Electromagnetic Compatibility (EMC)

Topic 7

Grounding

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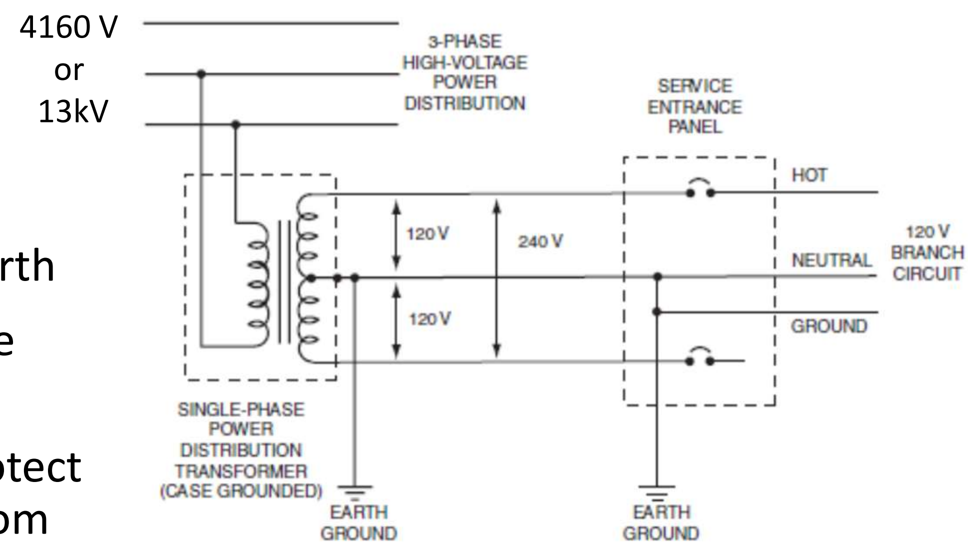
Introduction

- Grounding is one of the primary ways of **reducing unwanted noise** and of obtaining a **safe system**
- Noise-free is not necessarily a safe system, and vice versa, you need to design for both!
- A well designed grounding system will **reduce interference/noise**, and **provide safety** at the expense of **engineering time**. This should be considered while the system is designed. Again, waiting to fix issue after the fact will cost more than considering them while designing.
- Grounds fall into two categories:

  (1) **safety** grounds (carry currents only during faults)

  (2) **signal** grounds (current return paths during normal operation)
- We can also have "chassis ground" where the ground is connected to the chassis or system enclosure, and we can have "earth ground" when the system ground is connected via a low impedance path to earth (usually for safety).
- Always ***first make it safe, then make it work properly without compromising safety***!

Safety Grounds



Single phase residential service providing 120/240V

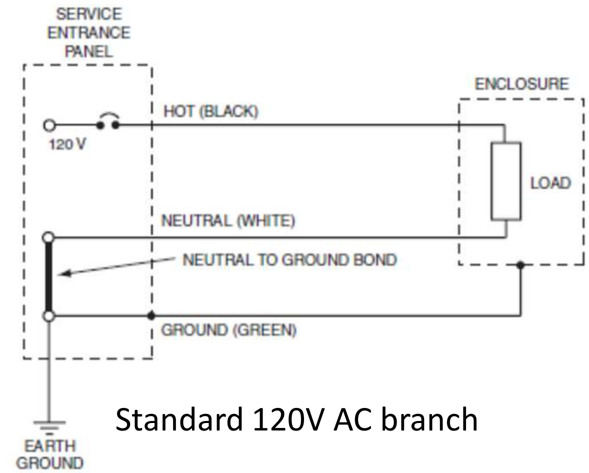
- In power industry, ground means connection to the earth
- Standards for AC power distribution are handled by the National Electric Code (NEC), article 250.
- The main purpose of power system grounding is to protect personnel, living creatures, structures and buildings from harm and fire
- For facility wiring, ensure

