Electromagnetic Compatibility (EMC)

Topic 10

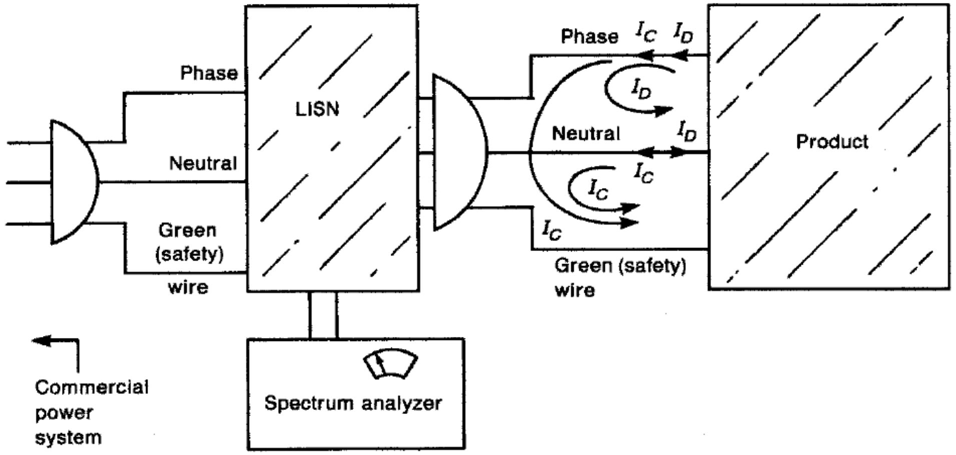
Conducted Emissions and Susceptibility

Mohammad S. Sharawi, PhD., P.E.

Introduction

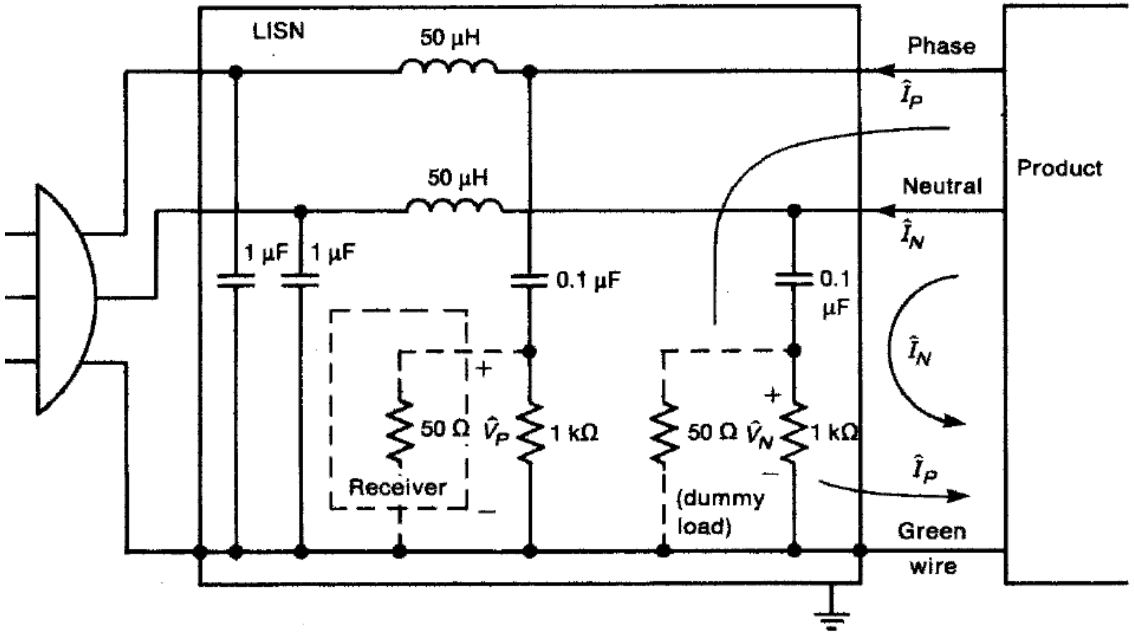
- The fact that the commercial power system consists of a large array or wires makes it a large “antenna” when noise is present on such wires (conducted emissions)
- Meaning that “conducted emissions” can lead to “radiated emissions” thus potentially causing interference
- It is usually simpler to reduce conducted emissions than fixing a radiation one, because conducted emissions have specific paths that can be identified and the exit path is the power supply one (unit’s power cord).
- It is known that if a product fails conducted emissions, it will definitely fail radiated ones!
- A product also should be insensitive to the disturbances present on the power system network (conducted susceptibility) in order to function properly
- Lightning is a major contributor noise currents in the power system and the susceptibility of the system is from such noise and disturbance currents
- The Line Impedance Stabilization Network (LISN) is used to measure conducted emissions as we saw before.

LISN



- A quick review.
- Two advantages of the LISN:
  (1) To provide a constant impedance (~50Ω) to the product's power cord outlet over the conducted emissions frequency range (to ensure repeatability of measurements)
  (2) The isolate the product from external contaminating noise and only measure the levels from the product itself

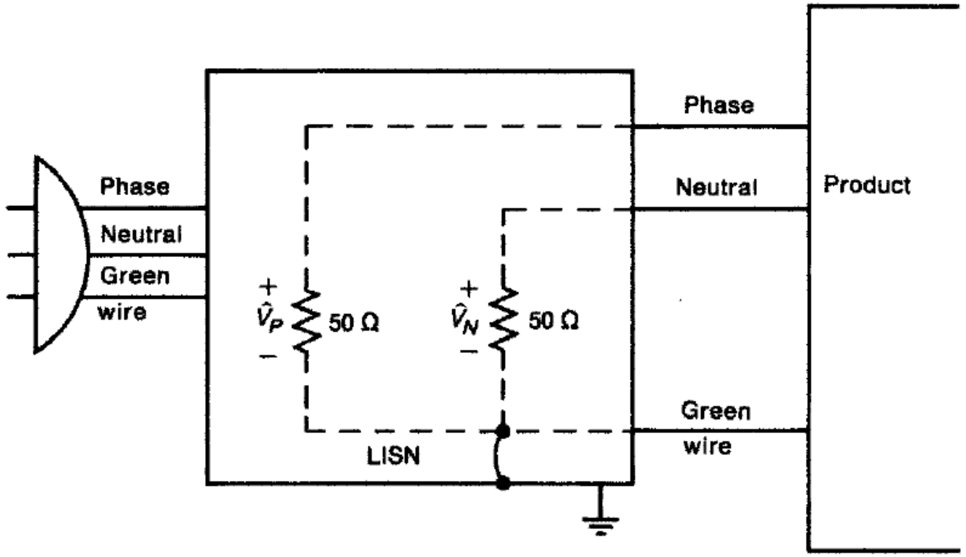
- The 1μF caps and 50μH are used to divert external noise and prevent it from contaminating the measurement
- The 0.1μF Caps are used to prevent any DC from overloading the input of the test equipment
- 1KΩ resistors act as static charge paths for 0.1μF caps if 50Ω are removed
- Measurements are conducted between 150 kHz – 30 MHz.



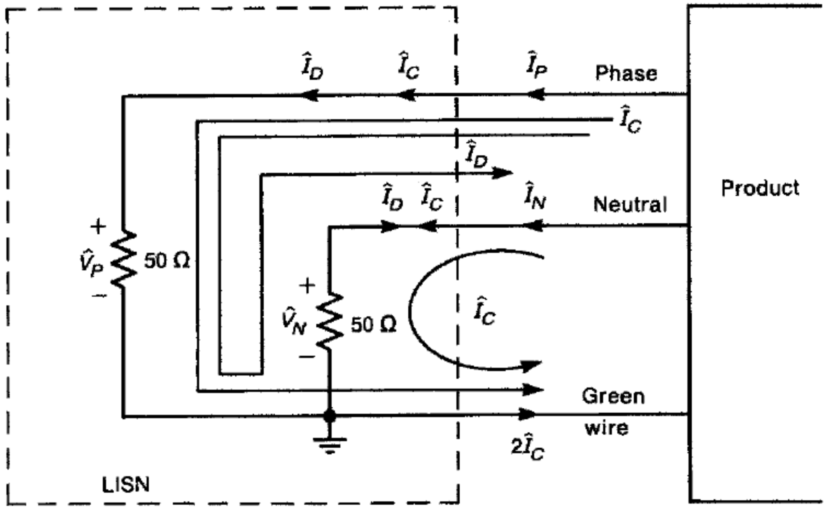
- While one 50Ω is for the test received (Spectrum Analyser – SA), the other is a dummy load to insure a fixed 50Ω impedance between the neutral and safety wires
- The voltages V_P and V_N are measured between the phase and neutral wires and the safety wire, respectively.
- Both voltages (V_P and V_N) should be below the specified limits across the complete frequency band
- Emission current are simply,

$$\hat{V}_P = 50\hat{I}_P$$
$$\hat{V}_N = 50\hat{I}_N$$

- Any current in the frequency range of the regulation that exists on the product power cord will be measured by the LISN and can contribute to the failure of the product to satisfy conducted emissions requirements



CM and DM currents (revisited)



- The phase and neutral currents consist of DM and CM currents,

$$\hat{I}_P = \hat{I}_C + \hat{I}_D \quad , \quad \hat{I}_N = \hat{I}_C - \hat{I}_D$$

- Solving,

$$\hat{I}_D = \frac{1}{2}\left(\hat{I}_P - \hat{I}_N\right) \quad , \quad \hat{I}_C = \frac{1}{2}\left(\hat{I}_P + \hat{I}_N\right)$$

