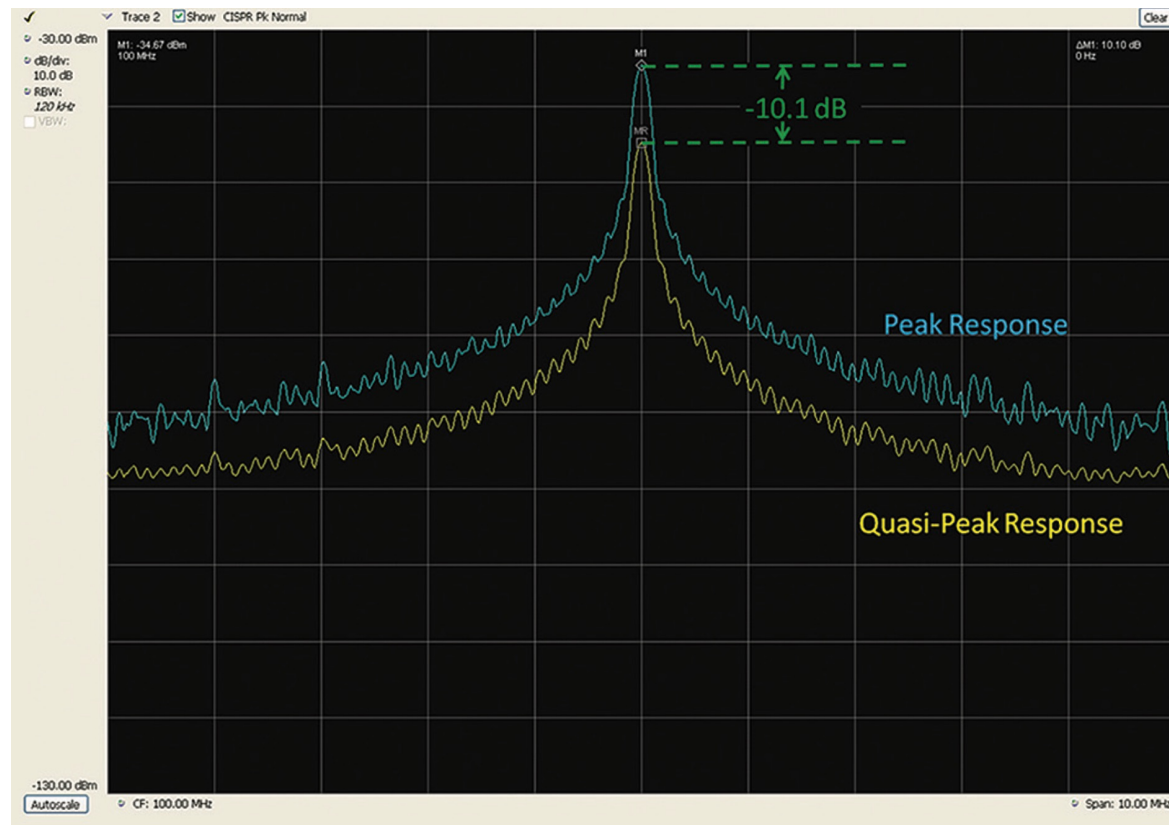
Quasi-peak values are always

- A. Equal-to or less-than peak values
- B. Equal-to or less-than average values
- C. Equal-to or greater-than peak values
- D. None of the above

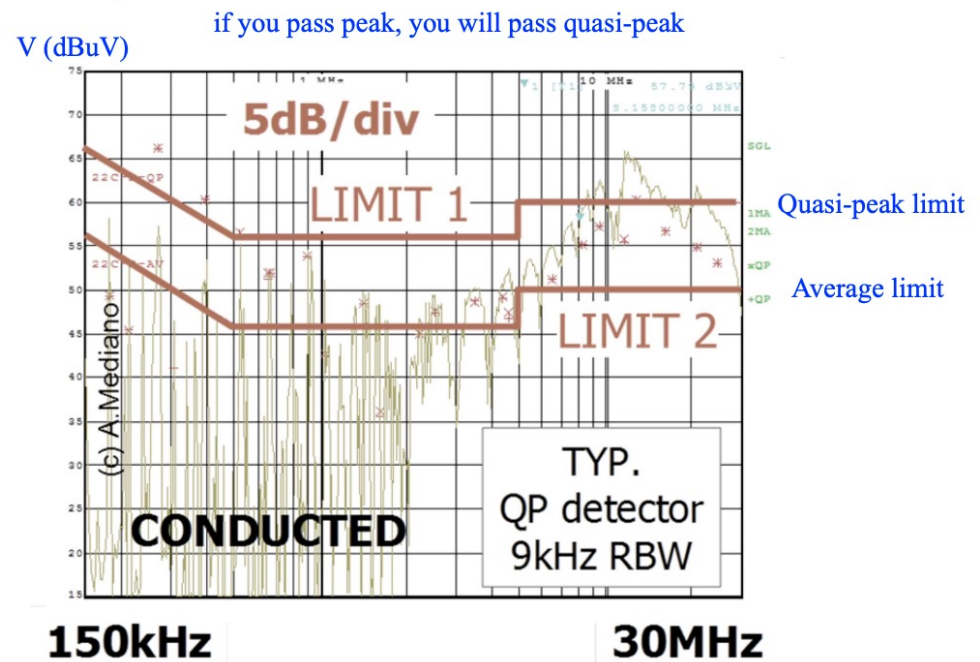


Example of peak and QP detection

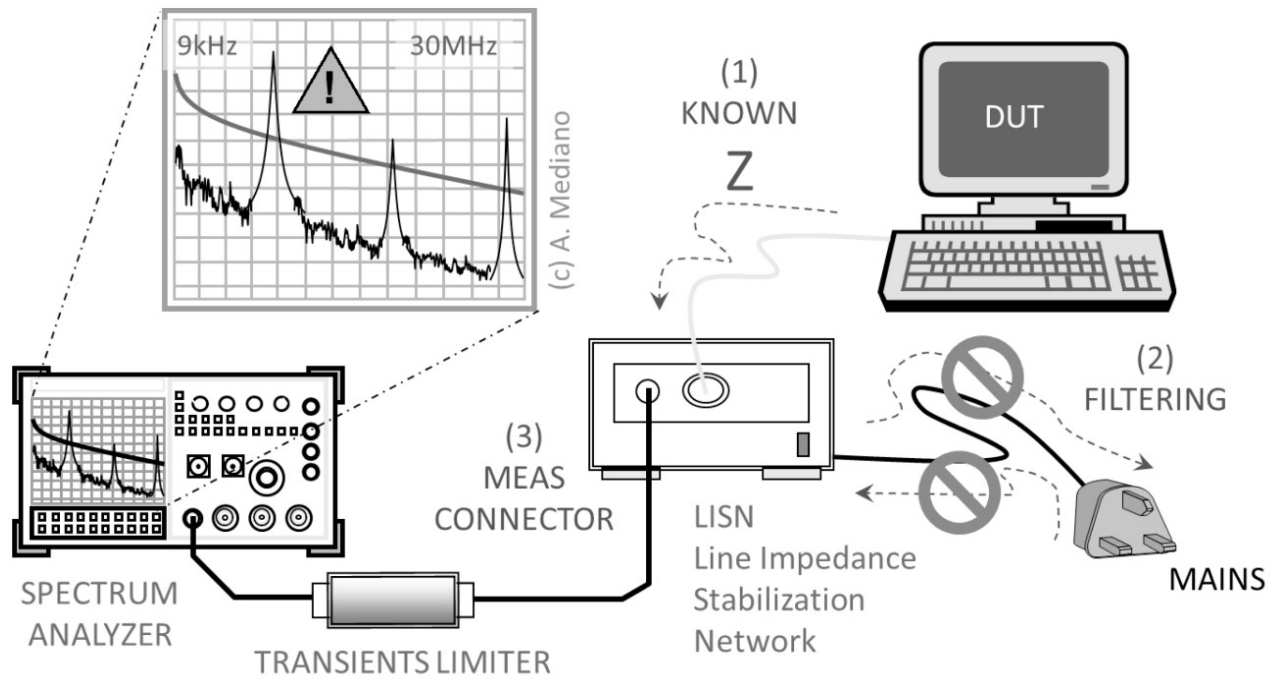
Emission from a signal with an 8 μ s pulse width and 10 ms repetition rate



Conducted Emission Test Example

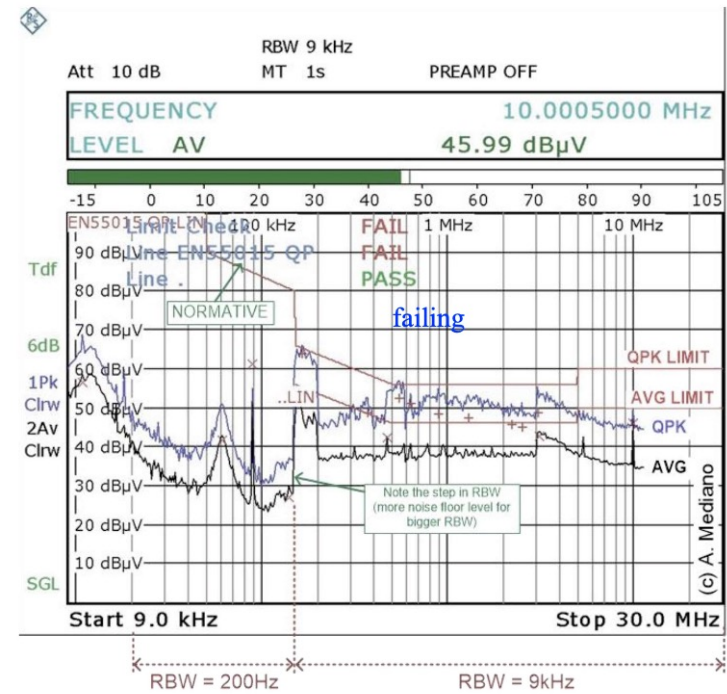
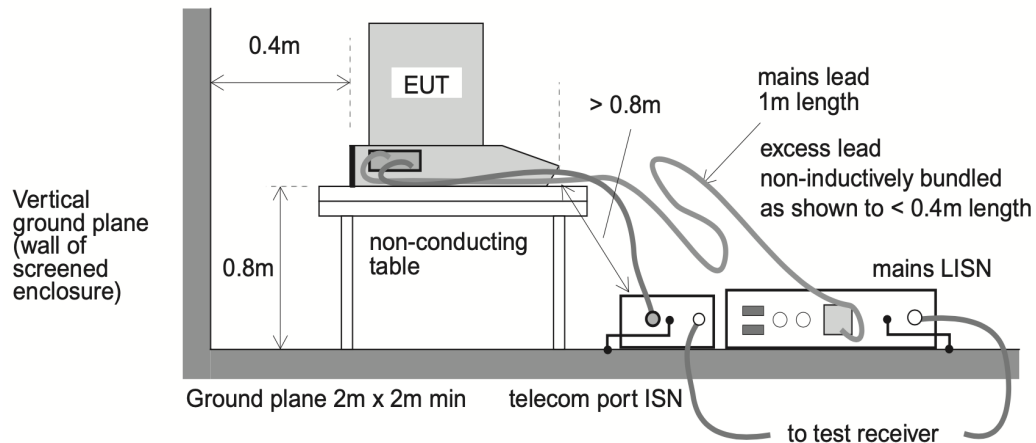


Conducted Emission Test Example



Conducted Emission Test Example

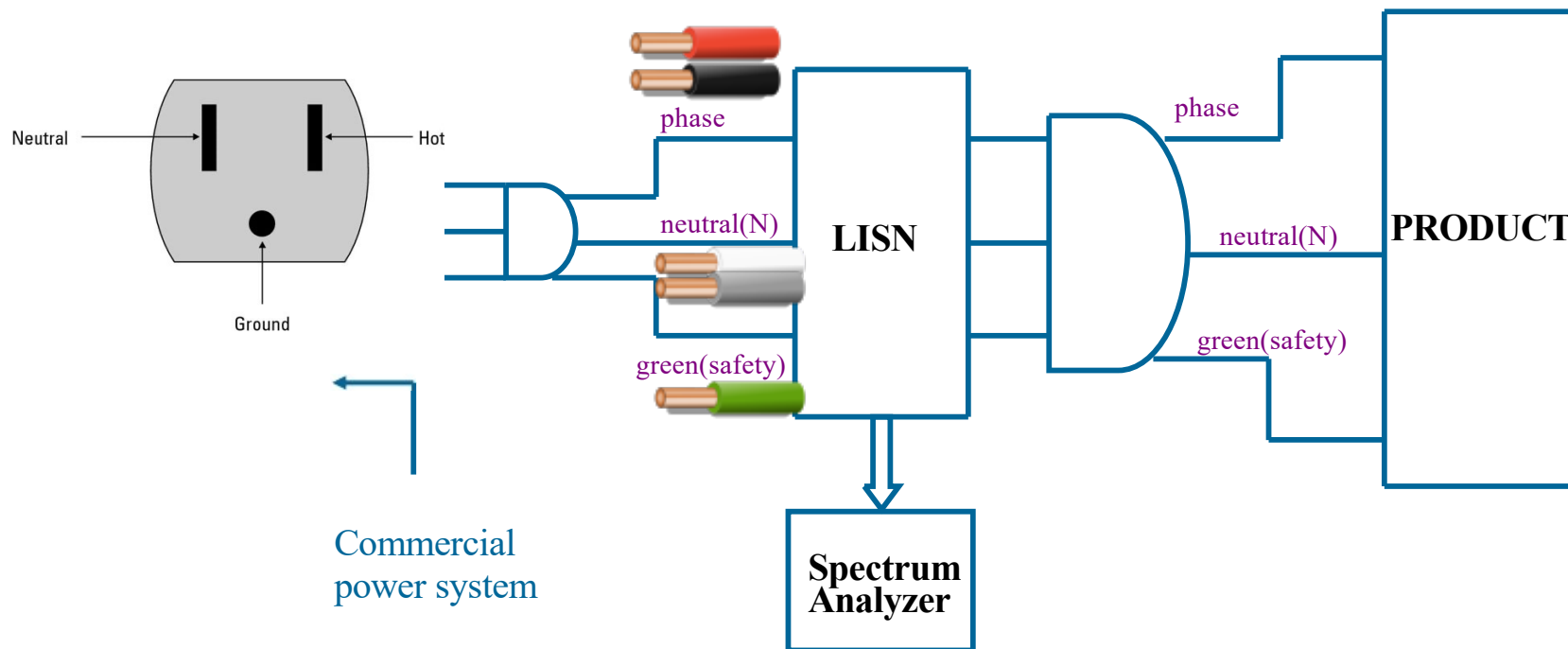
CONDUCTED EMISSIONS 9kHz-30MHz



From Prof. Arturo Mediano

1.1 LISN (Line Impedance Stabilization Network)

- LISN is used for conduction, radiation, and susceptibility testing.
- LISN is inserted between the commercial power outlet and products' ac power cord.



The line impedance stabilization network(LISN)

A. why use LISN?

1. The impedance seen looking into the AC power system wall outlets varies considerably over the measurement frequency range.
2. The measured data should be repeatable between measurement sites.