  (1) use of protecting devices (breakers/fuse) in the event of faults,

  (2) minimize potential difference between conductive enclosures

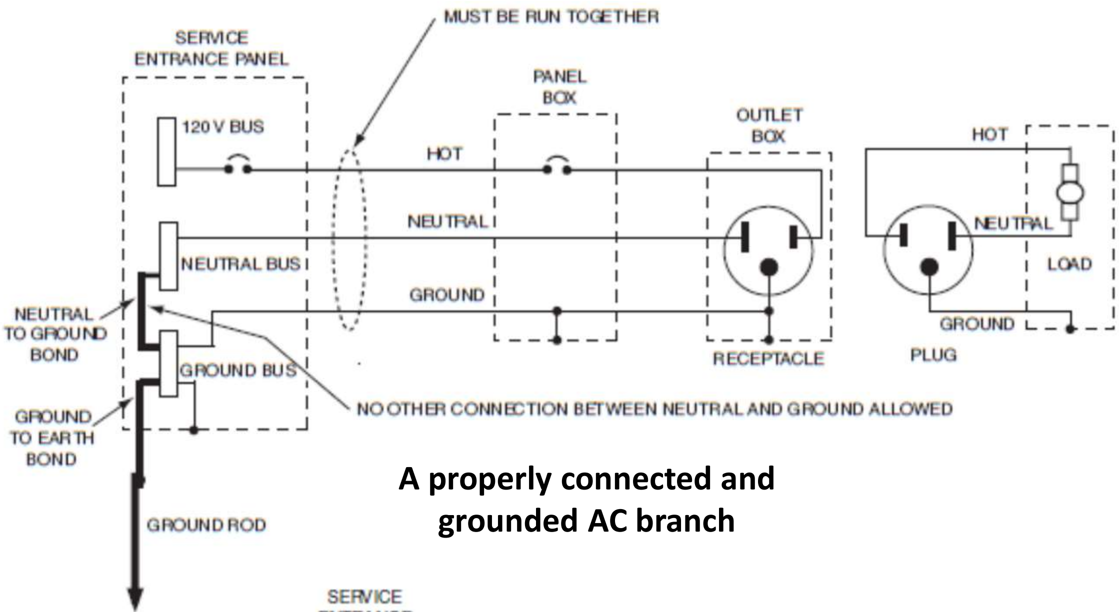
  (3) install/consider lightning protection
- Service entrance where metering occurs at user side. User is responsible for properly grounding his side
- Overcurrent protection circuits should be used (breakers/fuses)
- There is more than one acceptable way to achieve electrical safety

- **Branch circuits**:
  - The safety ground conductor/wire (green, green with yellow stripe or bare) must be connected to all non-current carrying metallic equipment hardware and enclosures, and it must run along with the black and white conductors/wires within the same conduit (multi-wire jacket).
  - We will call wires as hot, neutral and ground (safety ground)
  - The ground wire will only carry current momentarily when there is a **FAULT** until the overcurrent protection device opens the circuit (to protect the device, personnel, etc)