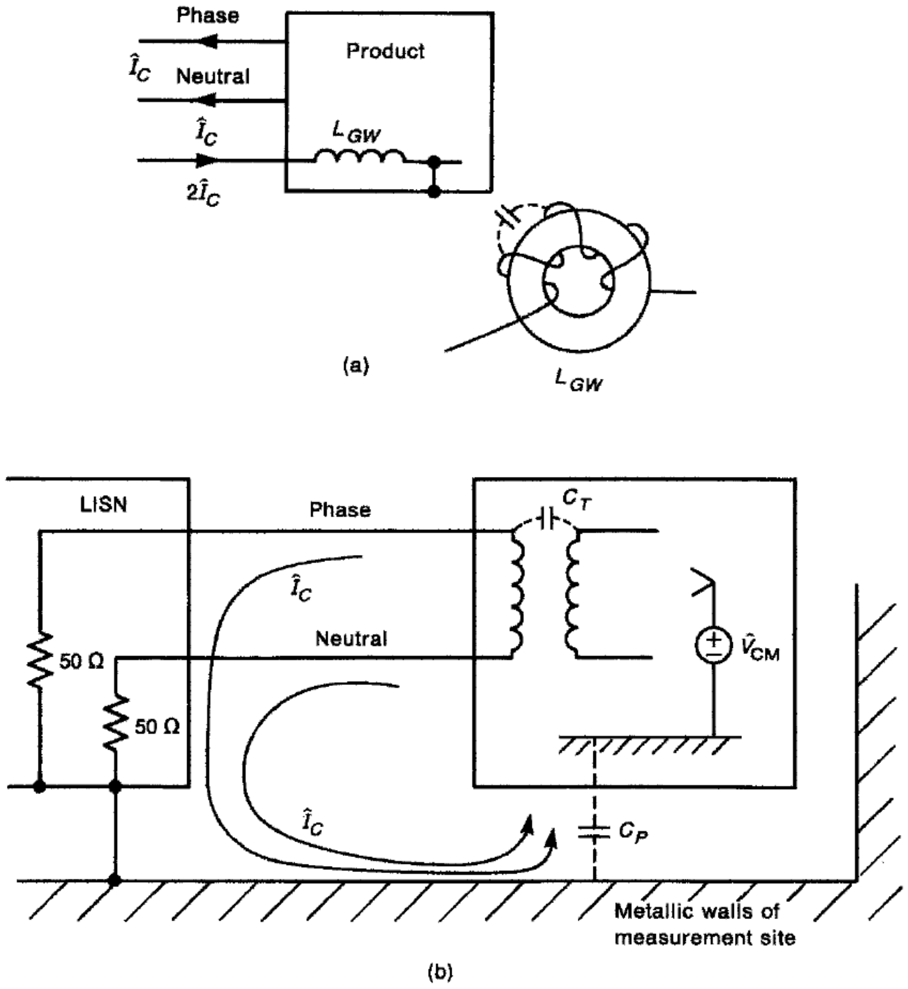
- Thus measured voltages are $\hat{V}_P = 50\left(\hat{I}_C + \hat{I}_D\right) \quad , \quad \hat{V}_N = 50\left(\hat{I}_C - \hat{I}_D\right)$

- As opposed to radiated emissions, CM currents can be of the same order of magnitude or exceed their DM counterparts in conducted emissions!
- Note that if the CM and DM currents are of the same magnitude, the values of VP and VN will not be the same.
- Usually one component dominates the voltages, i.e.

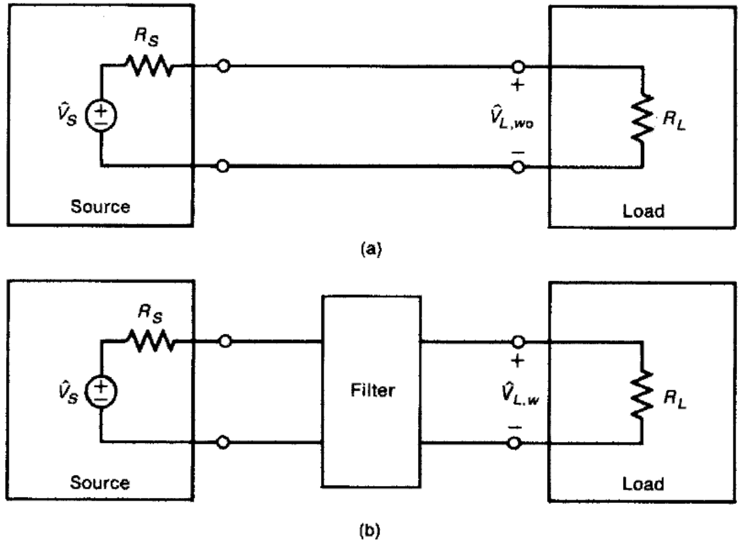
$$\hat{V}_P = \hat{V}_N = 50\left(\hat{I}_C\right) \text{ if } \hat{I}_C >> \hat{I}_D \quad , \quad \hat{V}_P = \hat{V}_N = 50\left(\hat{I}_D\right) \text{ if } \hat{I}_D >> \hat{I}_C$$

- All products have a power supply filters that can reduce either CM or DM currents
- Two common methods that are used to block the CM current path:
  (1) Using an inductor on the Green wire (ground) that will act as a high impedance to CM currents in the range of frequencies for the test (without blocking the fault current, thus safety is maintained). The inductor is wound around a ferrite toroid. Typical L_{GW} value is 0.5mH (see Figure (a)).
  (2) A Two-Wire product where only the phase and neutral are used and the safety wire is absent. This has a shock hazard potential as the neutral is connected to earth ground. This hazard can be avoided via the use of a 60 Hz transformer at the power entrance of the product

  The stray capacitance between the product chassis and the metallic walls of the test site act as the Green wire path to the LISN (Figure (b))

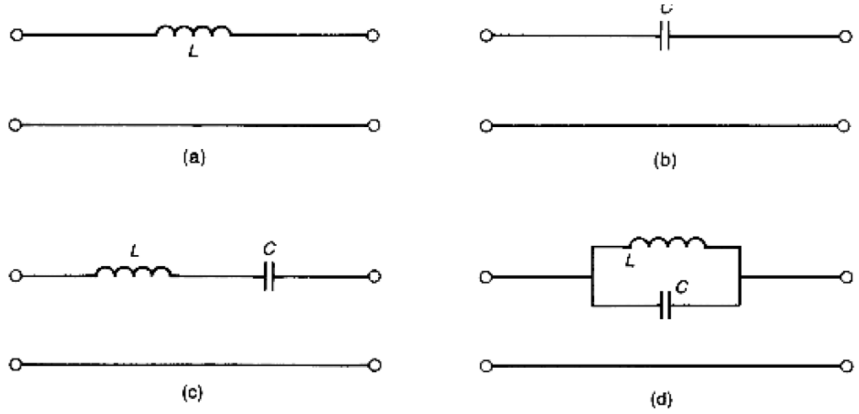


Power Supply Filters (revisited)



- No electronic equipment can comply with conducted emissions without the use of some sort of power supply filters
- Properly designed transformers can provide filtering
- There are several methods and techniques for filter design, and can be found in any electronics book. We will only focus on power supply ones here.
- The insertion loss (IL) of the filter is defined as,

$$IL_{dB} = 10\log_{10}\left(\frac{P_{L,wo}}{P_{L,w}}\right) = 10\log_{10}\left(\frac{V_{L,wo}^2 / R_L}{V_{L,w}^2 / R_L}\right) = 20\log_{10}\left(\frac{V_{L,wo}}{V_{L,w}}\right)$$

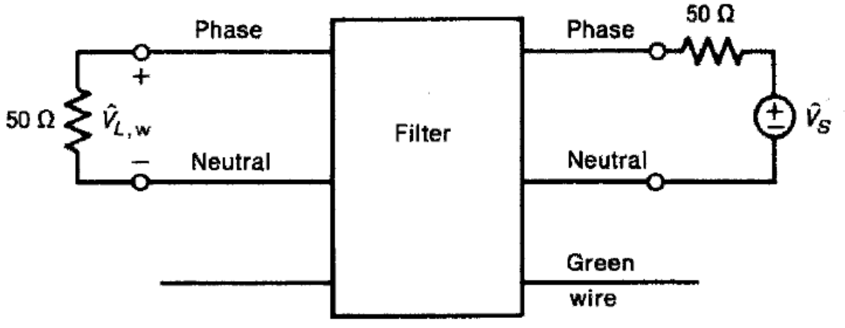


- In some conventional simple filter designs, the IL is a function of the source and load impedances, and we assume 50Ω. Consider (a),

$$V_{L,wo} = \frac{R_L}{R_L + R_s} V_s \quad , \quad V_{L,w} = \frac{R_L}{R_L + R_s} \frac{1}{1 + \left[j\omega L / \left(R_s + R_L \right) \right]} V_s$$