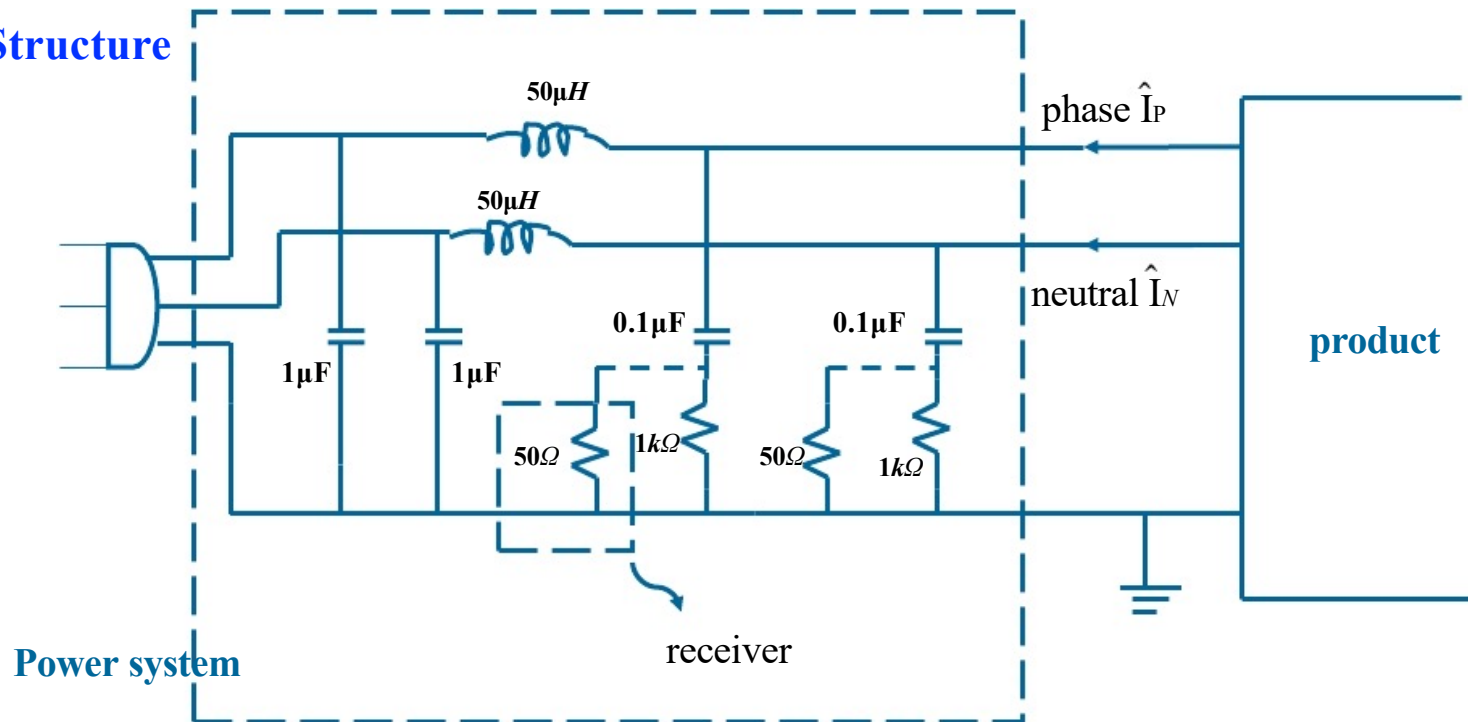
B. Three objectives for using LISN

1. Present a constant impedance to the product's power cord outlet over the frequency range of the conducted emission test.
2. Prevent the conducted noise on the power system net from contaminating the measurement.
3. Pass the 60Hz power required for operation of the product.



LISN

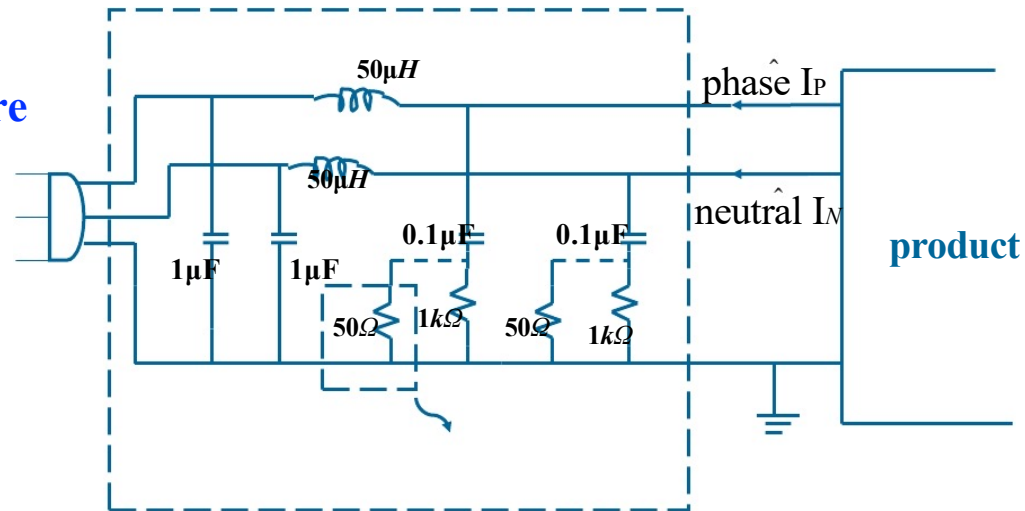
C. LISN Structure



Element	$Z_{60\text{Hz}}$	$Z_{150\text{kHz}}$	$Z_{30\text{MHz}}$
50µH	18.8mΩ	47.1Ω	9.42kΩ
0.1µF	26.5kΩ	10.61Ω	0.053Ω
1µF	2.7kΩ	1.06Ω	0.0053Ω

50µH: Block external noise
 1µF: Alternative noise path
 0.1µF: Prevent DC overloading
 1kΩ: Static charge path
 50Ω: Input Z of S.A.

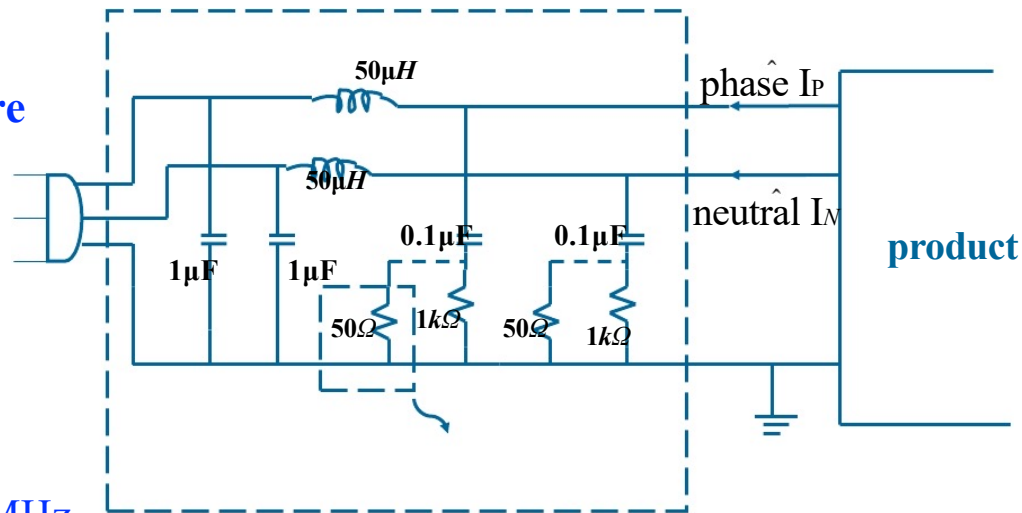
LISN Structure



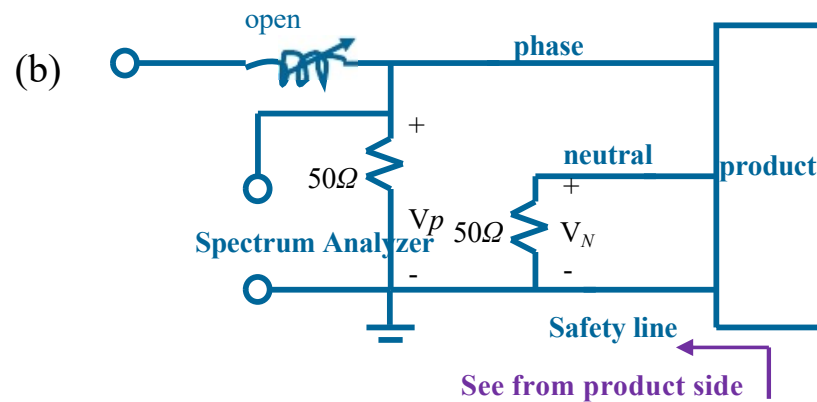
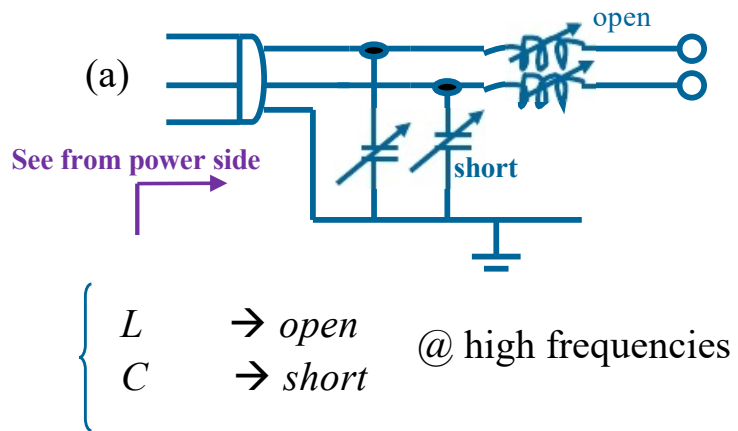
- 1) for 60/50Hz system, the equivalent circuit of LISN is below, no effect



LISN Structure



2) for $150\text{kHz} < f < 30\text{MHz}$



- prevent the current noise in power supply from flowing into product

LISN



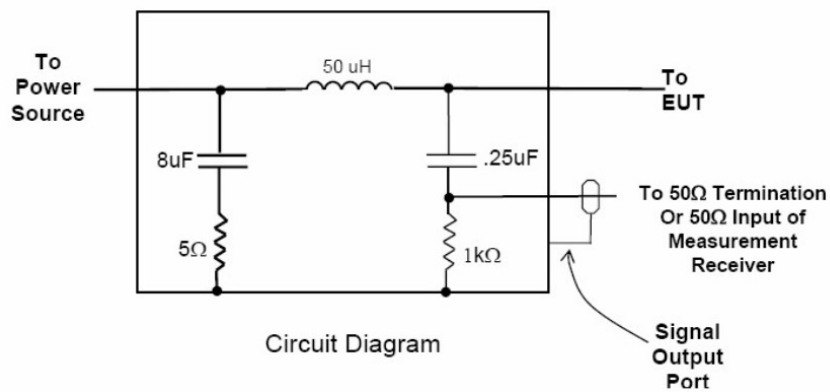
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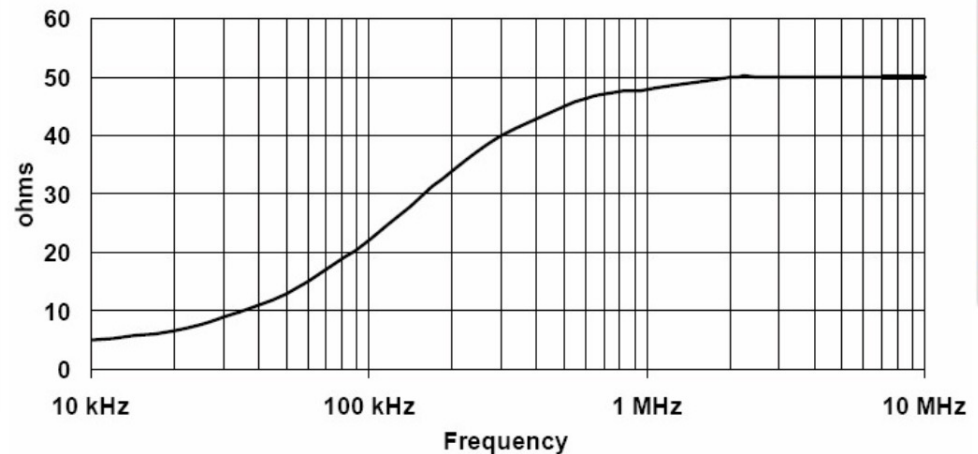
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Schematic Diagram for the FCC-LISN-50-(XXX)-1-(XX) Mil-Std. 462 Rev. D/E



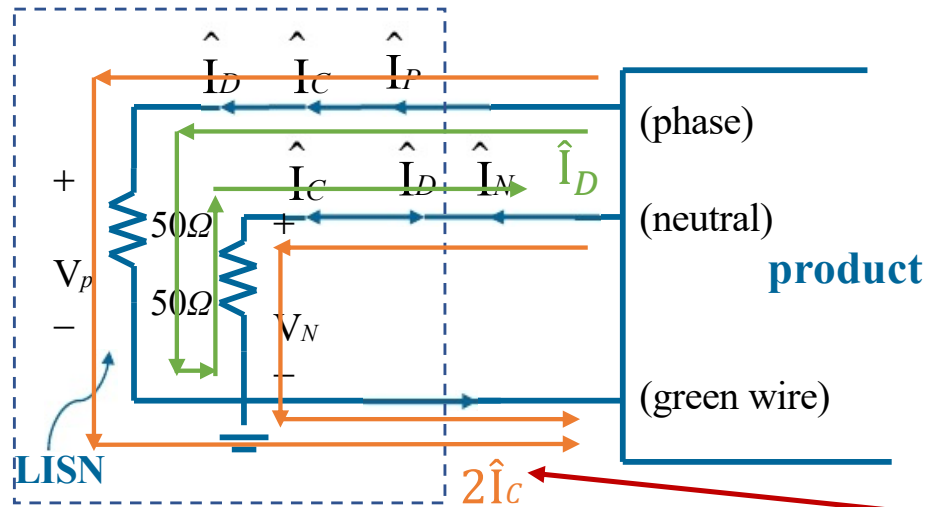
Typical Impedance vs Frequency chart
for the FCC-LISN-50-(XXX)-1-(XX) Mil-Std. 462 Rev. D/E



Frequency (MHz)
Network Inductance
Maximum Current
Voltage Options
Power Frequency
Number of Lines



1.2 Common and Differential-Mode Currents



Unintended.