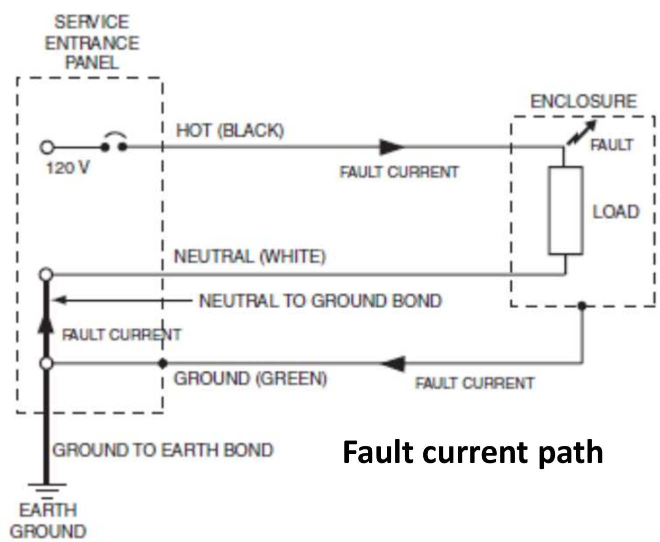


Standard 120V AC branch

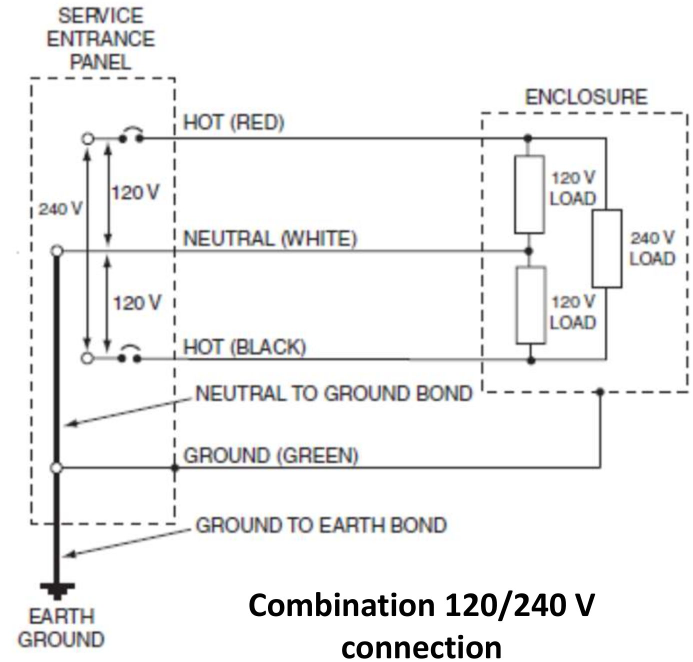
  - NEC indicates that neutral and ground wires, should be connected at **one and only one point** at the main service entrance panel.
  - NEC requires that the ground wire/conductor is connected to the earth ground at the service entrance panel, via a ground rod or some other means. This is referred to as “grounding electrode”
  - Some examples of 120V and 240V connections follow
  - When a fault occurs, a low impedance path that consists of the hot wire, the ground conductor and the neutral-to-ground bond exists, which draws a large fault current that quickly blows the fuse or open the circuit via the circuit breaker, thus moving the current away from the load and keeping it safe.
  - The earth connection is used to divert the lightning current to ground and limit the voltage imposed on the power system by lightning.



A properly connected and grounded AC branch



Fault current path

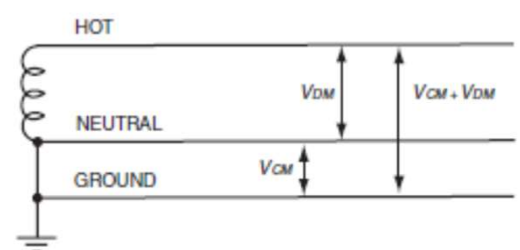


Combination 120/240 V connection

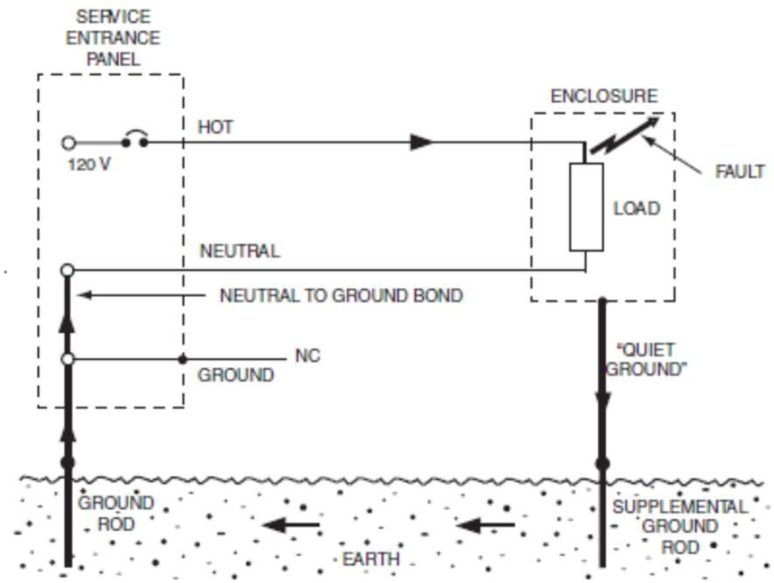
- **Noise Control**:
  - NEC does not details issues related to noise control and interference, it is mostly concerned about safety and fire protection
  - The IEEE std. 1100-2005 “Recommended Practice for Powering and Grounding Electronic Equipment”, is the one to use to obtain a low noise system
  - Noise can be differential mode (hot to neutral, denoted DM), or common mode (neutral to ground, denoted CM).
  - Grounding will only have an effect on CM noise
  - To control interference and noise levels, one needs to create a low-impedance ground system that covers low and higher frequencies (i.e. 50 Hz up to MHz). To achieve this, we need supplemental ground conductors such as ground straps, ground grids, ground planes (to have low impedance)
  - NEC add two conditions for such noise reduction method:

    (1) these additional grounds are in addition to the ground conductors required by NEC, and not replacing them