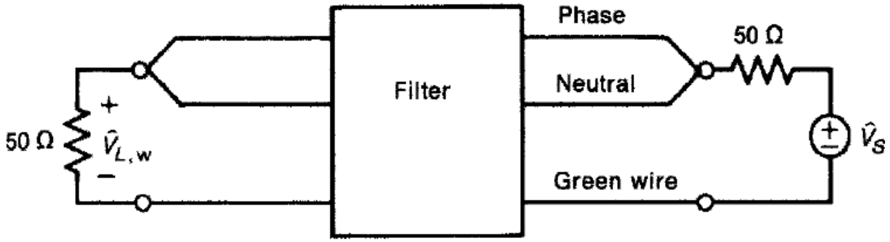
$$IL = 20\log_{10}\left| 1 + \frac{j\omega L}{\left(R_s + R_L \right)} \right| = 20\log_{10}\left| \sqrt{1 + \left(\omega\tau \right)^2} \right| = 10\log_{10}\left| 1 + \left(\omega\tau \right)^2 \right| \quad , \quad \tau = \frac{L}{\left(R_s + R_L \right)}$$

- When designing filters be mindful of the following when it comes to conducted emissions compliance,
  1. The impedance of the source/Load is not guaranteed to be 50Ω (might change with frequency) – note that LISN will show 50 Ω load
  2. There are two types of currents that we need to consider, the CM and DM ones



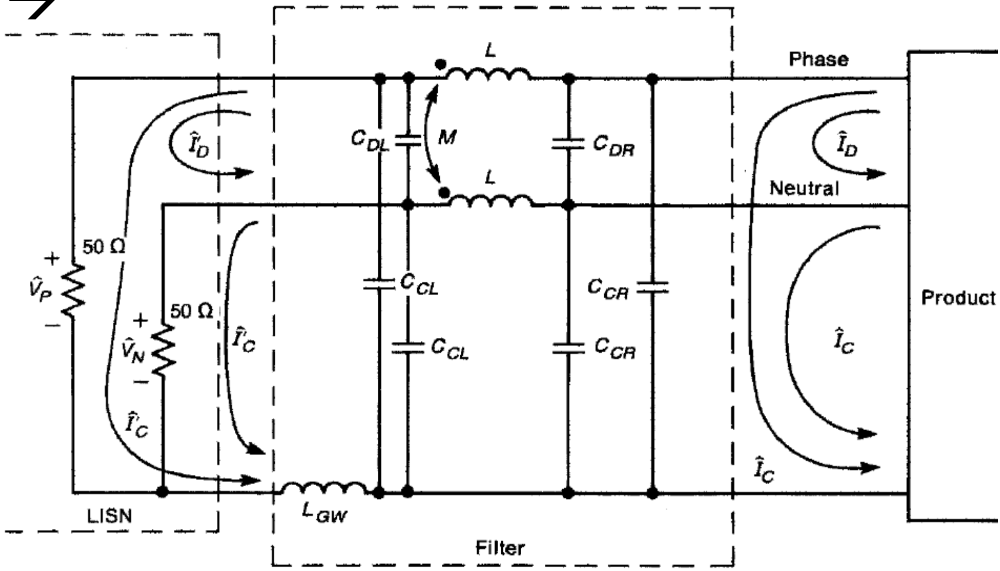
(a)

- Note the filter connection for DM and CM currents in the figure→ shown



(b)

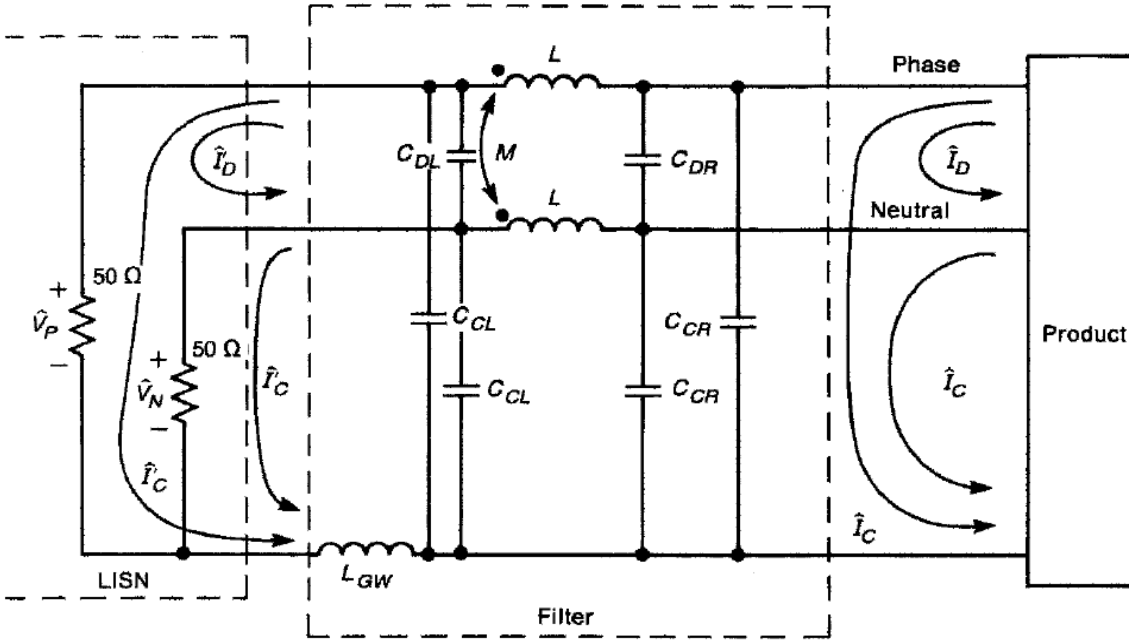
- A generic pi-structure based filter for power supplies is shown →
- Objective of filter is to reduce the unprimed currents to the primed levels such that the primed currents give measured voltages that are below emissions limits for all frequencies



$$V_P = 50\left(I_C^{'} + I_D^{'}\right)$$

$$V_N = 50\left(I_C^{'} - I_D^{'}\right)$$

- Caps between phase and neutral wires, C_{DL} and C_{DR}, are for diverting DM currents (line-to-line caps also called X-caps)
- Caps between phase-green and neutral-green wires, C_{CL} and C_{CR}, are used to divert CM currents (line-to-ground caps also called Y-caps)
- X and Y caps should have safety considerations and voltage ratings (special for power supplies)
- While the shown pi-topology is generic, depending on the device/system, you might use left (L), right (R), or both caps in the filter. You need to decide.
- Typical values for $C_D \approx 0.047$ µF and $C_C \approx 2200$ pF.
- Consider the C_{CL} cap, which is parallel to the 50Ω LISN impedance. This CM cap will be effective only if its impedance is lower than 50Ω so that it diverts the CM current. Simple calculation shows that C_{CL} will have 50Ω impedance at 1.5MHz, meaning that it will have lower than 50Ω impedance only above 1.5MHz.



EX: what would be the maximum line-to-ground capacitance to satisfy a leakage current requirement of 150µA?

<u>*Sol:*</u>

$$|Z_C| = \left|\frac{V}{I}\right| = \frac{1}{\omega C}$$

$$\frac{120}{150\times10^{-6}} = 800000 = \frac{1}{2\pi(60)C}$$

$$C = 3.316nF = 3316\,pF$$

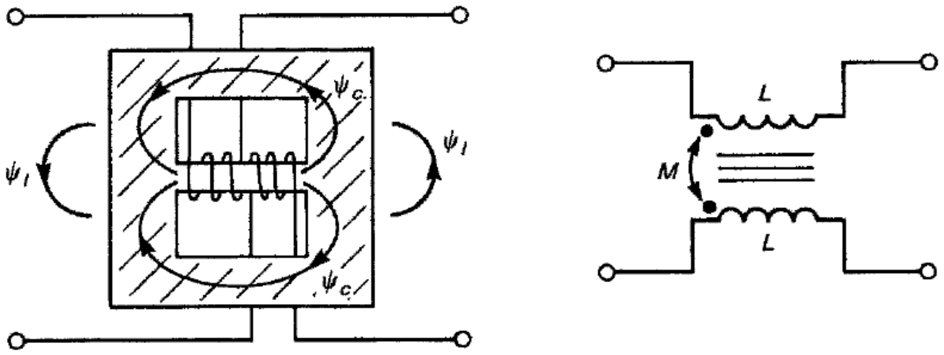
- Another element that is part of the filtering process is the common-mode choke (coupled inductors) shown between the phase and neutral lines
- Again, the purpose of the CM choke is to block CM currents without affecting DM ones
- Recall that L-M is the leakage inductance, and thus **ideally** when L=M no effect (voltage drop) happens on DM currents

$$V = j\omega L I_D - j\omega M I_D = j\omega\left(L-M\right)I_D$$

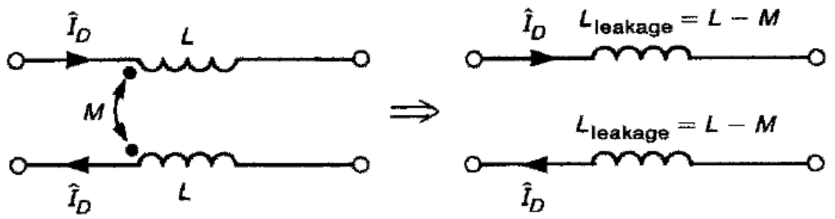
- For CM currents, we have L+M contribution, thus high voltage drop and blockage of CM currents occur

$$V = j\omega L I_C + j\omega M I_C = j\omega\left(L+M\right)I_C$$

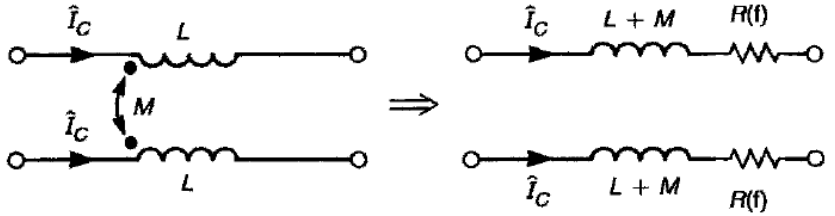
- Typical values of L $\approx$ 10mH, the impedance values of 18.8kΩ at 150KHz and 3.77MΩ at 30MHz.
- Note that the CM choke inductance values depends on the ferrite core saturation and the parasitic capacitance between the windings. High 60Hz currents can saturate the core material, and thus lowers the inductance values and reduces CM rejection.