The green wire exists to provide a path for current at 60 Hz in the event of a ground fault so that the circuit breaker or the fuse of the AC power can be blown.

$$\langle 1 \rangle \hat{I}_P = \hat{I}_C + \hat{I}_D$$

$$\hat{I}_D = \frac{1}{2} (\hat{I}_P - \hat{I}_N)$$

$$\hat{I}_N = \hat{I}_C - \hat{I}_D$$

$$\hat{I}_C = \frac{1}{2} (\hat{I}_P + \hat{I}_N)$$

< 2 > The measured voltages are

$$\hat{V}_P = 50(\hat{I}_C + \hat{I}_D)$$

$$\hat{V}_N = 50(\hat{I}_C - \hat{I}_D)$$

$$\hat{I}_C = \frac{1}{2} \frac{(\hat{V}_P + \hat{V}_N)}{50 \Omega}$$

$$\hat{I}_D = \frac{1}{2} \frac{(\hat{V}_P - \hat{V}_N)}{50 \Omega}$$

3) As opposed to radiated emissions

1. $\hat{I}_C$ can be of the order of $\hat{I}_D$, or exceed $\hat{I}_D$ in conducted emission.
2. $\hat{I}_D$ here is not the functional 60Hz power line currents.
3. Generally, $\hat{I}_C$ or $\hat{I}_D$ dominates in the C.E.

$$\left. \begin{array}{l} \hat{V}_P = 50I_C \\ \hat{V}_N = 50I_C \end{array} \right\} \quad \text{for } \hat{I}_C \gg \hat{I}_D$$

$$\left. \begin{array}{l} \hat{V}_P = 50\hat{I}_D \\ \hat{V}_N = -50\hat{I}_D \end{array} \right\} \quad \text{for } \hat{I}_D \gg \hat{I}_C$$

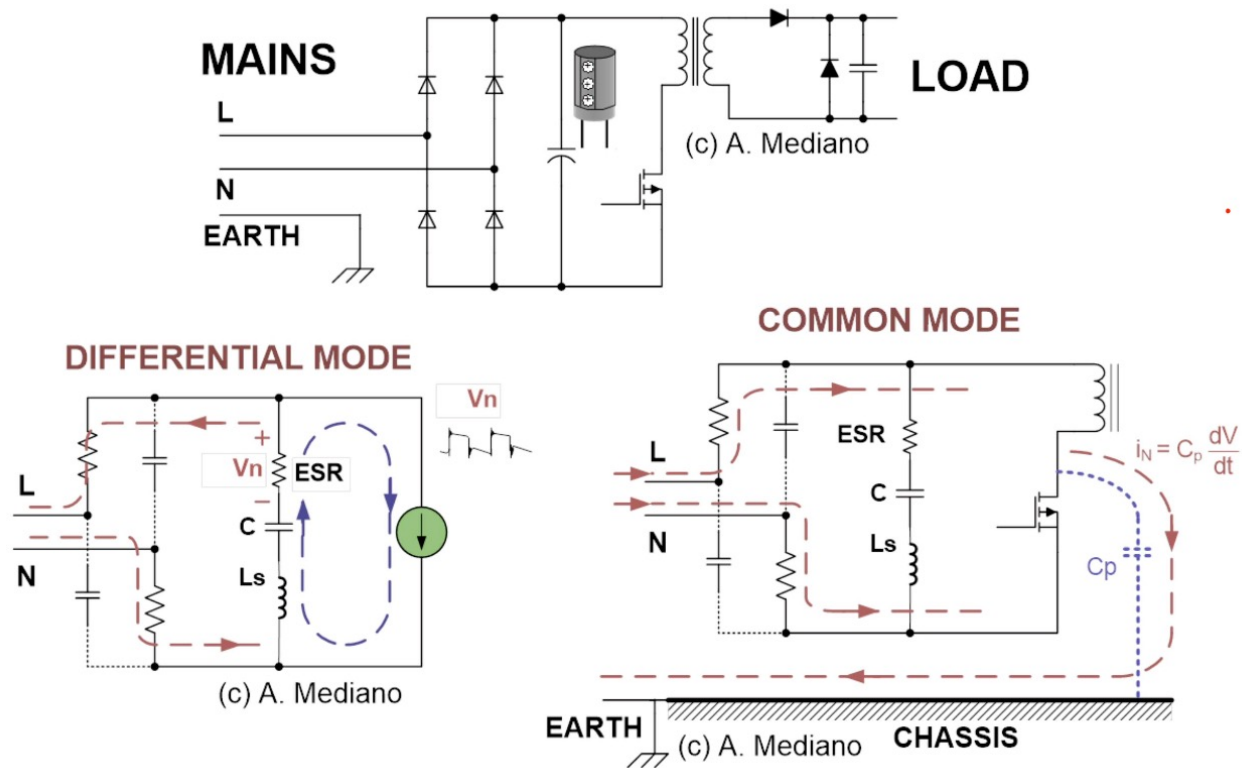
Measured voltage in S.A.

$$\hat{V}_P = 50(\hat{I}_C + \hat{I}_D)$$

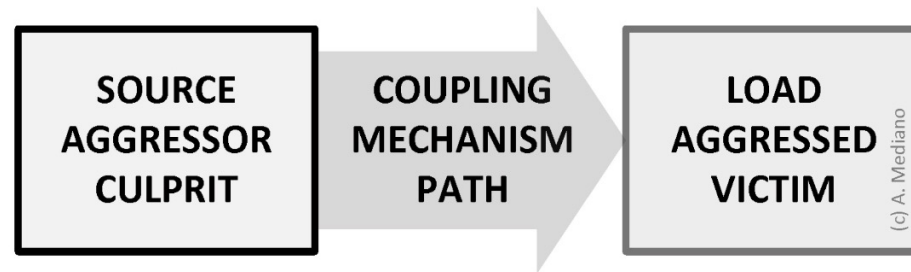
$$\hat{V}_N = 50(\hat{I}_C - \hat{I}_D)$$

Need **power supply filters**! It contain components to reduce either $\hat{I}_C$ or $\hat{I}_D$.

How Conducted Emissions are Created



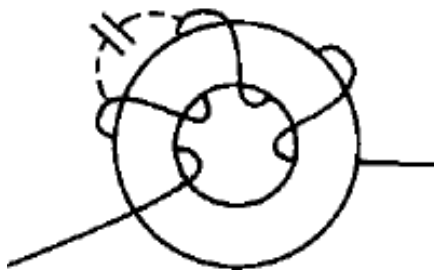
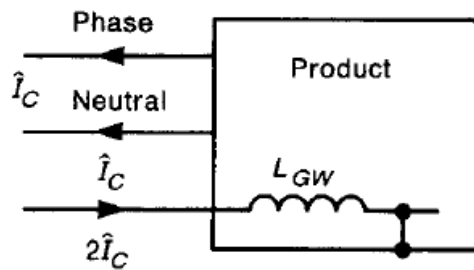
Methods of reducing the common-mode contribution to conducted emissions



- Reduce dV/dt
- Optimize layout and placement
- EMI sources far from power supply cable
- Spread spectrum

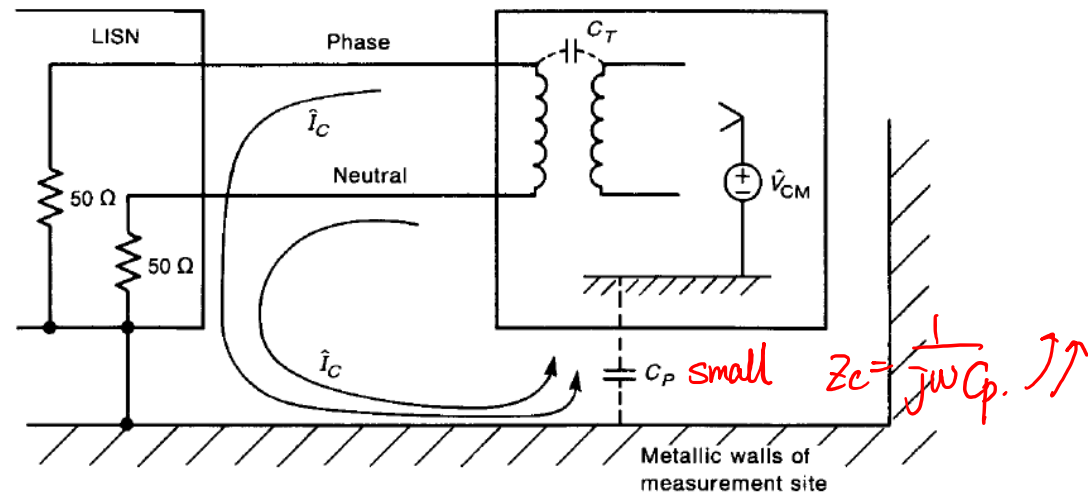
- Filtering inside of device (^{γ/x} ~~X~~-caps)
- Shielding (i.e. transformers)
- Snubbers
- Etc.

Methods of reducing the common-mode contribution to conducted emissions



$$Z_{GW} = j\omega L_{GW}$$

Method 1: a green-wire inductor

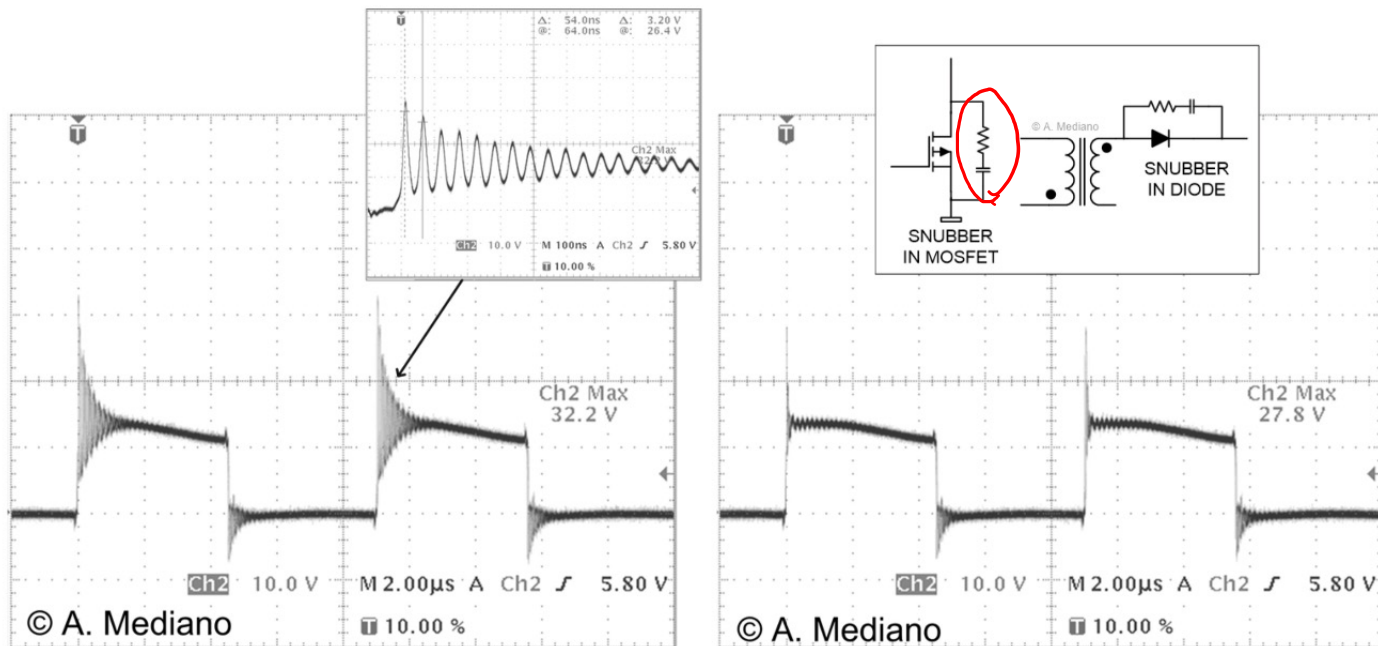


Method 2: creating a two-wire product
(no green wire)

Methods of reducing the common-mode contribution to conducted emissions

Method 3: Use Snubbers

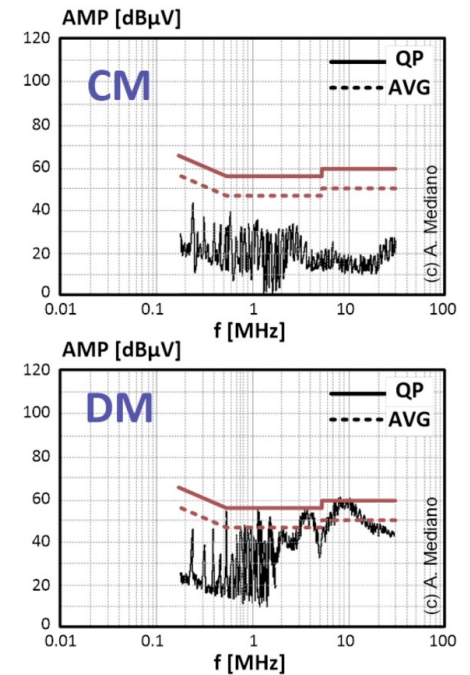
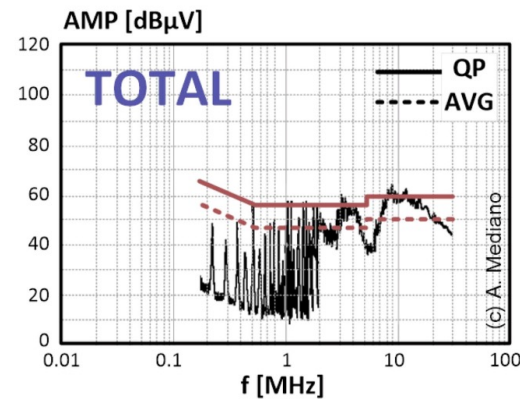
A snubber is a device used to suppress ("snub") a phenomenon such as voltage transients in electrical systems



Methods of reducing the common-mode contribution to conducted emissions

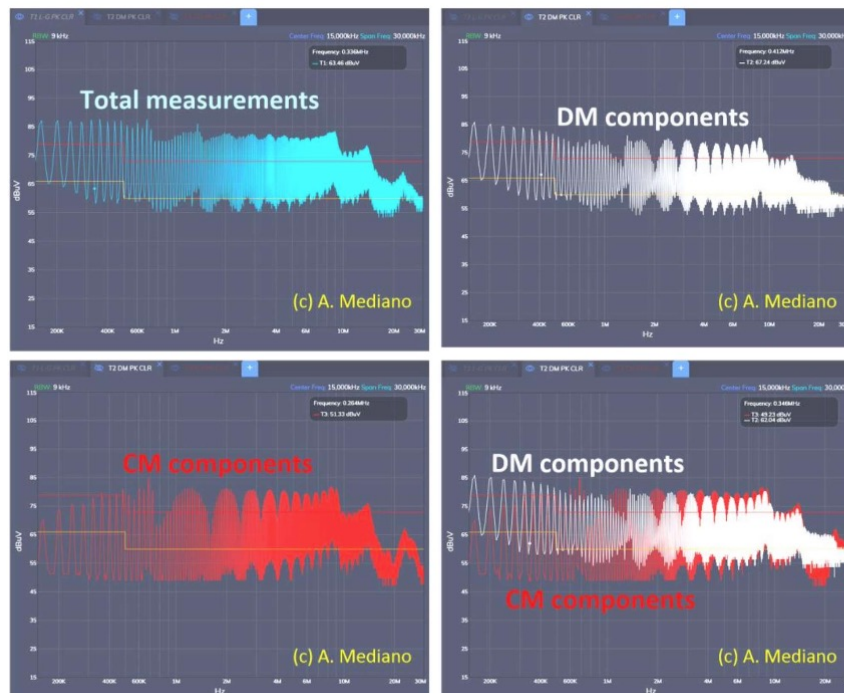
Method 4: CM and DM separation

CM dominates - need common mode choke
DM dominates - need decoupling capacitor



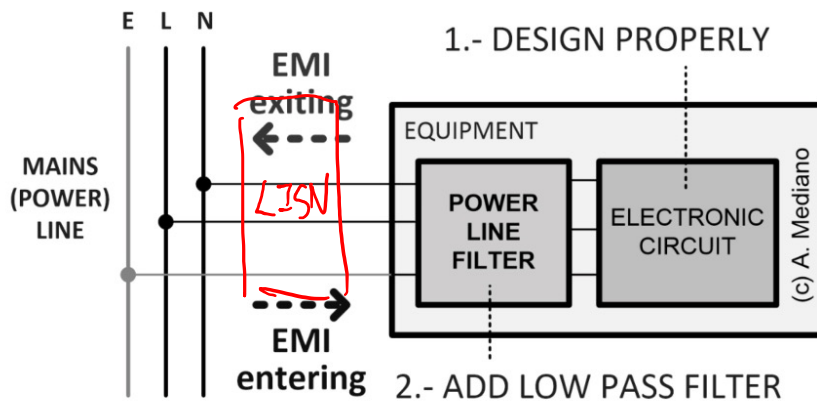
Methods of reducing the common-mode contribution to conducted emissions