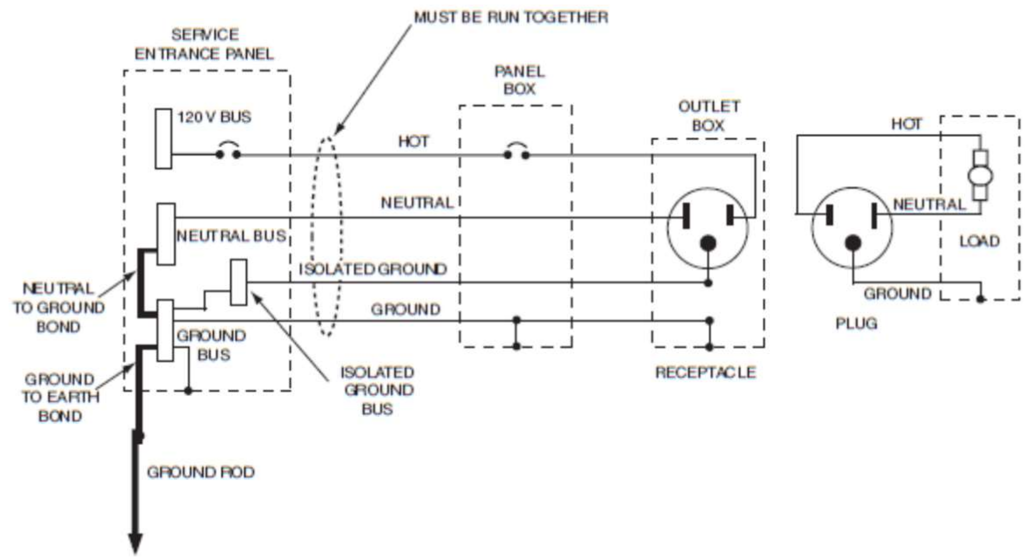
    (2) they must be bonded to the NEC required grounds
  - Best method is to connect to a Solid Ground plane for wide frequency ranges and separated equipment. This plane is called a **Zero Signal Reference Plane (ZSRF)**



- **Earth Grounds**:
  - Myth: “Connecting equipment to earth ground reduces interference and noise”
  - Note that the situation in the figure shown should never be used, and the so called Quiet Ground will not provide a low enough impedance (10-15 ohm), thus not causing the fuse or breaker to open the circuit (not enough current drawn) thus causing a major equipment or other electrical issue.
  - According to NEC, The earth shall not be considered as an effective fault-current path (250.4(B)(4)).
  - Also the shown configuration will seldom reduce noise or interference (not equipotential, pick up noise from other equipment, etc)

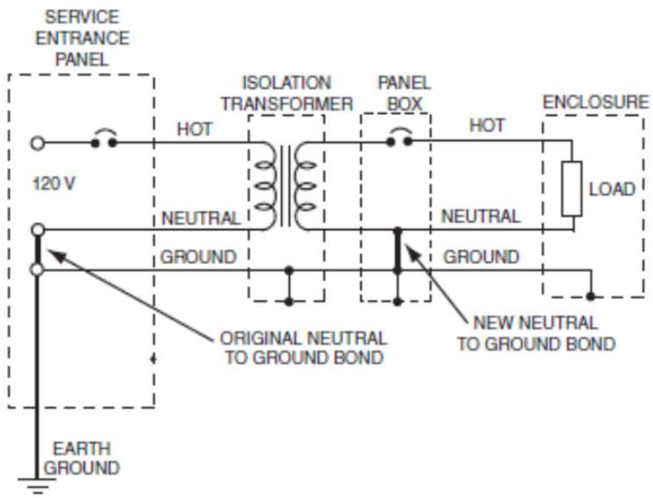


- **Isolated ground**:
  - For purposes of reducing EMI on the ground of sensitive equipment, the NEC allows for the use of a receptacle in which the ground terminal is insulated from the receptacle mounting structure as shown in the figure (250.146(D)).
  - An Isolated Ground (IG) receptacle is one in which there is no direct electrical connection between the ground terminal on the receptacle and any other metal part on the assembly.
  - IG receptacles are usually colored orange



- The system now has two grounding wires. The IG conductor connects the receptacle ground pin and ground only the device connected to the receptacle.
- The normal safety ground conductor, grounds all other devices as well as the outlet box and any intermediate panel boxes.
- Now the AC power wiring is a 4-conductor system.
- The benefits of IG is not universally accepted!! Any noise improvement (if any) will be related to CM noise and not DM noise.