(a)



(b)



(c)

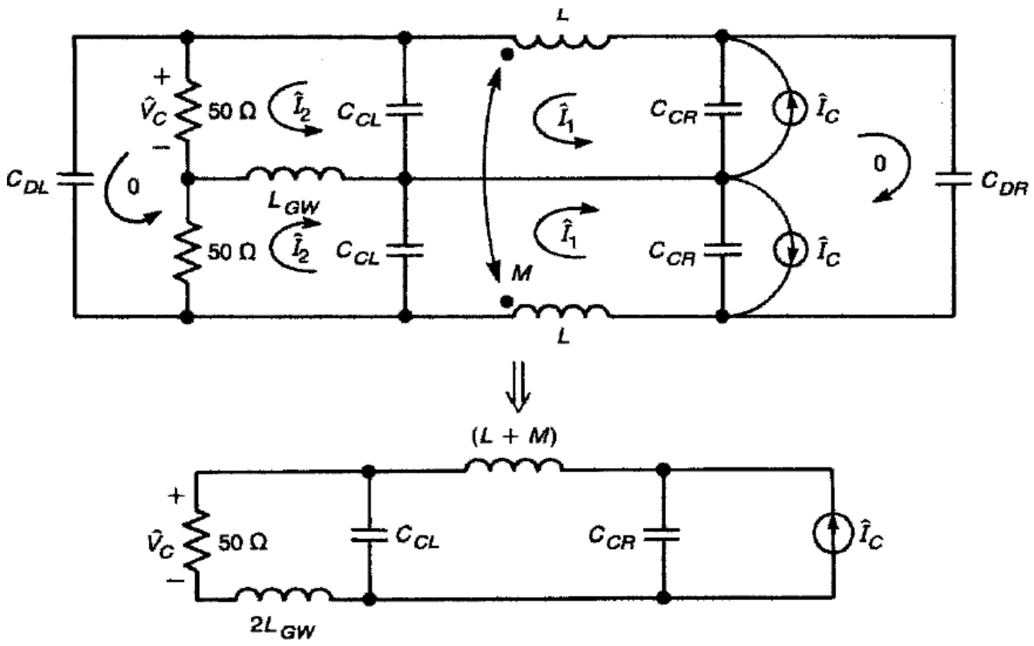
- We will assume that the filter in regards to phase and neutral is symmetric for DM and CM currents.
- Let us investigate **CM current filters**. Check the equivalent circuit shown.
- Note that we have L+M as the equivalent inductance, line-to-line caps have no effect (C_{DL}=C_{DR}=0, i.e. open, no current), and L_{GW} has 2 times the current I2. Thus we have the equivalent circuit below.
- Note that the Green-wire inductance will play a role in blocking CM currents if C_{CL} is present. Typical values of L_{GW} ~ 2mH, while L+M ~ 55mH.
- We can use current division to find,

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

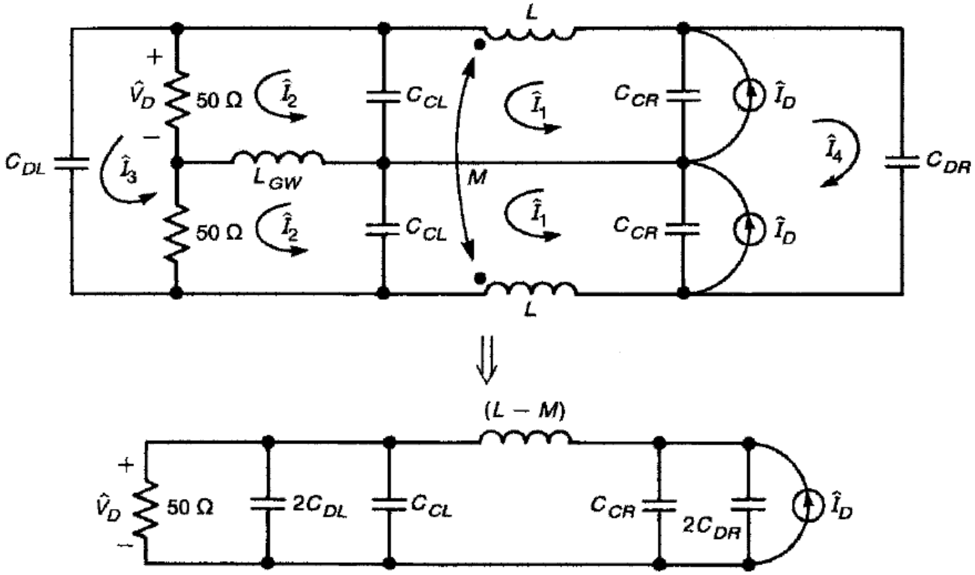
- The break frequency occurs at f0, with -40dB/decade afterwards

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

- If L_{GW}=1mH, and C_{CL}=3300pF, the f_0=62kHz, which is below 150kHz. The -40dB/decade will aid in reducing CM currents, thus L_{GW} will play a positive role.

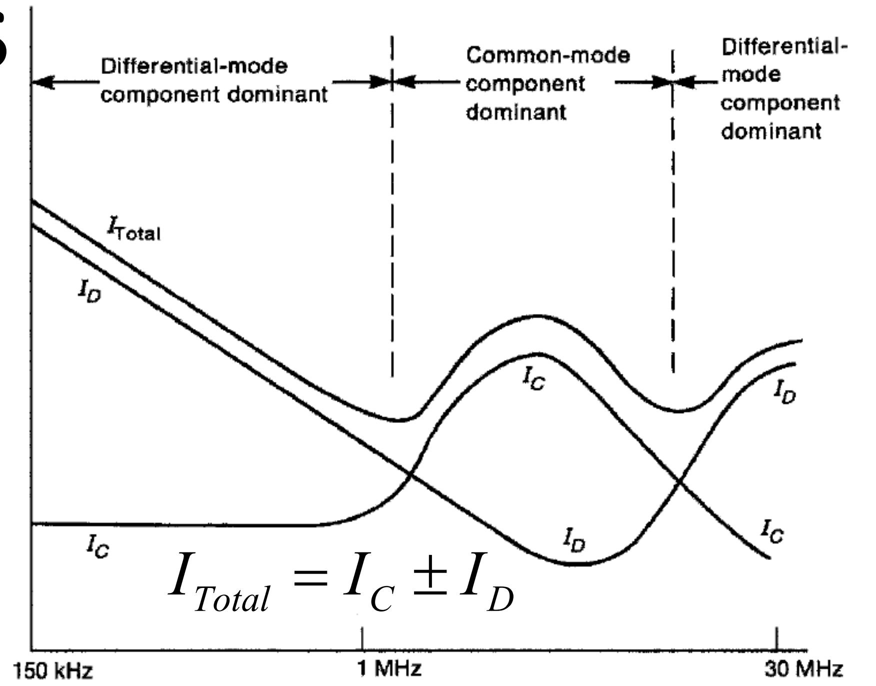


- For **DM currents**, we have the equivalent circuit shown.
- Again, we assume symmetric filters applied, and since the current directions of DM currents in the LGW are opposite, its effect is canceled.
- Line-to-line caps are doubled, and line-to-ground caps are present, and thus have an effect on DM currents. But the effect of C_C caps are not significant due to their smaller values as compared to C_D ones.
- Note also that the CM choke is transparent to DM currents because its value is L-M, and ideally both are equal.
- In real designs, $L \neq M$, and thus more analysis and considerations should be considered.

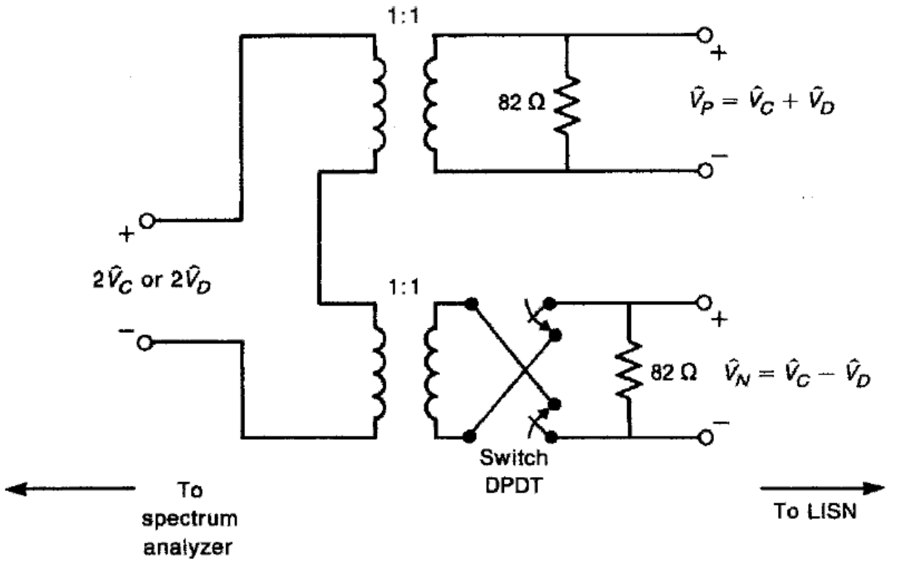


Separation of DM and CM emissions

- The most important point to realize in the course of changing a power supply element (to filter out CM or DM currents) to reduce conducted emissions is presented in the figure shown.
- It is important to realize that the total current is the sum or difference of the CM and DM components.
- If one current dominates, then the total current is dominated by this component.
- If we want to reduce the total conducted emissions in a certain band, we need to reduce the dominant component in that region
- Change the filter component(s) that affect and reduce the dominant component of the total current to reduce conducted emissions.
- There exists some circuits that can separate the CM and DM components of the total conduction emissions. One circuit is shown based on [1].