Method 4: CM and DM separation



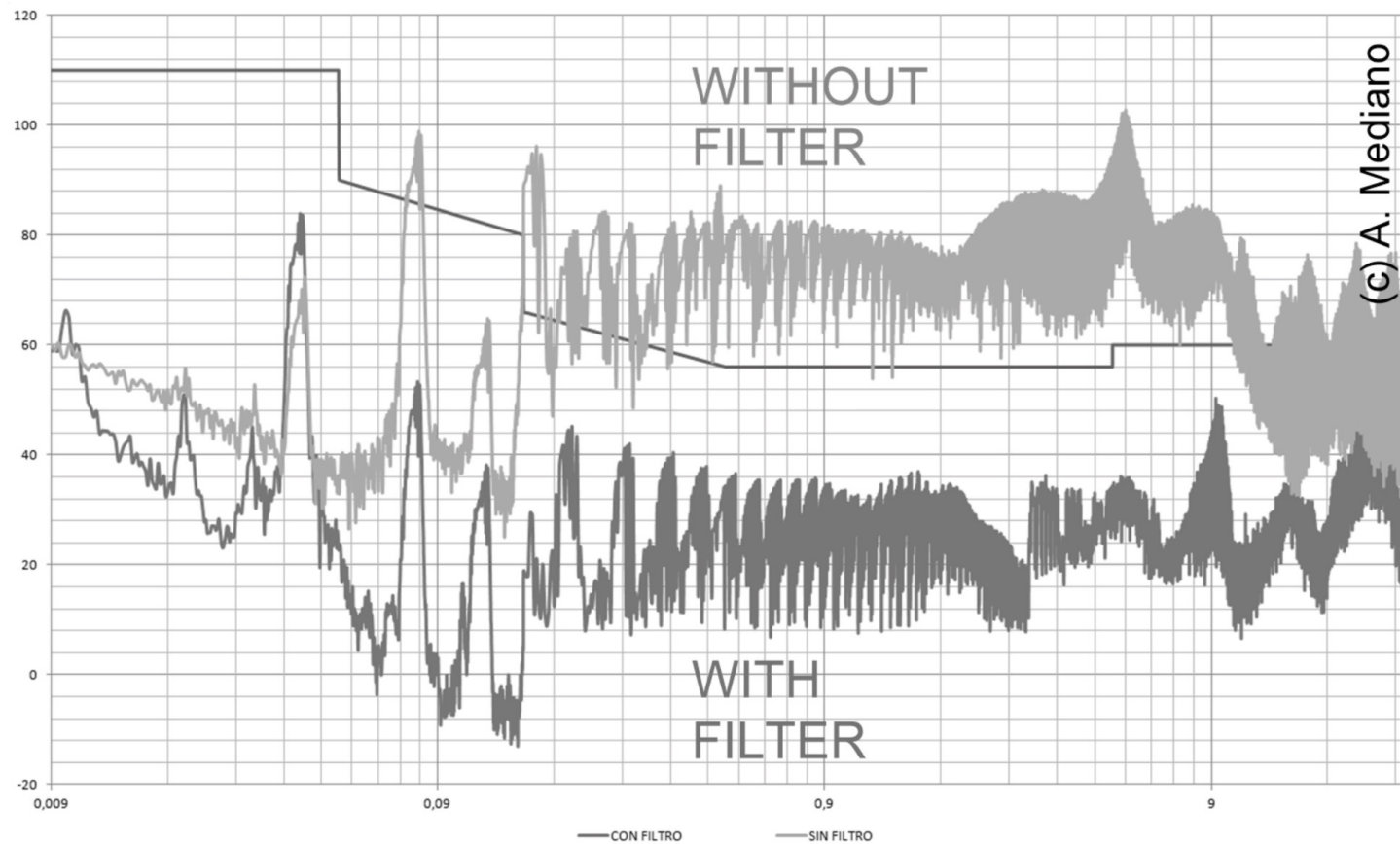
2 Power supply filters

Filters: Solution for conducted emissions!



- **Filter purpose**
To reduce conducted EMI to mains.
- **Problems**
Size and cost.
- **How filter works**
REFLECTION
Impedance mismatching.
No ABSORTION.
- **How to characterize**
INSERTION LOSSES
(Z_s and Z_L influence).
- **Caution**
Parasitics.
Saturation
V/I limits
- **Prediction of performance**
Easier in DM than CM

EMI/EMC Measurements w/wo Filter



Insertion Loss

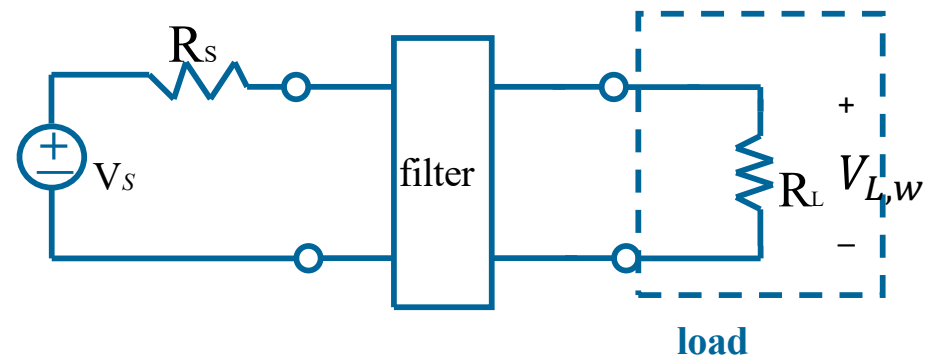
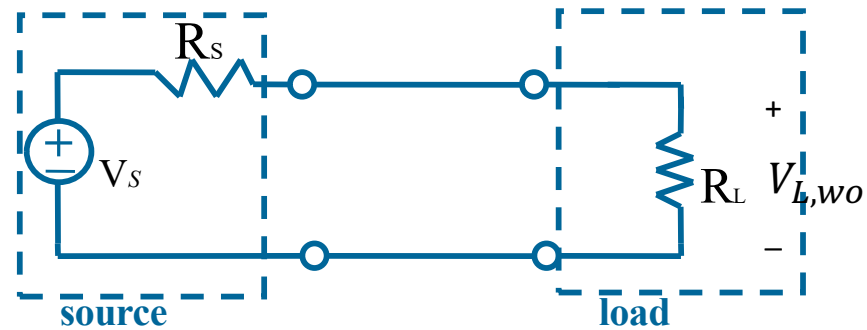
Basic properties of filters

1. Insertion Loss (IL)

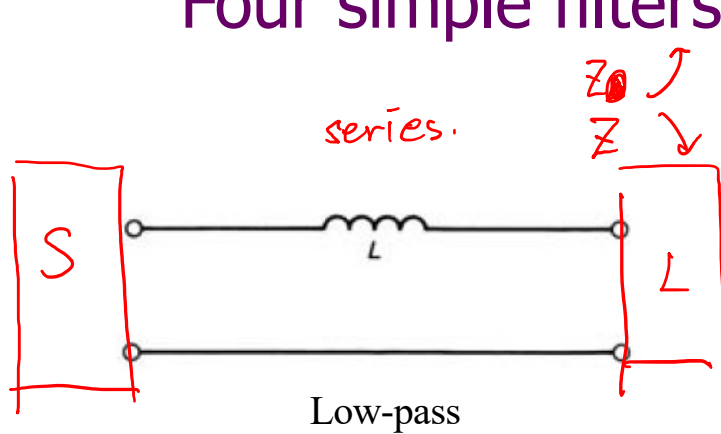
$$IL = 10 \log_{10} \left(\frac{P_{L,wo}}{P_{L,w}} \right)$$

$$= 10 \log_{10} \left(\frac{V_{L,wo}^2 / R_L}{V_{L,w}^2 / R_L} \right)$$

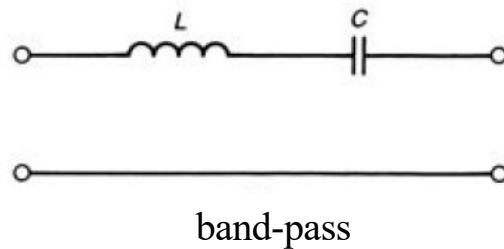
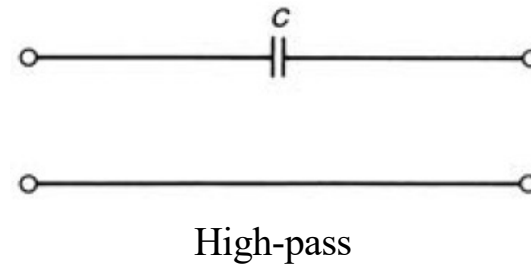
$$= 20 \log_{10} \left(\frac{V_{L,wo}}{V_{L,w}} \right)$$



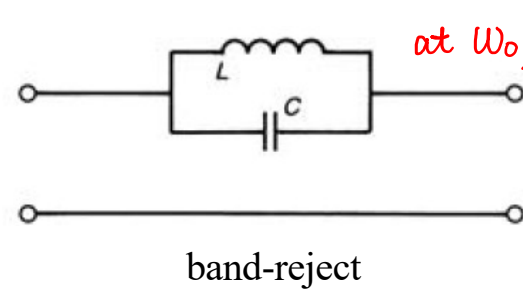
Four simple filters



more attenuation
no effect.



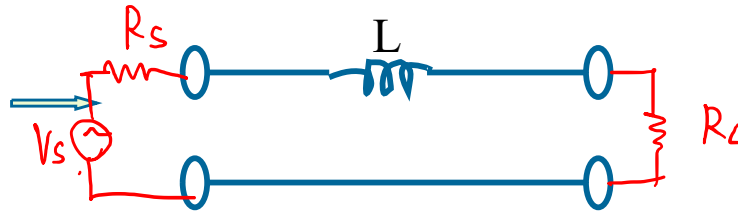
at $\omega_0 = \frac{1}{\sqrt{LC}}$. $Z_S = 0$.



at ω_0 , $Y_{11} = 0$,
 $Z \rightarrow \infty$.

Example:

Lowpass Filter



$$1). V_{L,wo} = \frac{R_L}{R_S + R_L} V_S \quad \text{V DL.}$$

$$2). V_{L,w} = \frac{R_L}{R_S + j\omega L + R_L} V_S = \frac{R_L}{R_S + R_L} \frac{1}{1 + j\omega L / (R_S + R_L)} V_S$$

$$3). IL = 20 \log_{10} \left| 1 + \frac{j\omega L}{R_S + R_L} \right| = 20 \log_{10} \sqrt{1 + (\omega\tau)^2}$$

$$= 10 \log_{10} [1 + (\omega\tau)^2]$$

RL circuit

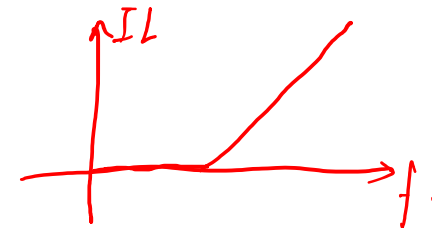
where $\tau = \frac{L}{R_S + R_L}$ Time constant

$$3\text{dB point of IL} \rightarrow \omega_{3dB} = 1/\tau \quad 1 = \omega\tau.$$

From DC to $\rightarrow \omega_{3dB}$ IL: 0 dB

$\omega \gg \omega_{3dB}$ IL: +20dB/decade

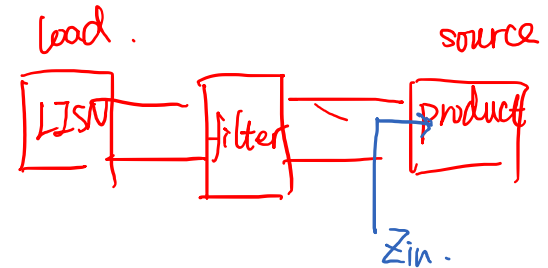
$$20 \log_{10} (\omega\tau).$$



- IL is dependent on the source and load impedance. Manufacturers provide freq. response plots of I.L. of a particular filter, with $R_L = R_S = 50 \Omega$.
- But when the filter is used in the product and is tested for C.E., what is R_L and R_S ?:

$R_L = 50 \Omega$ (impedance of LISN)

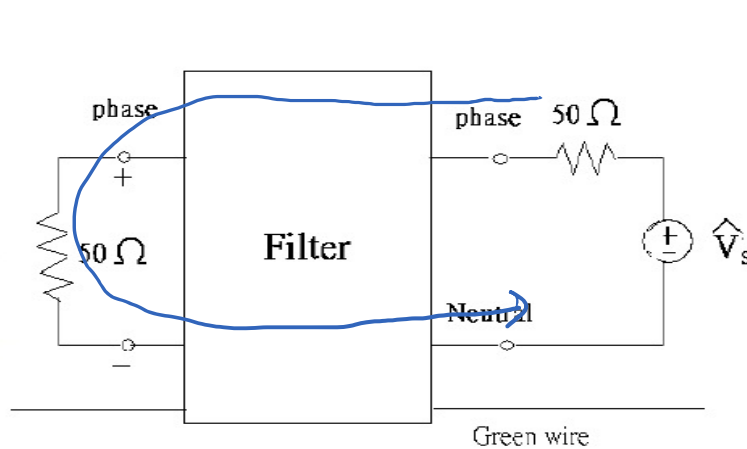
$R_S = ?$ (Looking back into product power input)



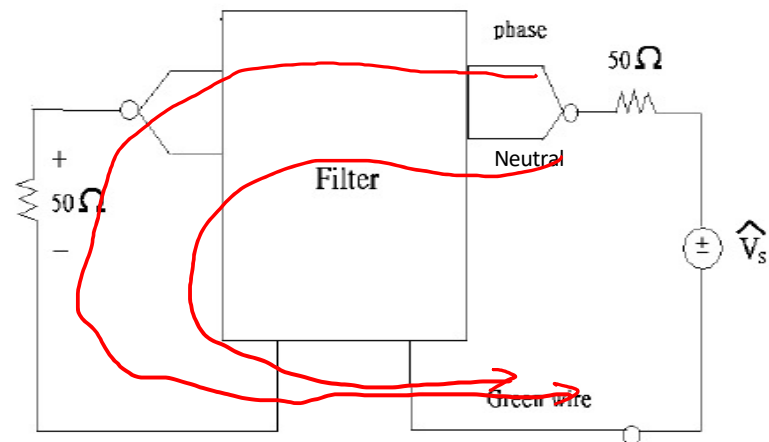
So, the data sheet is just for reference.

Insertion loss tests for differential mode and common mode.