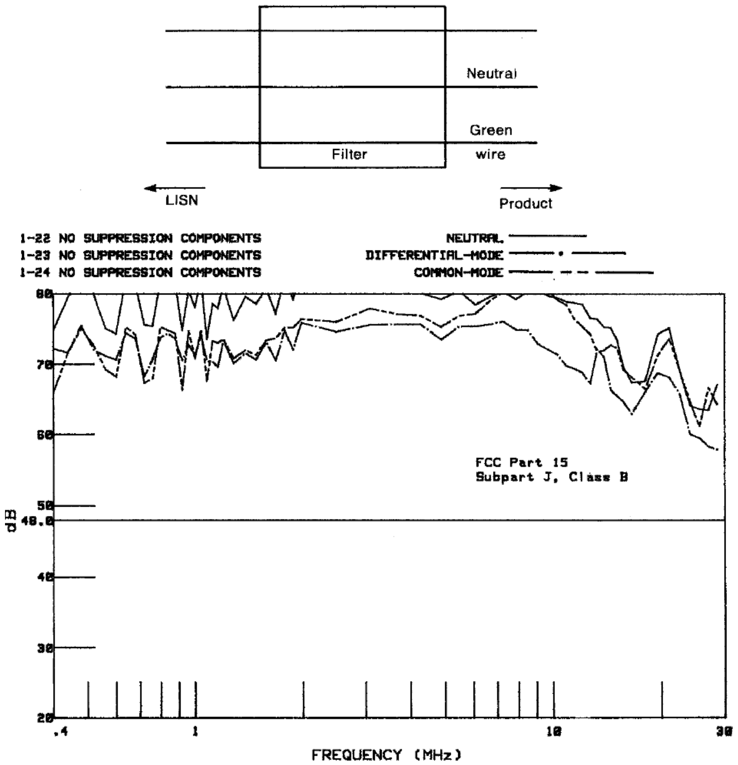
$$I_{Total} = I_C \pm I_D$$

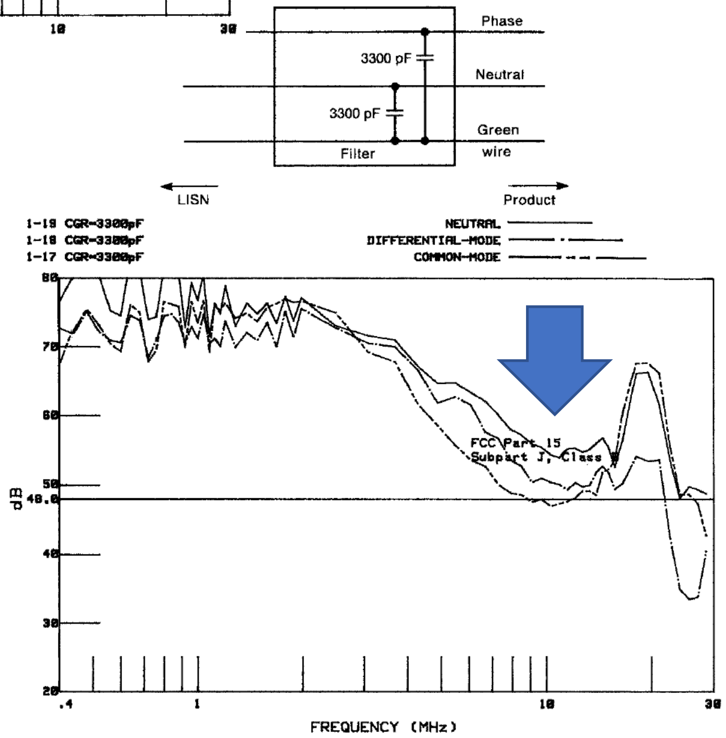


[1] C. Paul et. Al. , “Diagnosis and reduction of conducted noise emissions,” IEEE Transactions on Electromagnetic Compatibility, Vol. 30, pp. 553-560, 1988.

Example

- A typical electronic device was tested with a switching power supply.
- Without any filtering, the conducted emission levels were more than 30dB above limits of FCC Class B → Fail!
- CM and DM components were measured (using the circuit proposed in [1]) along with the total current from the LISN.
- First, we ADD 3300pF line-to-ground caps. Reduction to both CM and DM occurred above 2MHz. Note that break frequency was around 1MHz

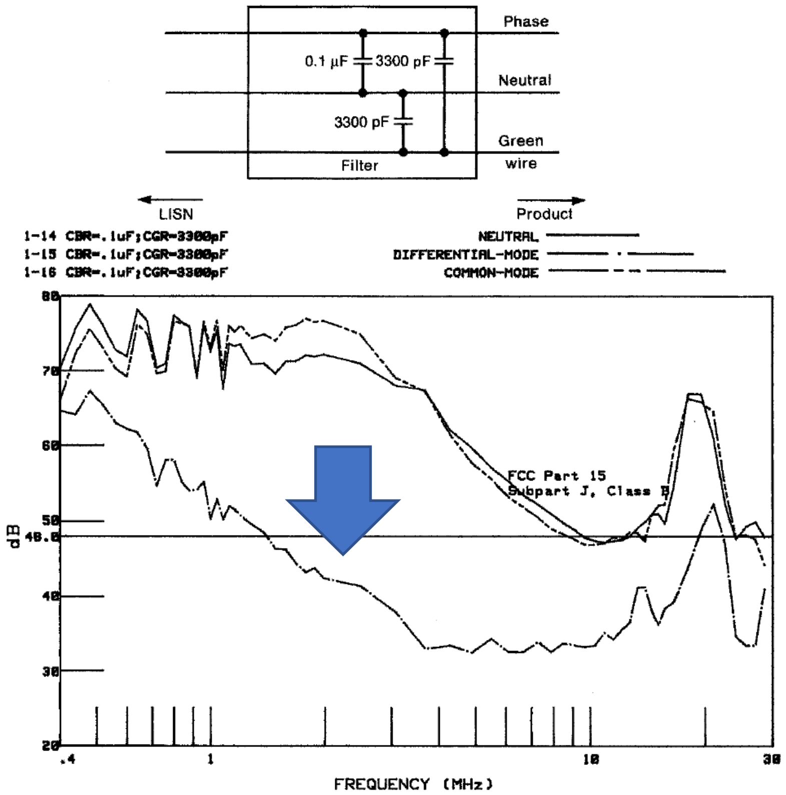




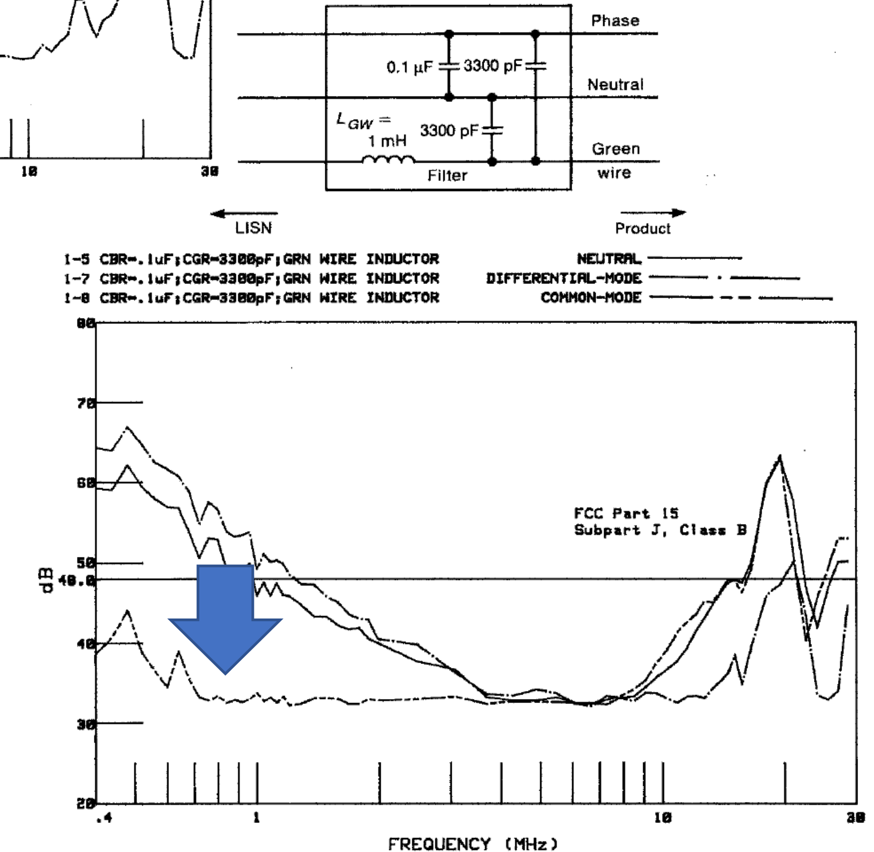
- Next we add a 0.1µF line-to-line cap. This affected only the DM component and not the CM one. This is expected, as according to the figure in slide 12, the break frequency will be when

$$C_T = 2C_D + C_C = 0.203\mu F$$

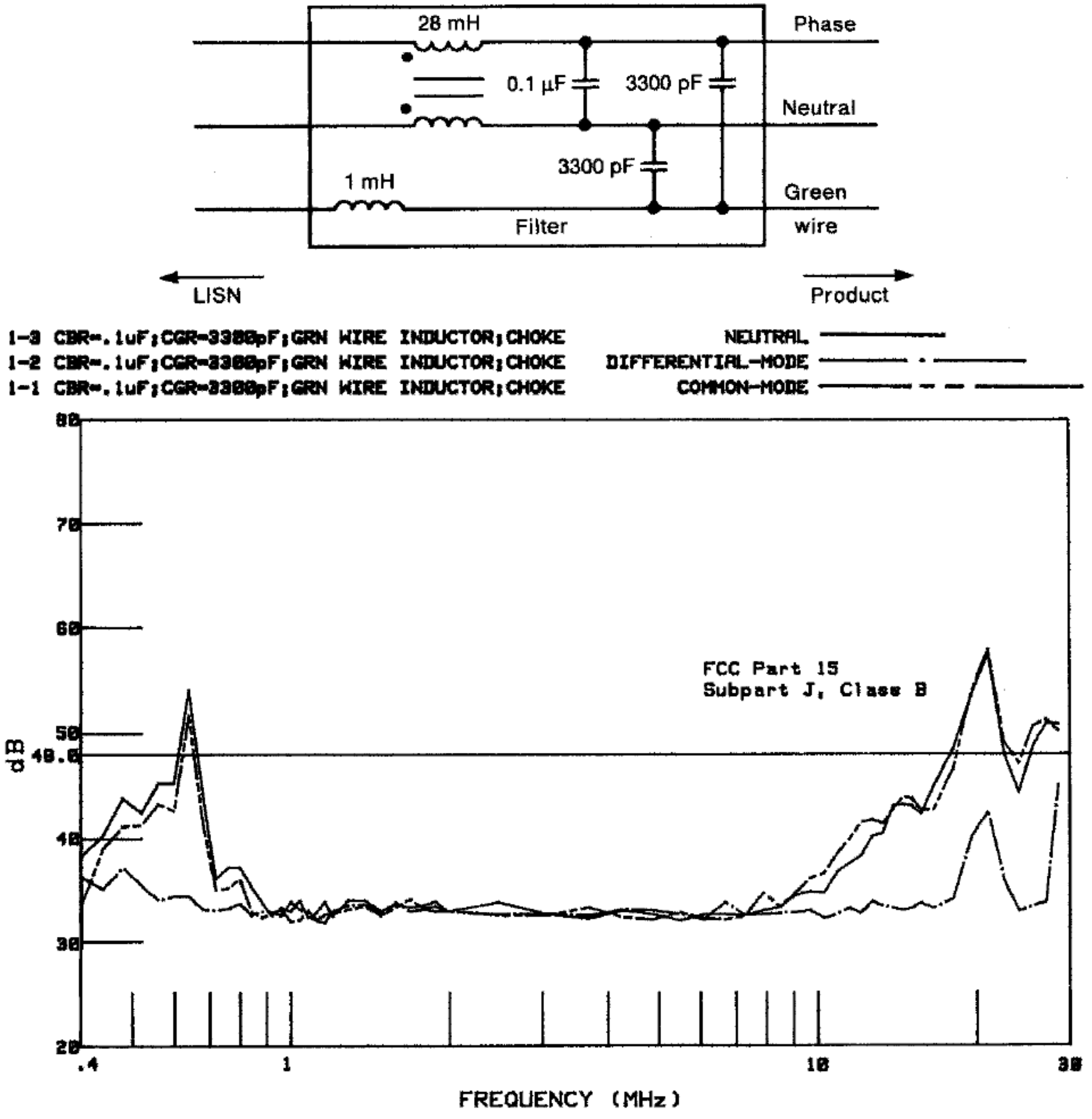
$$|Z_{CT}| = 50 \rightarrow f = \frac{1}{2\pi(50)C_T} = 15.7kHz$$



- Next, add the inductance on the green wire L_{GW} = 1mH. The CM levels are reduced as shown. The reduction in CM should occur when the impedance of $2L_{GW}$ = 50, which is around 4KHz.



- Finally, we add a 28mH common-mode choke between phase and neutral lines
- Note that the choke has reduced the DM currents and not much the CM ones. This is because the CM ones have been already reduced by the L_{GW}. And the effect on DM currents is because of the **non-ideal leakage** inductance of the choke. This is an example where non-ideal behavior plays to our advantage.

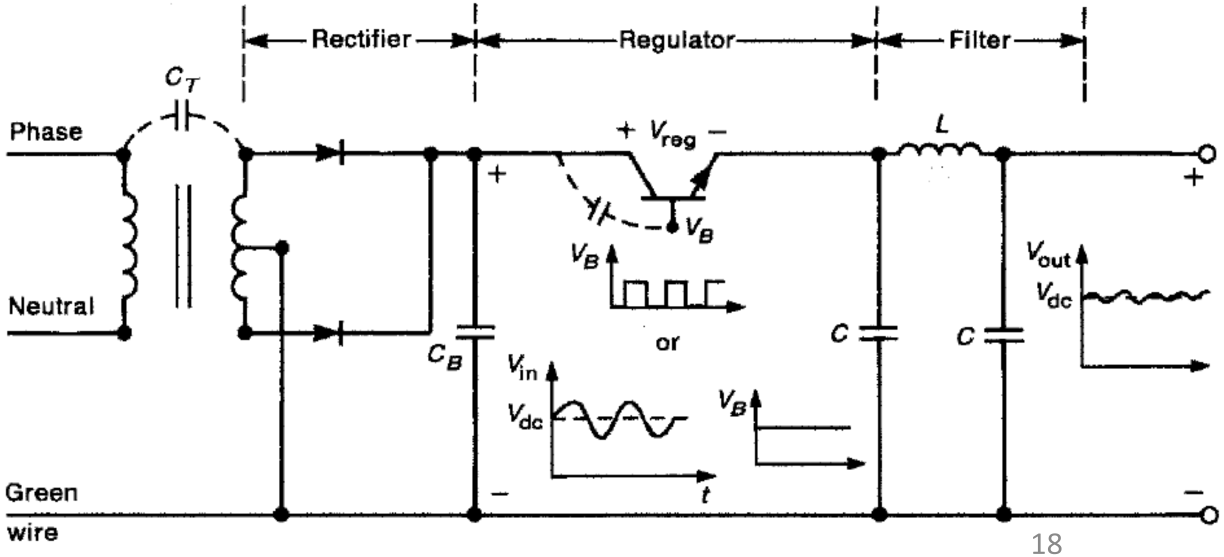


Common types of Power supplies

- The primary source of conducted emissions is generally the power supply of the product
- Also, coupling from nearby high speed circuits and lines (i.e. clock signal) will make sure noises appear at the output of the power cords and detected by the LISN.
- Power supplies various kinds of noises, and the best way to supress such noises from propagating to the lines and causing conducted emissions is to supress them at their source.
- Regulation of the power supply voltage is the process of maintaining its DC value within a certain fluctuating limits (i.e. 1%) of its nominal fixed value (i.e. 5V).
- We will discuss two very common types of power supplies:
  - **Linear** power supplies: less noisy, dissipate more power, less efficient
  - **Switched mode** power supplies: more noisy, dissipate less power, more efficient

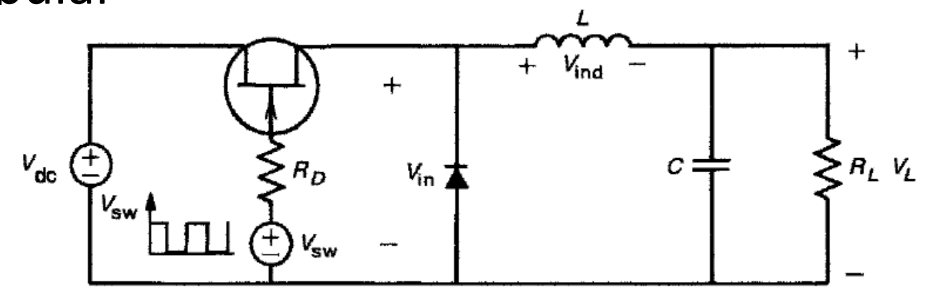
- **Linear, regulated** power supplies were dominant for converting AC to DC voltages to power electronic devices.
- A transformer is used to step-down the AC signal to a lower value one before passing it to a full-wave rectifier (rectifies the negative sine wave half into positive, i.e. flips it)
- The capacitor will then make the voltage fluctuate around the average DC value.
- A low-pass filter (60Hz) follows to further smooths the DC voltage around the desired fixed value.
- The transistor is used to regulate the voltage levels and fixes its values regardless of the load currents (since the load can draw various amounts of currents, a regulating circuit will maintain the voltage level unchanged regardless of the drawn current, of course, within the device limits), thus the transistor acts as a variable resistor such that: $V_{out} = V_{in} - V_{reg}$
- Linear power supplies are not very noisy
- Efficiencies in the order of 20-40%
- Transformer core is large in size (60Hz)
- Since it conducts current all the time, it suffers

From high power dissipation!