- Manufacturers typically give separate IL test for $\hat{I}_c$ and $\hat{I}_d$



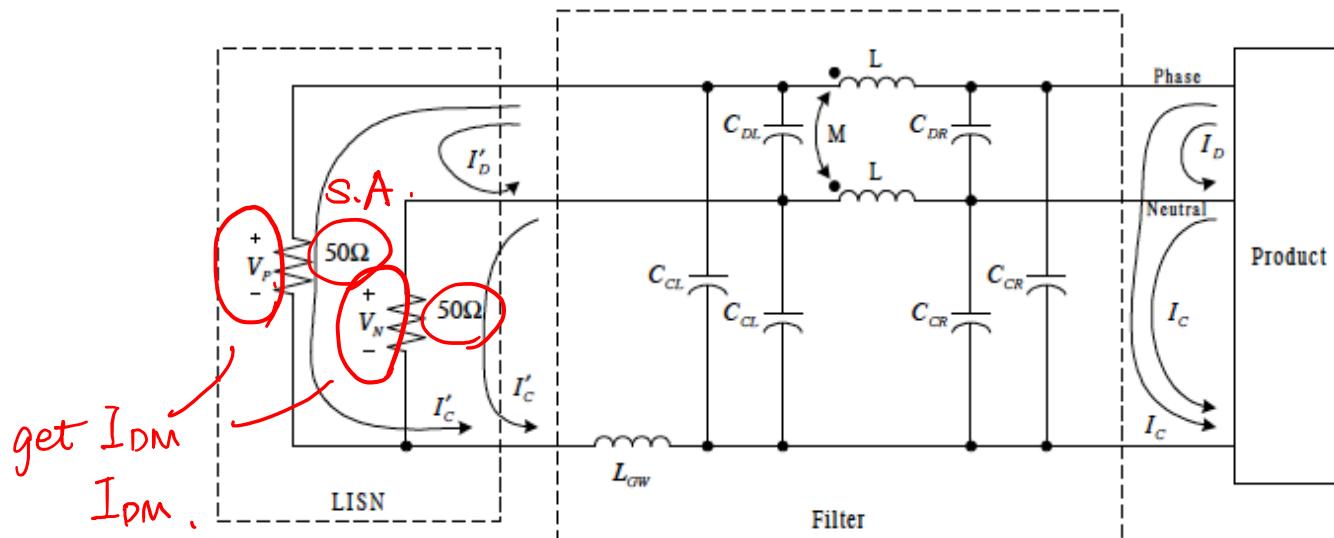
$\hat{I}_D$ test set up



$\hat{I}_C$ test set up

3 A Generic Power Supply Filter Topology

Typical topology



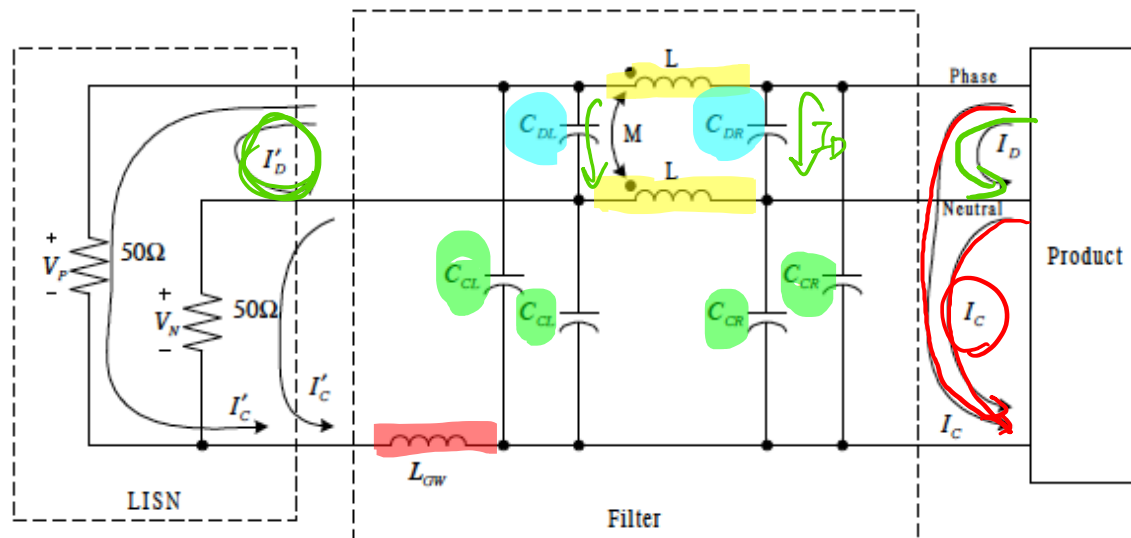
The voltages that S.A measures are

$$\hat{V}_P = 50(\hat{I}'_C + \hat{I}'_D)$$

$$\hat{V}_N = 50(\hat{I}'_C - \hat{I}'_D)$$

need to be below the conducted emission limit

3.1 Effect of the filter elements on common-mode and differential-mode currents



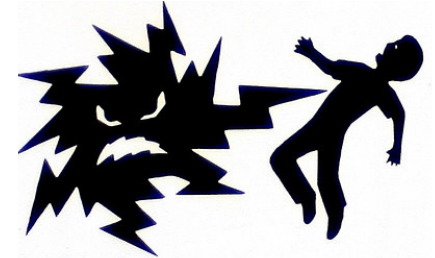
- 1) Green wire inductor L_{GW} : Block the common-mode currents.
- 2) C_{DL}, C_{DR} (Line-to-line capacitors): to divert the differential-mode currents.
- 3) C_{CL}, C_{CR} (line-to ground capacitors): to divert the common-mode currents.

Typical value for C_C and C_D . $C_C \approx 2200 \text{ pF}$, $C_D \approx 0.047 \text{ } \mu\text{F}$. $C_D \gg C_C$. Why?

- ① only mitigation for I_{DM} .
- ②. Leakage current.

f	60Hz	150kHz	30MHz
$Z_C (\Omega)$	1.21M	482.3	2.41
$Z_D (\Omega)$	56.4k	22.6	0.11

- The line-to-ground capacitors C_{CL} and C_{CR} can be limited by the **leakage current** specified by Regulatory standards (like IEC 60950 or IEC 60364) for preventing the shock hazard.



- **Example 1:** Determine the maximum line-to-ground capacitance to satisfy a leakage current requirement of $1mA$ for $60Hz$ in $120V$ power system.

$$Z_c = \frac{1}{j\omega C_c} \quad \hat{I} = \frac{\hat{V}}{Z_c} = j\omega C_c \hat{V}$$

$$C_c = \frac{1}{2} \times 10^{-3} (A) / (120(V) \times 2\pi \times 60(Hz)) = 5526 pF.$$

Half of the maximum leakage current, Why?

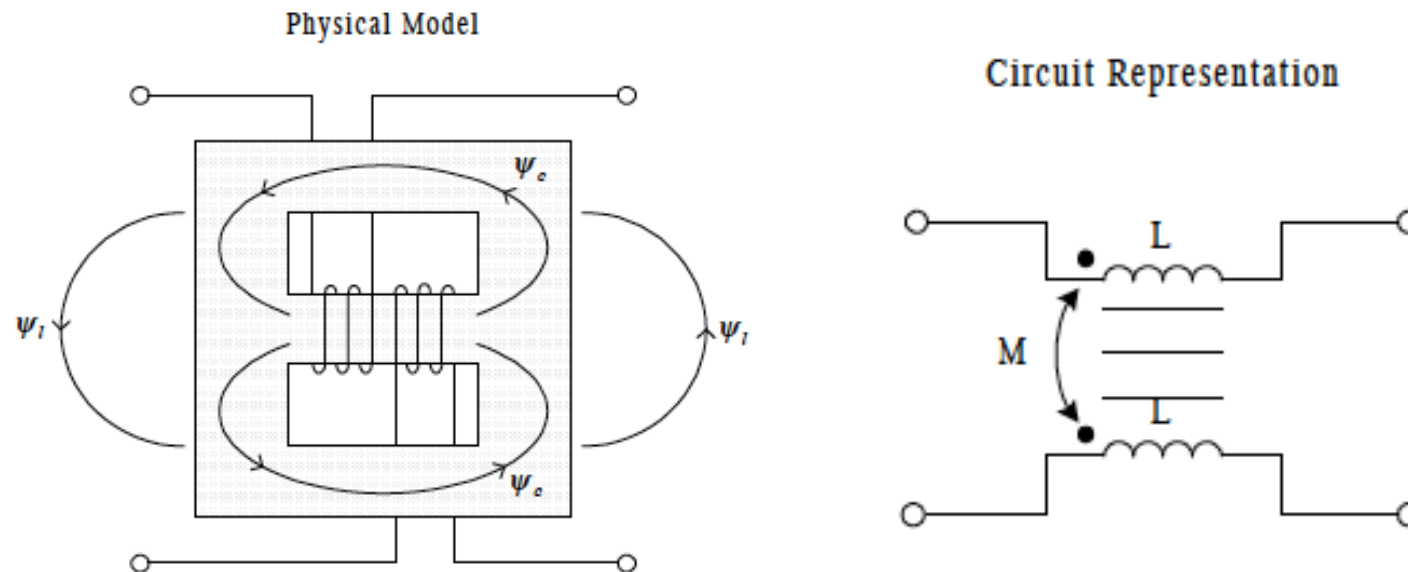
- **Example 2:** Find the valid frequency range for C_C to divert common-mode current.

$$C_C = 2200 \text{ pF.}$$

at $1.45MHz$, $Z_C = 50\Omega$, C_C is valid for $f > 1.45MHz$.

$$Z_C = 50\Omega. \quad \frac{1}{j\omega C_C} < \overline{Z_{SA}} = 50\Omega.$$

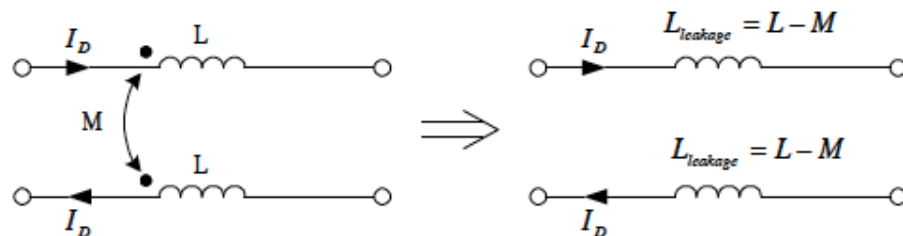
Common-mode choke to block the common-mode current



$$\text{coupling coefficient } k = \frac{M}{\sqrt{L_1 L_2}} \approx \frac{M}{L}$$

$$M \approx L \rightarrow k \approx 1$$

Differential mode

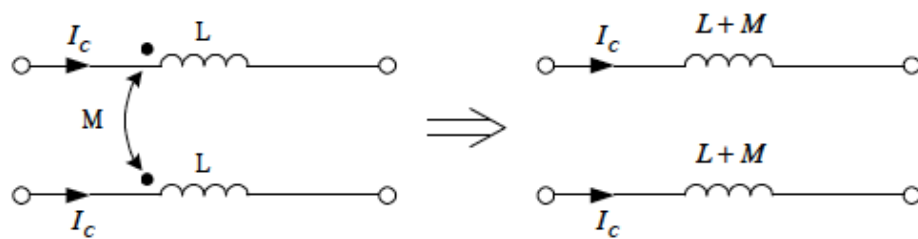


$$\hat{V}_D = j\omega L \hat{I}_D - j\omega M \hat{I}_D = j\omega(L - M) \hat{I}_D$$

→ Leakage inductance $L - M$

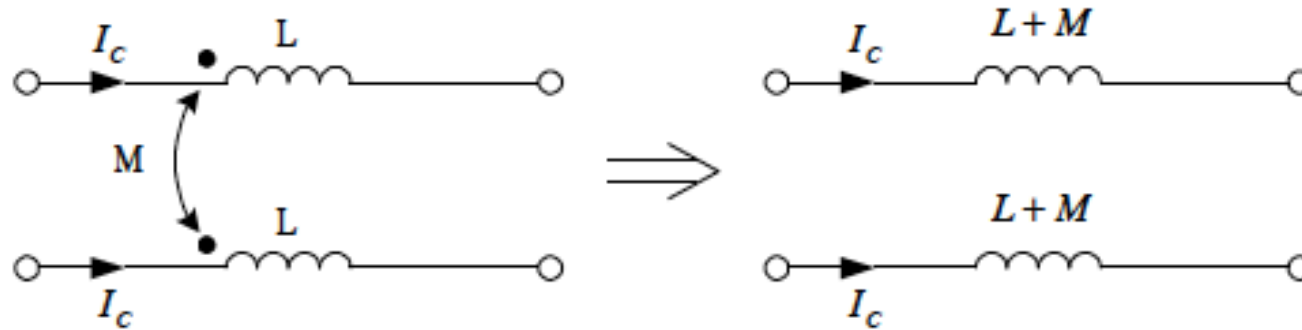
is due to the magnetic flux that leaks out the core and does not couple between the winding.

Common mode



$$\hat{V}_C = j\omega L \hat{I}_C + j\omega M \hat{I}_C = j\omega(L + M) \hat{I}_C$$

Common mode



$$\hat{V} = j\omega L \hat{I}_c + jM \hat{I}_c = j\omega(L + M) \hat{I}_c$$

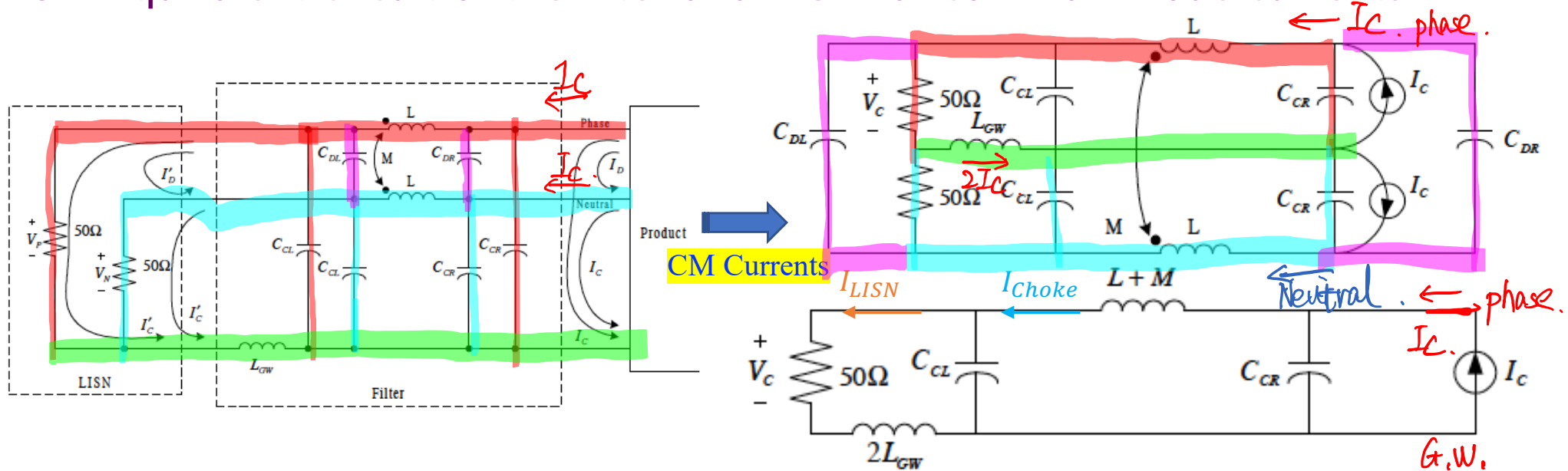
Note: typically, $L \approx M = 1 \text{ mH}$.

$$j\omega(L + M) = 0.75 \Omega. \quad f : 60 \text{ Hz}$$

$$= 1,885 \Omega. \quad f : 150 \text{ kHz}$$

$$= 0.377 \text{ M}\Omega. \quad f : 30 \text{ MHz}$$

3.2 Equivalent circuit of the filter and LISN for common-mode currents`



$I_L \rightarrow 20 \log_{10} \left(\frac{I_C}{I_{LISN}} \right)$ The common-mode current reaching the LISN is determined by current division between the LISN/green-wire path and the line-to-ground capacitor C_{CL} .

Current division

$$\frac{I_{LISN}}{I_{Choke}} = \frac{\frac{1}{j\omega C_{CL}}}{50 + j\omega 2L_{GW} + \frac{1}{j\omega C_{CL}}}$$

$$= \frac{1}{1 - \omega^2 2L_{GW}C_{CL} + j\omega 50C_{CL}}$$

Observations: 1. Green wire

2. C_{CL} must present

Bold plot of I Ratio of the common-mode choke

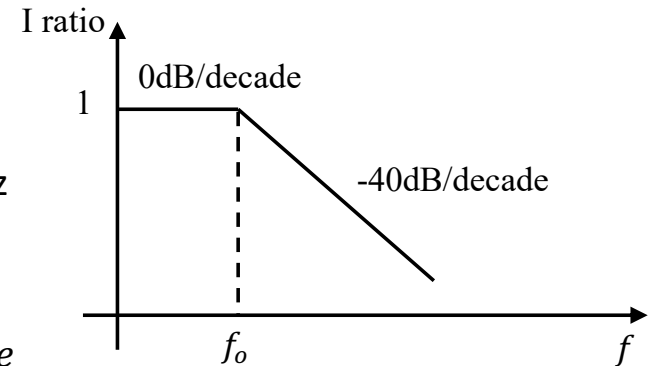
$$\frac{I_{LISN}}{I_{Choke}} = \frac{\frac{1}{j\omega C_{CL}}}{50 + j\omega 2L_{GW} + \frac{1}{j\omega C_{CL}}}$$

$$= \frac{1}{1 - \omega^2 2L_{GW}C_{CL} + j\omega 50C_{CL}}$$

Breakpoint frequency

$$f_0 = \frac{1}{2\pi\sqrt{2L_{GW}C_{CL}}} = 61.95\text{kHz}$$

$$\begin{cases} \text{DC} \sim f_0: 0\text{dB/decade} \\ f_0 \sim \infty: -40\text{dB/decade} \end{cases}$$



For $L_{GW} = 1\text{ mH}$ $C_{CL} = 3300\text{ pF}$ $L+M = 55\text{mH}$ then $f_0 = 62\text{ kHz}$

For $L_{GW} = 0$

$$\frac{I_{LISN}}{I_{Choke}} = \frac{\frac{1}{j\omega C_{CL}}}{50 + \frac{1}{j\omega C_{CL}}}$$

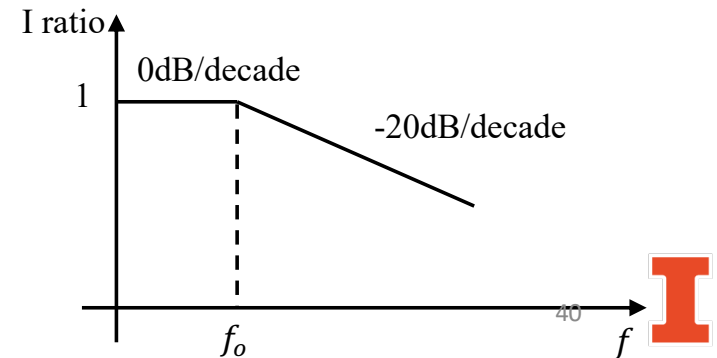
$$= \frac{1}{1 + j\omega 50C_{CL}}$$

Breakpoint frequency

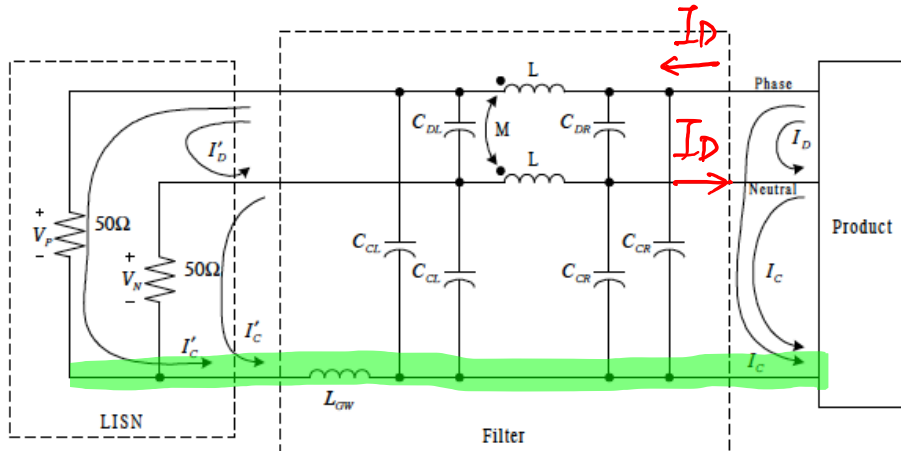
$$f_1 = \frac{1}{2\pi 50C_{CL}}$$

$$f_1 = 965\text{ kHz}$$

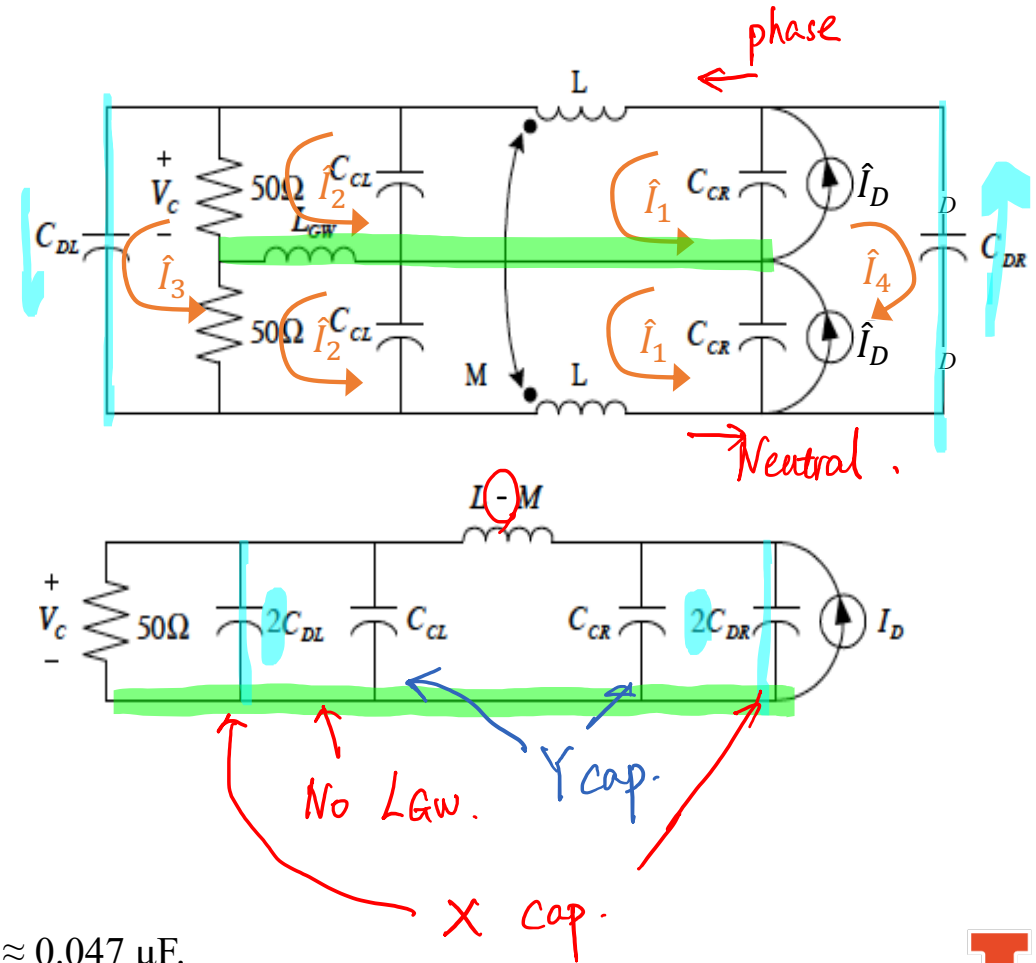
$$\begin{cases} \text{DC} \sim f_0: 0\text{dB/decade} \\ f_0 \sim \infty: -20\text{dB/decade} \end{cases}$$



Equivalent circuit of the filter and LISN for differential-mode currents

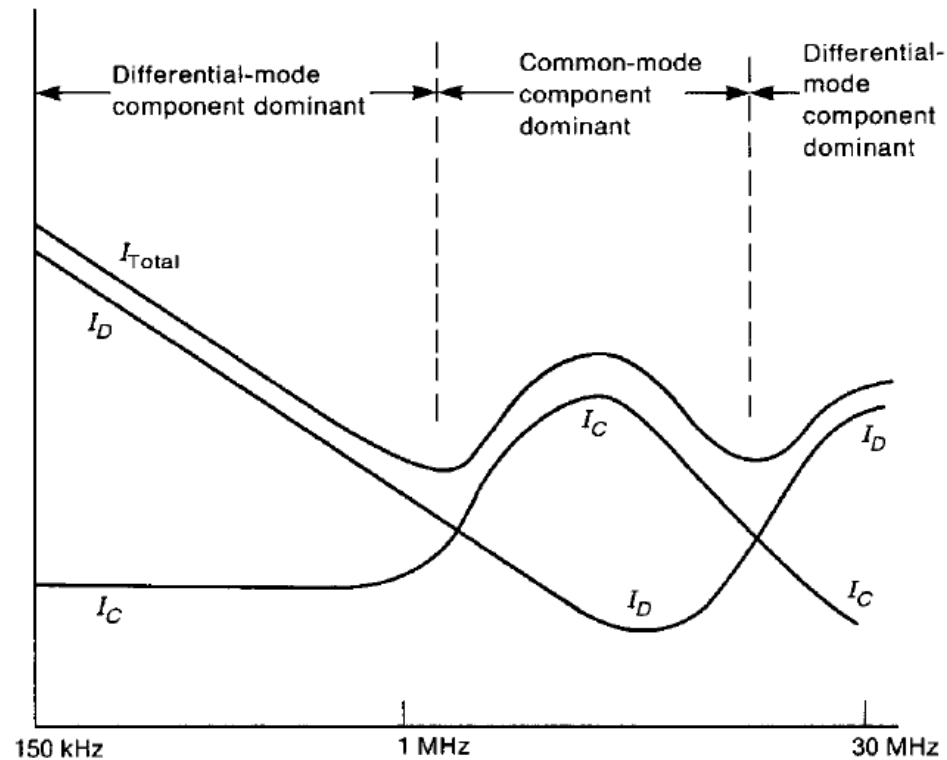


f	60Hz	150kHz	30MHz
$Z_C (\Omega)$	1.21M	482.3	2.41
$Z_D (\Omega)$	56.4k	22.6	0.11



Typical value for C_C and C_D . $C_C \approx 2200 \text{ pF}$, $C_D \approx 0.047 \text{ } \mu\text{F}$.

3.3 Separation of C.E. into common-and differential-mode currents for $\hat{I}_{\text{Total}} = \hat{I}_C \pm \hat{I}_D$



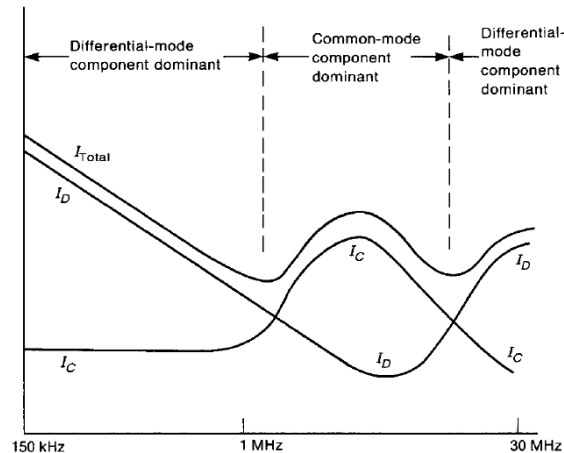
At some freq. range, the I_C is dominant.
At some freq. range, the $\hat{I}_D$ is dominant.

4 Conducted Emission: Line Filter Design

How to design the values of the C and L in the power line filter?

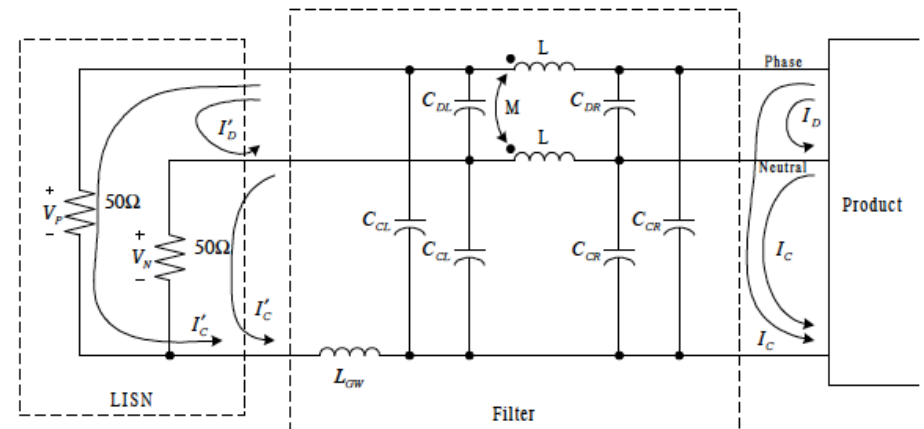
The **key** is to understand the contribution of the common-mode and differential-mode noise on the conducted emission.

A **Diagnostic tool** that can separate the total C.E. into its C.M. and D.M. components at each frequency is useful for the filter design



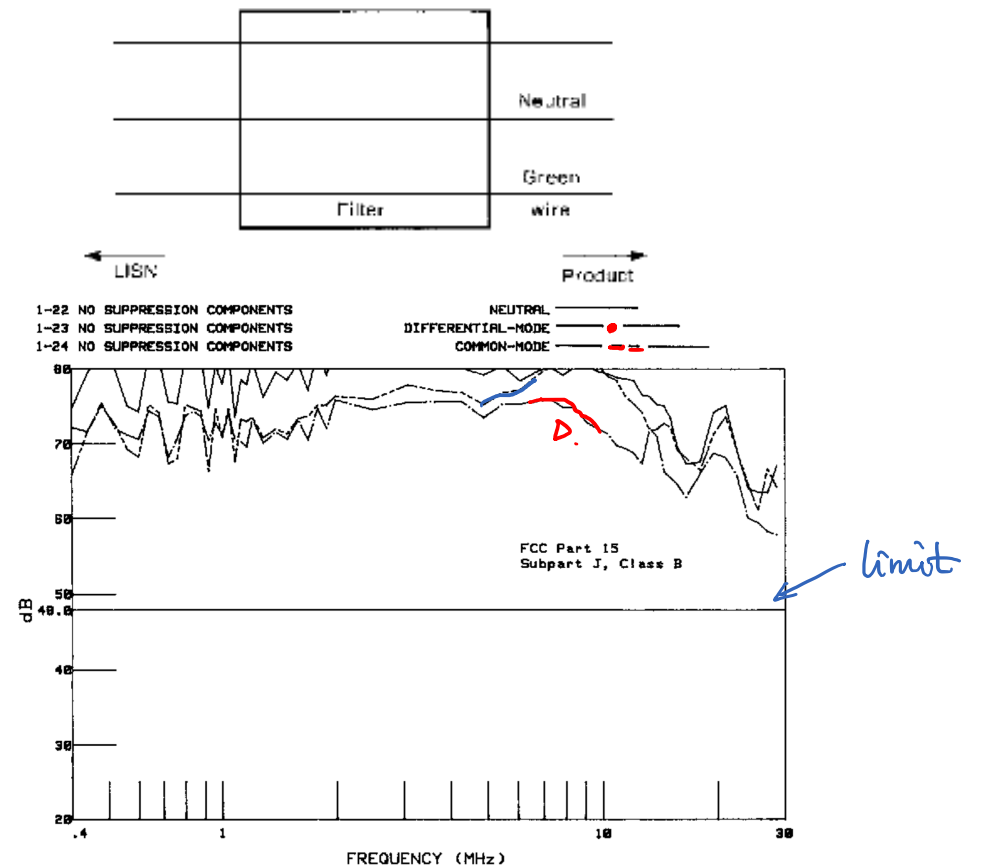
Approach to solve the C.E. problem:

1. Check out the freq. point that does not comply the regulations.
2. Determine if it is due to $\hat{I}_C$ or $\hat{I}_D$.
3. If $\hat{I}_C$, $\Rightarrow$ then change the component values of C_C , L_{GW} , or L in choke.
Increase the green-wire inductance
4. If $\hat{I}_D$, $\Rightarrow$ then design the values of C_{DR} , C_{DL} .
Increase the value of the line-to-line capacitance



Example 1: Line Filter Design for Conducted Emission

No filter



Measured conducted emissions of a typical digital product separated into differential- and common-mode components with no power supply filter