- Switched-Mode power supplies (SMPS) can provide much higher efficiencies as compared to Linear ones, with levels between 60 – 90%. They are very popular
- They dissipate less power! Transistor on or off!
- They are noisier than their linear counterparts

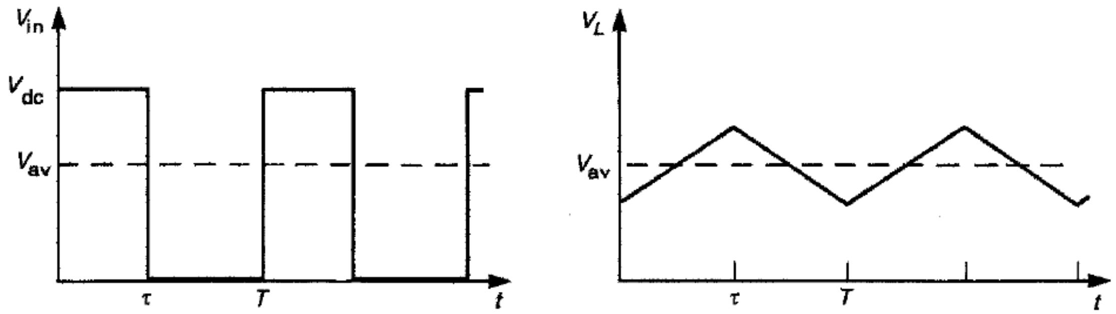
→ EMC issues!



- They need transformers that work at 20-100KHz

→Smaller size cores → less heavy

- The circuit shown is for a Buck regulator
- The DC voltage (from the rectifier) is passed to a

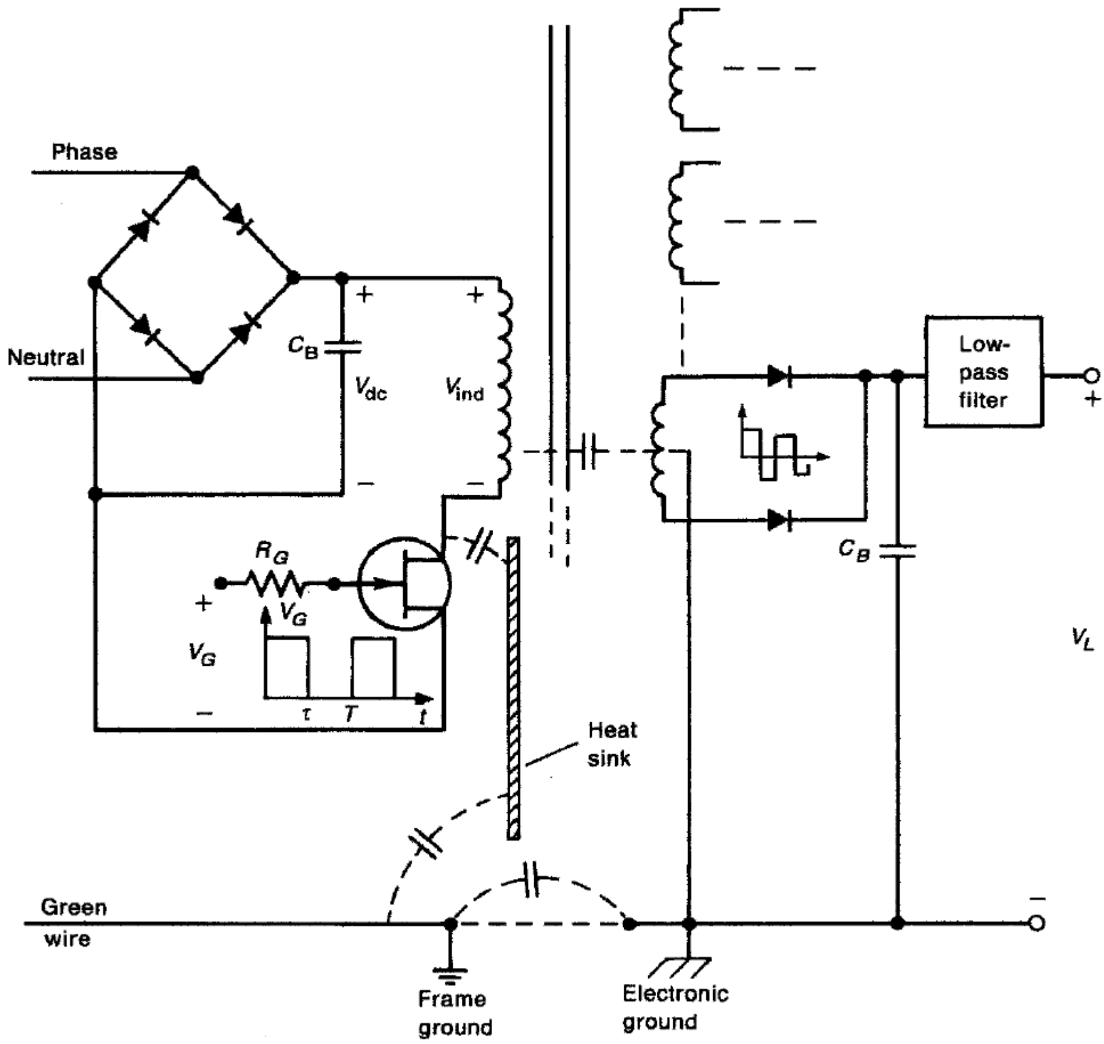


Switching element (i.e. transistor). Switching waveform has a pulse width τ and period T, thus providing an average DC value of:

$$V_{avg} = \frac{\tau}{T} V_{DC}$$

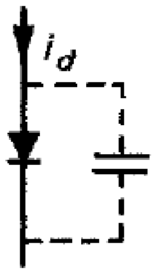
- The average value can be changed and controlled by the pulsed waveform.
- A low-pass filter is used to reduce the ripple
- The diode provides a path to discharge the capacitor with the transistor is off
- Two types of switchers: Primary side and secondary side (switching location)

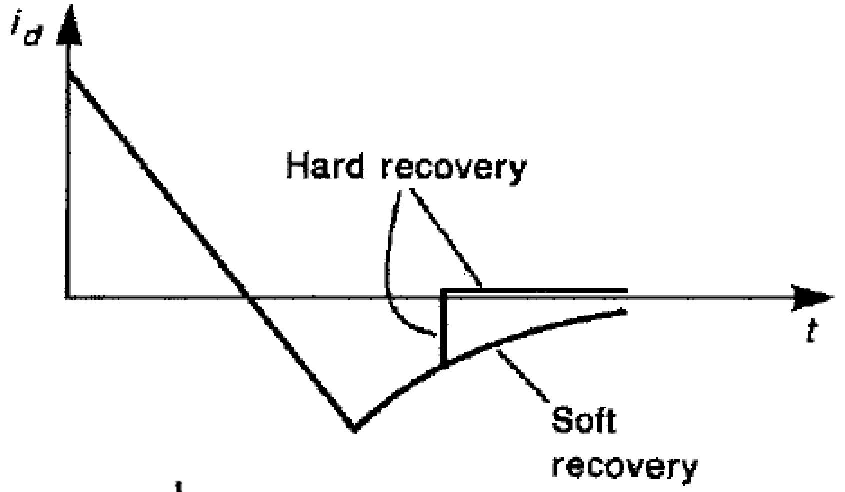
- **Primary side switcher example**
- regulation is done via varying the duty cycle
- Primary switcher is called a **Flyback converter**
- A Full bridge rectifier rectifies the AC signal
- The cap creates the pulsating wave around DC value
- The switching element will control the average DC values obtained.
- The resistor RG will control the rise/fall times of the pulses, thus trading more ON time (more power dissipation, more heating and less efficiency) of the transistor for slower edges (less noise)
- A heatsink is used to dissipate heat and is attached to the transistor. This produces a parasitic capacitance with ground thus creating a CM current path
- At secondary, we can have multiple taps for multiple output voltages, i.e. 5, 12, -12, etc.
- Note that the noise from switching circuit is fed back through the bridge rectifier to the AC lines! Not transformer there.

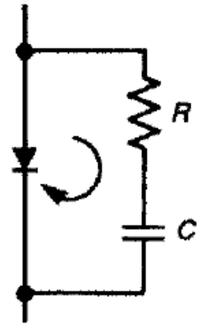


Effect of power supply components on conducted emissions

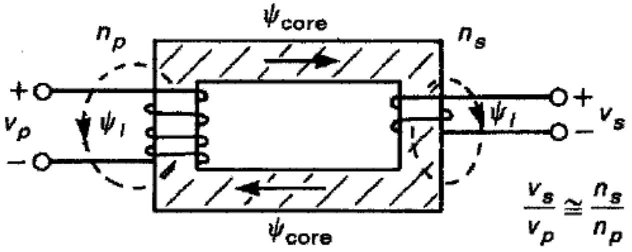
- When a **diode** is forward biased, **charge** is stored within its junction capacitance. When it is turned off, this charge should be removed.
- **Fast/hard recovery diodes** can instantly snap off, which will create high frequency content noise. Slow recovery diodes take more time to discharge and thus less noise generation.
- We can reduce noise from hard recovery diodes via the use of a **Snubber circuit** (RC). Pay attention to make sure the loop created for this discharge current is small so that it does not radiate as well (remember the loop current issue!)
- Parasitic capacitors provide numerous current paths for noise currents to exit the switcher and ass to the products conducted emissions.