Example 1: Line Filter Design for Conducted Emission

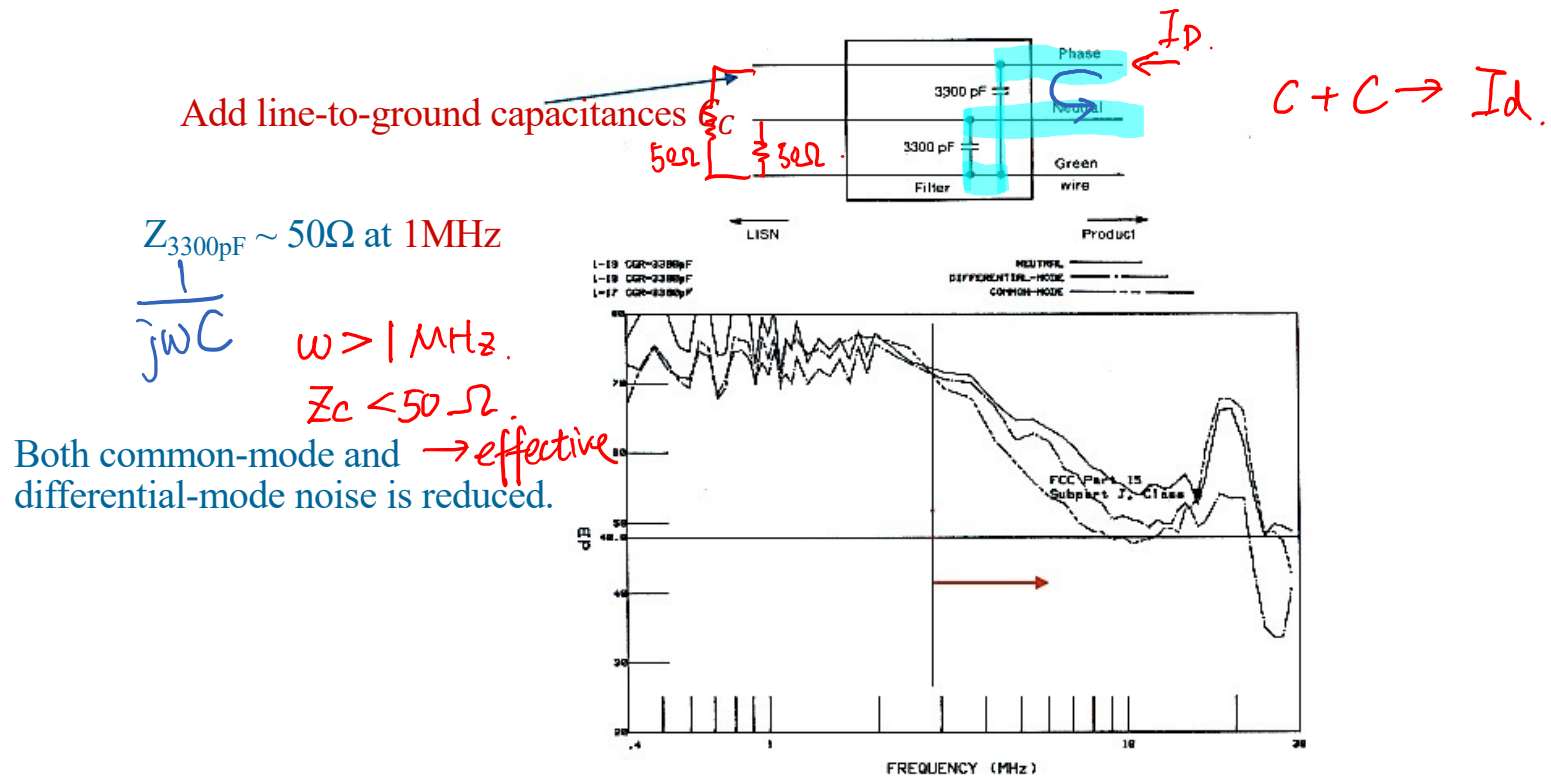


FIGURE 9.17 Measured conducted emissions of a typical product separated into differential- and common-mode components with 3300 pF line-to-ground capacitors added.

Example 1: Line Filter Design for Conducted Emission

$$2C_{DL} \parallel C_{CL}$$

Add line-to-line capacitance C_D

$$2C_{DL} + C_{CL} = 0.203 \mu F \leftrightarrow 50\Omega \text{ at } 15.7 \text{ KHz}$$

Differential-mode noise is decreased significantly

Common-mode noise is unchanged

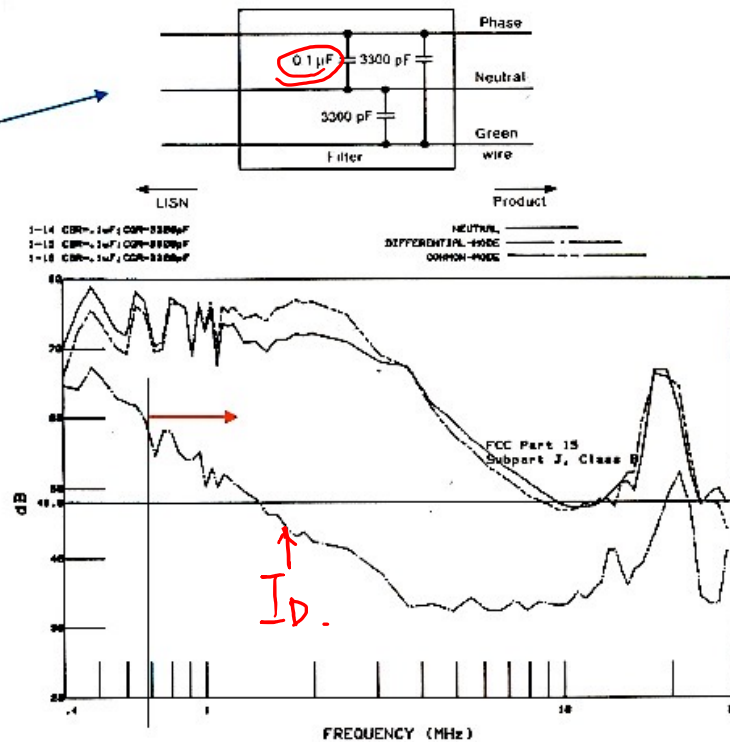


FIGURE 9.18 Measured conducted emissions of a typical product separated into differential- and common-mode components with a 0.1 μF line-to-line capacitor added.

Example 1: Line Filter Design for Conducted Emission

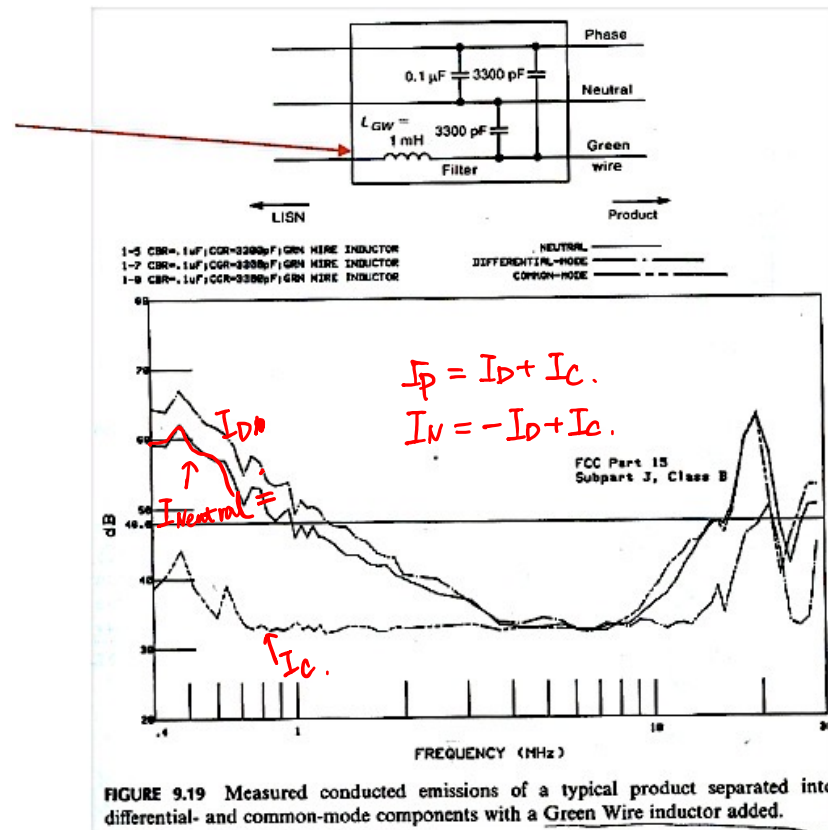
Add 1mH Green wire inductance

$$2|Z_{GW}| = 2\omega L_{GW} > 50\Omega \text{ at } 4\text{KHz}$$

$\uparrow I_c$.

Common-mode noise is decreased significantly

Differential-mode noise is unchanged



Example 1: Line Filter Design for Conducted Emission

Add common-mode choke(28mH)

Differential-mode noise is decreased significantly

Common-mode noise is unchanged

Why?

↑ already decreased to minimum.
↓ Id dropped

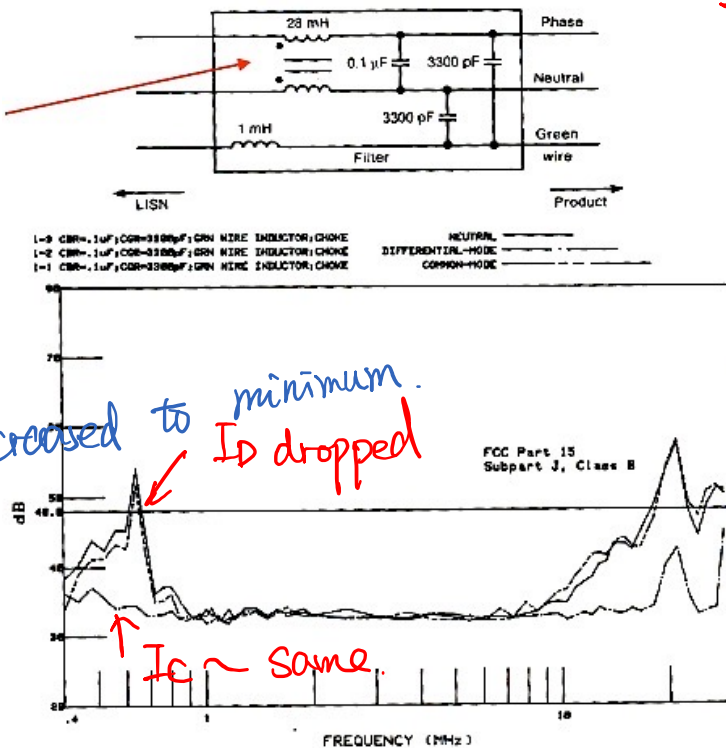


FIGURE 9.20 Measured conducted emissions of a typical product separated into differential- and common-mode components with a common-mode choke added.

Ideal case.

$$Z_{CM} = j\omega(L+M)$$

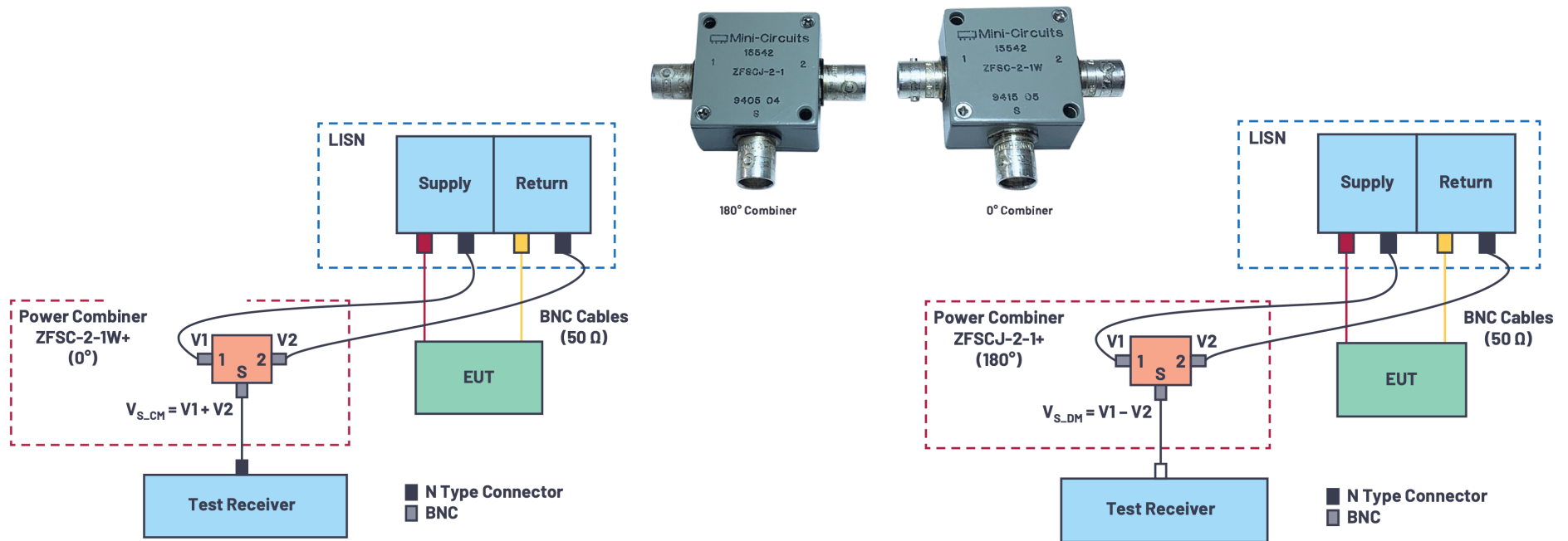
$$Z_{DM} = j\omega(L-M)$$

$$k = \frac{M}{\sqrt{L_1 L_2}} \rightarrow 1$$

Real $k < 1$.
leakage

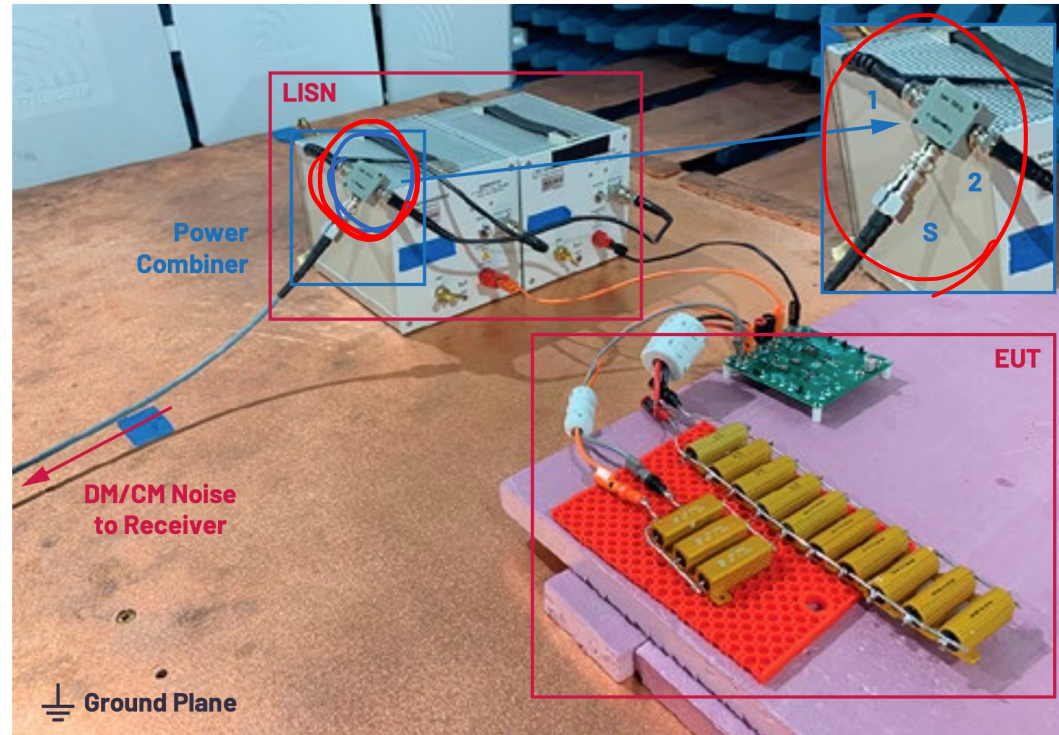
$$Z_{DM} \sim L-M \neq 0$$

Example 2: Line Filter Measurement for Conducted Emission



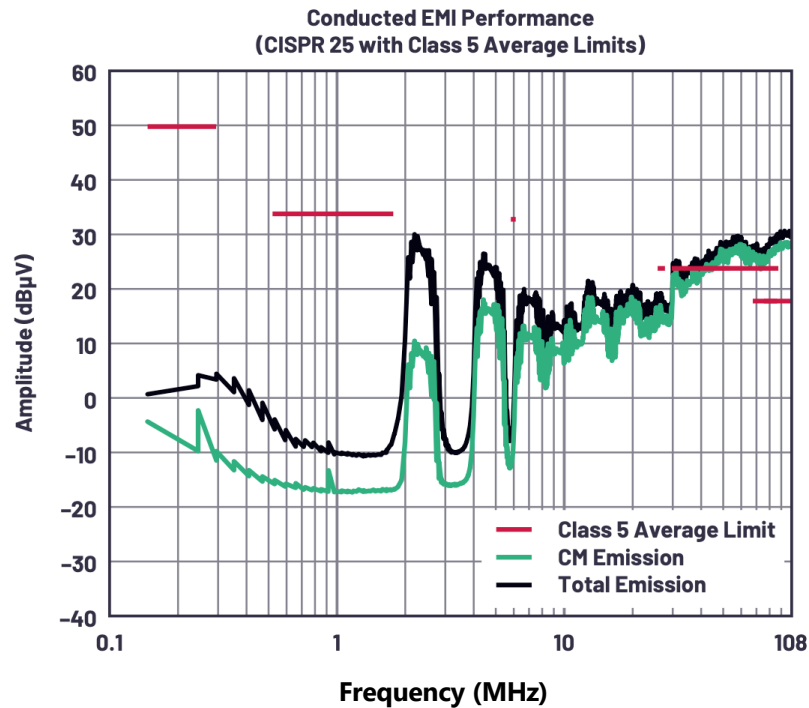
Experimental setup for measuring (a) V_{CM} and (b) V_{DM} .