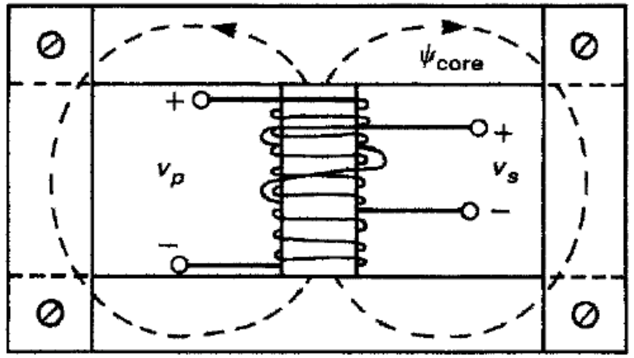


- **Transformers** are widely used in power supplies. In linear type supplies, the core of such 60 Hz transformers is heavy and large to reduce eddy-currents losses within it.
- Because of the much lower reluctance values in the ferromagnetic core as compared to air, the majority of the magnetic flux circulates within the core and couples to the secondary.
- Several ways are devised to construct cores with low reluctance and low **eddy-current losses** such as the I-core and the **E-core** shown.
- The air gap in the E-core will reduce the saturation possibility that might result from high current levels that lead to high flux densities. The gaps can be made via plastic spacers that will insert air-gaps within the core, thus increasing its reluctance and reducing the flux levels within it and maintaining its proper operation.



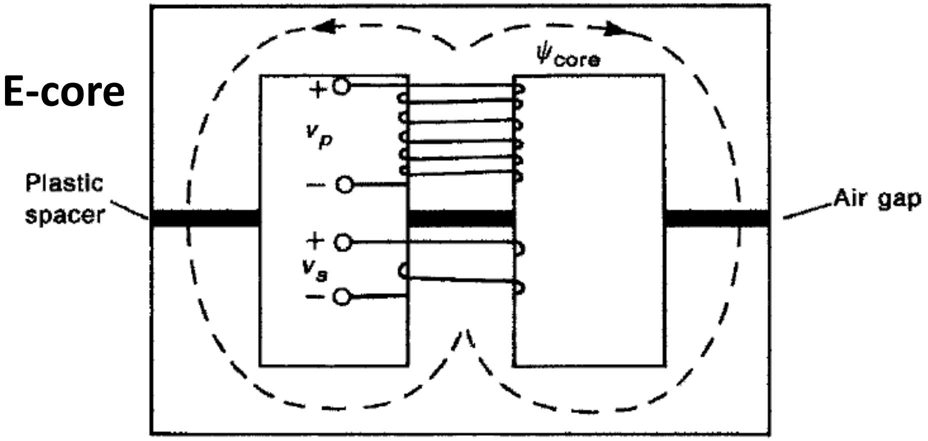
(a)

I-core



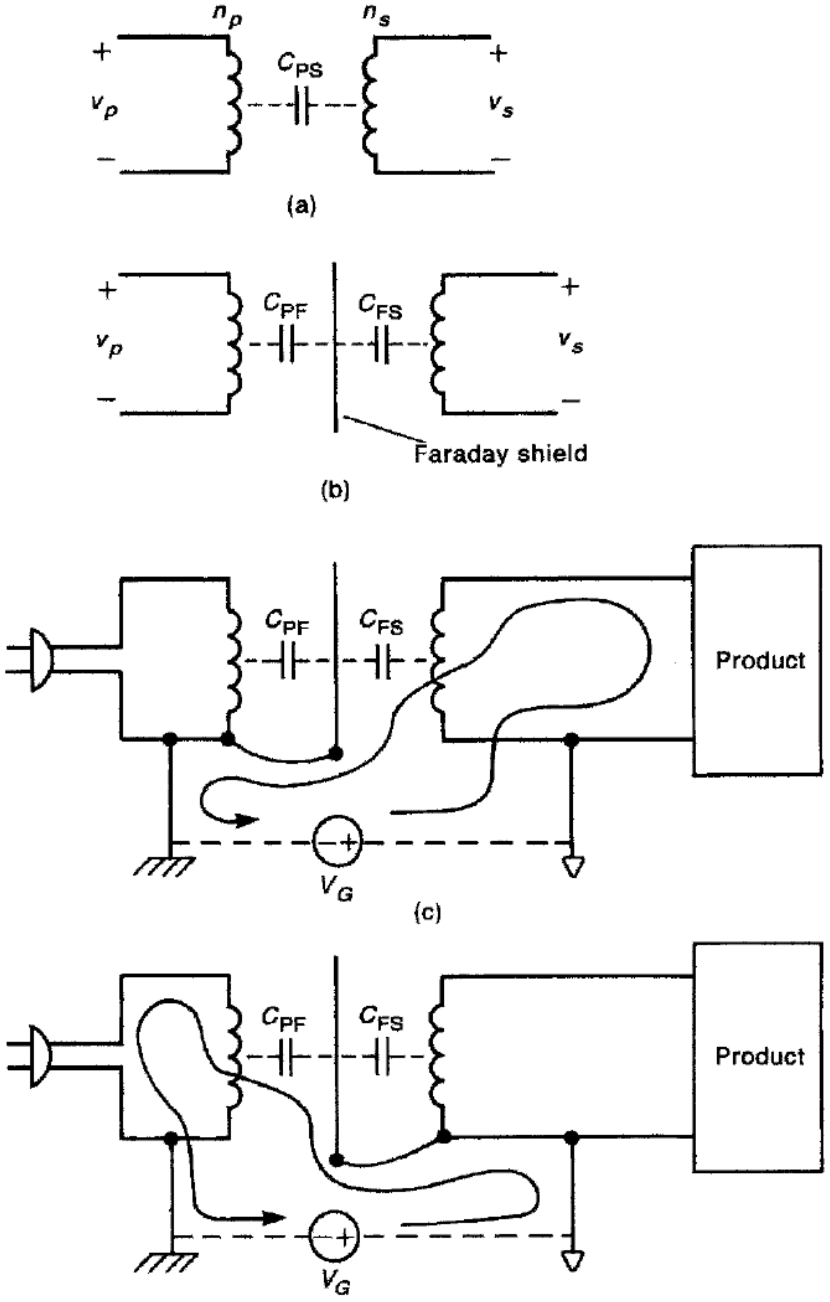
(b)

E-core



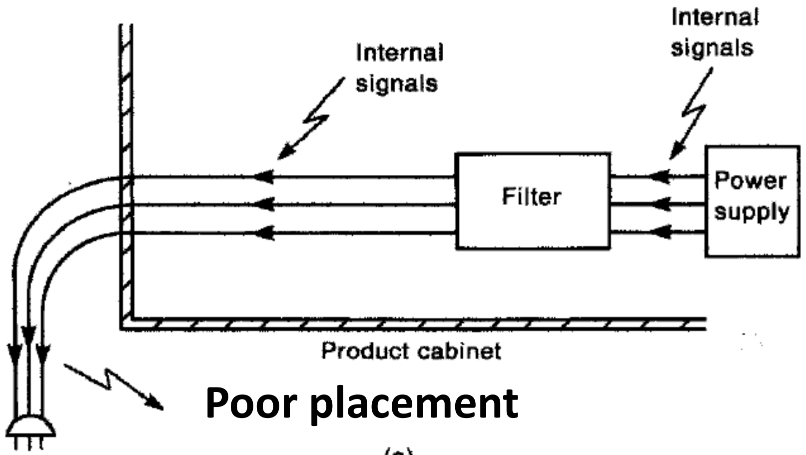
(c)

- Another effect that is worth mentioning is the fact that placing the two windings of the transformer close to one another introduces **capacitive coupling** between them thus providing a path for the noise to couple from the primary to the secondary sections.
- One way to reduce this coupling is via a **Farady shield** (metallic shield between them)
- The noise current generated by the difference between the primary and secondary voltages (VG) will flow according to the way we connect the Farady shield to ground.
- If we ground on the primary side, the current flow will not reach the LISN and will be on the product side, and this is advisable and preferable.
-



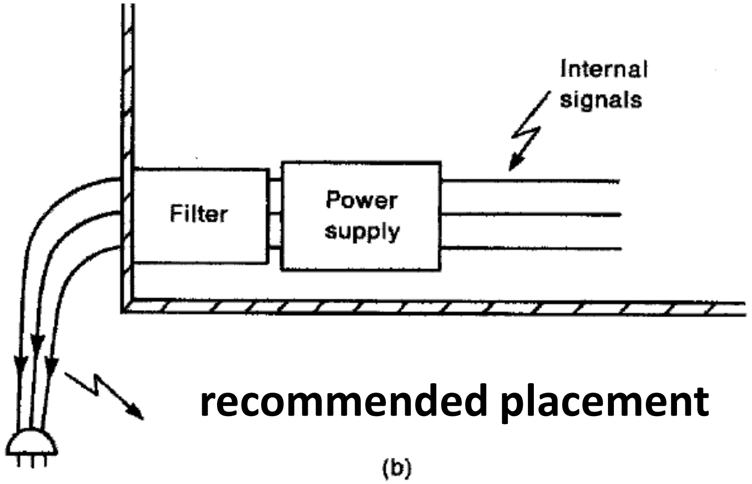
Power supply Filter placement

- location of components and routing of wires within a product are important considerations in the reduction of conducted emissions
- The power supply filter should be placed directly at the exit of the power cord from the product. The power supply should be placed as close as possible to the filter.



Poor placement

(a)



recommended placement

(b)

- Conducted susceptibility (noise coming into the device from the AC lines) usually occurs due to large transients in the power system network. Such transients occur when large disturbances happen, such as lighting. Filters or ferrite beads at the input of the system power supply cord can be added to reduce such effects.

Next time …

- Radiated Emissions …