Example 2: Line Filter Measurement for Conducted Emission

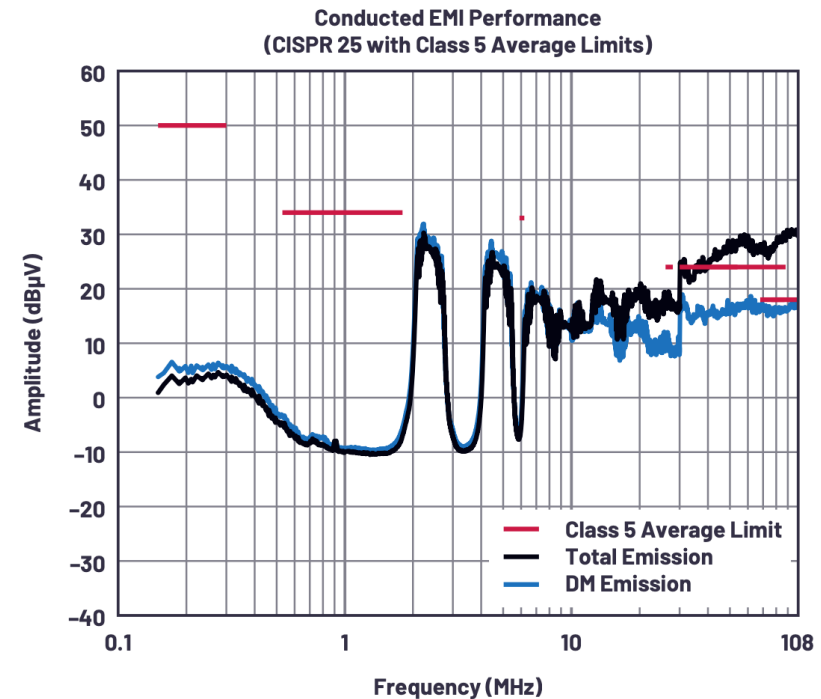


Test setup for measuring CM noise and DM noise.

Example 2: Line Filter Measurement for Conducted Emission



Measured CM noise vs. total noise



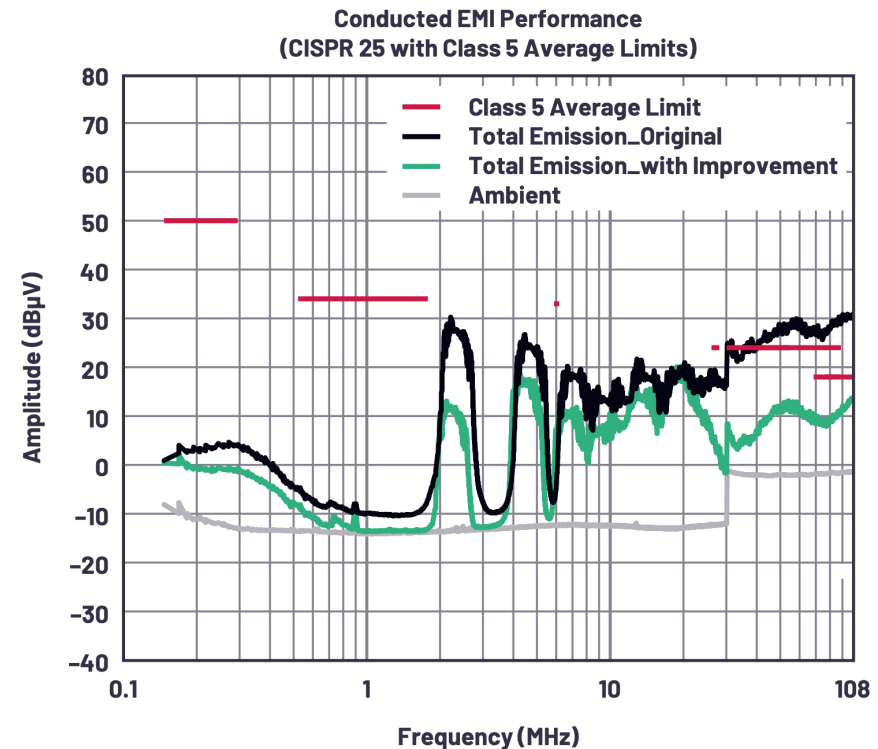
Measured DM noise vs. total noise

Conducted EMI Performance (CISPR 25 with Class 5 Average Limits)

Example 2: EMI Measurement after Re-design EUT

Proposed CM noise mitigation techniques:

- Identify CM noise source
 - Possible from high dV/dt signals in switching circuit.
- Redesign power line filter
 - Increase Z_{CM} by change the component values of C_C , L_{GW} , or L in choke



$$V_p, V_N.$$

$$V_p = 50(I_C + I_D)$$

$$V_N = 50(I_C - I_D)$$

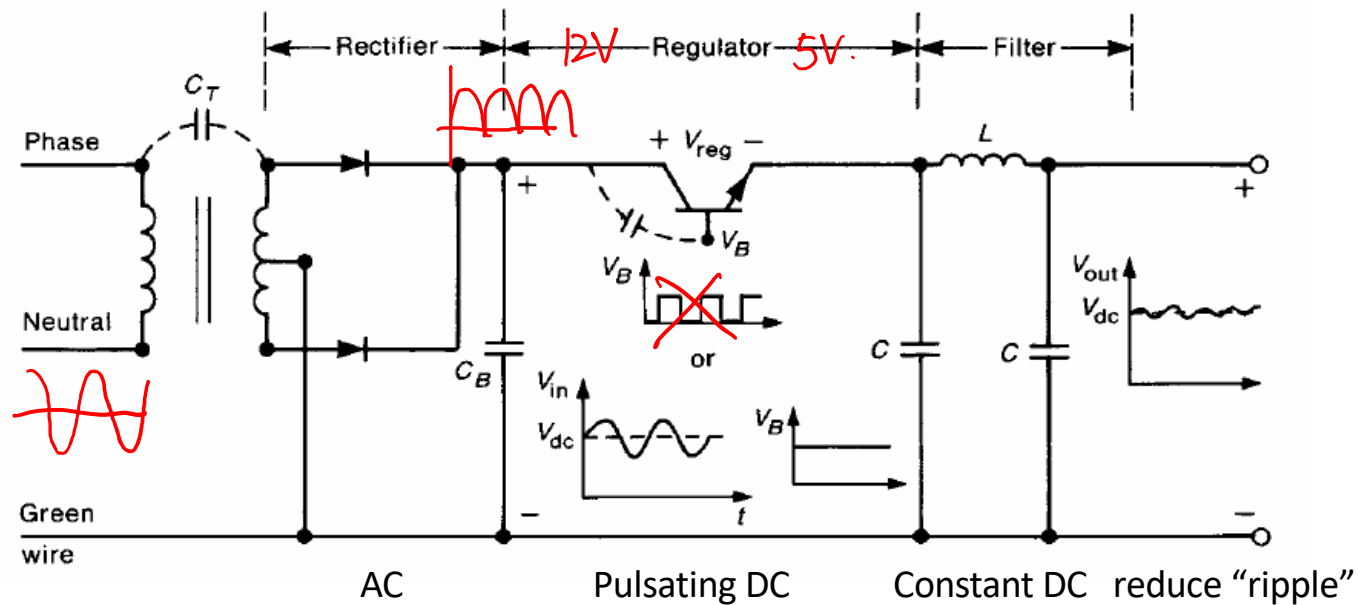
Conducted EMI Performance (CISPR 25 with Class 5 Average Limits)

5 Power Supplies

- The primary source of conducted emissions is generally the **power supply of the product**.
 - Linear Power Supply
 - Switched-Mode Power Supply
- The most effective method for reducing conducted emissions is to suppress them at their source.



5.1 Linear Power Supplies



$$V_{out} = V_{in} - V_{reg} \quad (R_L \uparrow, V_{out} \downarrow, V_{reg} \downarrow \Rightarrow V_{out} \uparrow)$$

Pro: Clean;
Con: Bulky, inefficient.

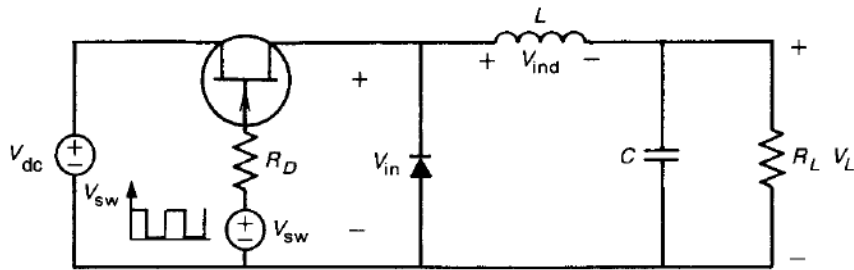
Illustration of a linear, regulated power supply

5.1 Linear Power Supplies

- Pro: Clean;
 - The transformer core is designed to operate at the commercial power frequency (60 Hz), but is very inefficient at the higher frequencies where conducted emissions are measured.
 - Not a strong source of high frequency signals themselves.
- Con: Bulky, inefficient.
 - the transformer core that is used at the 60 Hz power frequency is typically very large and heavy.
 - Linear power supplies are not very efficient.

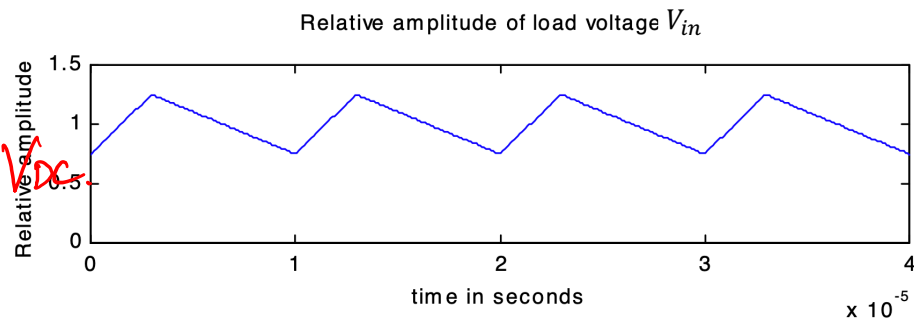
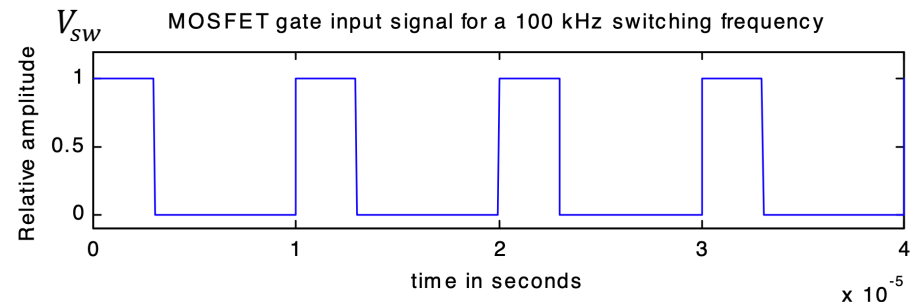


5.2 Switched-Mode Power Supplies (SMPS)



A DC voltage V_{DC} is modulated by V_{sw} at the gate of the MOSFET.

$$V_L = \text{Duty cycle} \times V_{DC}$$



A simple “buck regulator” switching power supply

Pro: Efficient, lighter in weight;
Con: High freq. noises.

6 Conducted Immunity

Conducted immunity refers to a product's resilience to electromagnetic interference coupled in through its AC power cord.

- reduced by the product's power supply and its power supply filter;
- the primary reason that conducted emissions are a problem is that electromagnetic energy finds its way to the power distribution network (a house, a building, etc.) where it is radiated and received by another product.

Conducted immunity problems are primarily due to large variations or transients on the power distribution network.

- Lightning, electromagnetic pulses (EMP) and power surges

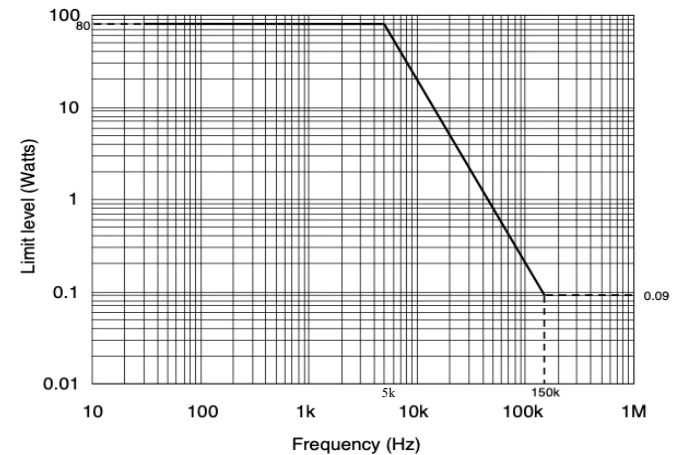
Automotive industry

- EMI can couple into/out of an electronic module from its DC power lines, bus lines, and sensor lines.
- inject current over a large frequency range on each input line to the module



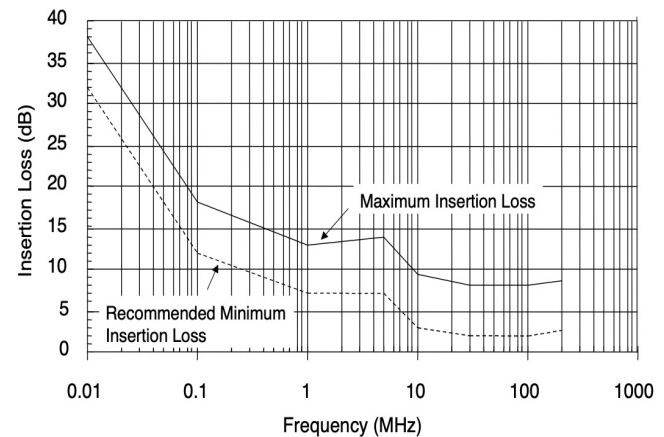
Conducted Immunity Military Regulations

- Low frequency conducted susceptibility
 - MIL-STD-461E, CS101, conducted susceptibility, low frequency, 30 Hz to 150 kHz



CS101 power limit for all applications

- High frequency conducted susceptibility
 - MIL-STD-461E, CS114, conducted susceptibility, high frequency, 10 kHz to 400 MHz



CS114 Maximum insertion loss for injection probes

Summary of Protection techniques

Many techniques are available for protection against conducted emissions.

Think Source-Path-Victim model:

- Source: reduce the noise being generated
 - reduce dv/dt or di/dt
 - snubbers
 - source-side filtering
- Path: make it harder for noise to propagate
 - common-mode choke
 - ferrite bead
 - shielding / grounding / cable routing
- Victim: reduce how much noise enters or affects the sensitive circuit
 - input filter / decoupling capacitor
 - RC, LC, or ferrite filtering
 - common-mode filter on an interface
 - shielding
 - improve circuit immunity / increase noise margin