- **Separately derived systems**:
  - A Separately Derived System is a wiring system in which the hot and neutral conductors have no direct electrical connection to the main electrical service. Examples are a generator, a battery, or a transformer.
  - In such a wiring, we start all over again as if we are at a service entrance panel for each panel box
  - An isolation transformer can be often be used to reduce CM noise as a new connection between neutral and ground is established at each panel box, reducing CM noise
  - Effective technique when feeding sensitive equipment to CM noise
  - DM noise will not be reduced by the isolation transformer and will couple directly through the transformer to the equipment.

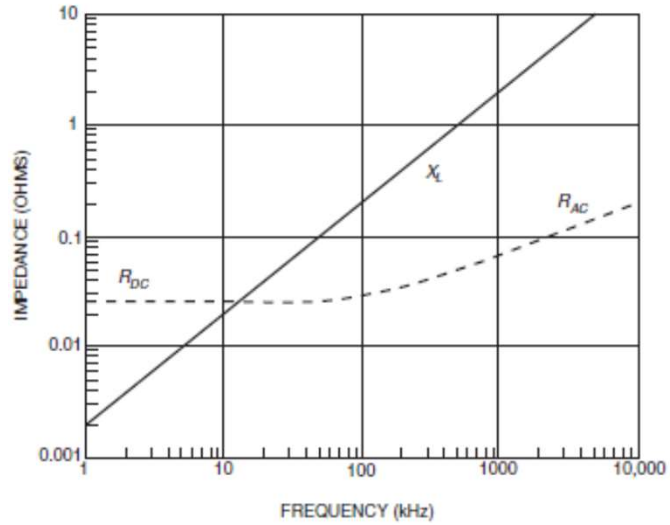


Signal Grounds

- The voltage definition of ground is an equipotential surface that serves as the reference potential for the system or circuit
- Another definition for the signal ground is a low impedance path for the current to return to its source
- The current definition is more solid as the voltage is relative (with respect to what) but the current is definitive and will always want to return to the source
- The current return path will determine the radiation emission or susceptibility of the a circuit
- Three basic objectives of signal grounding:
    (1) Not to interrupt the ground return path
    (2) Return the current through the smallest loop possible
    (3) Be aware of possible common impedance coupling in the ground

- Most important characteristic of a ground conductor is its impedance

$$Z_g = R_g + j\omega L_g$$



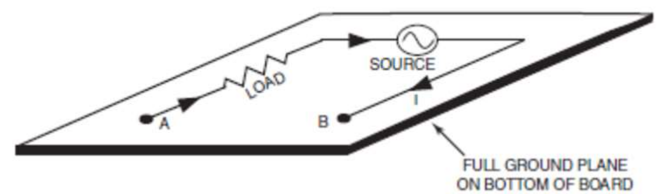
- Ground voltage is given by

$$V_g = I_g Z_g$$

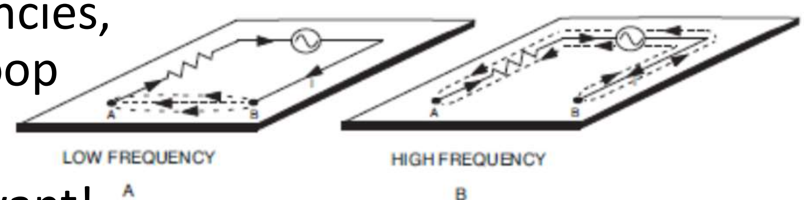
- Thus, two ways to minimize ground noise voltage

  (1) minimize ground impedance (high frequency ground plane)

  (2) decrease I_g by forcing the ground current to flow through another path (low frequency single point grounding)



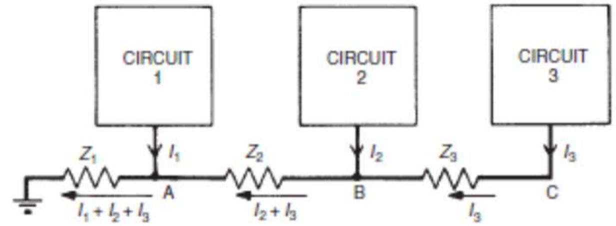
- Consider the two layer board. At low frequency, current will go through the path of least resistance, while at high frequencies, it will go through the path of least inductance (smallest loop area covered)!



- We usually force low frequency current to go where we want!

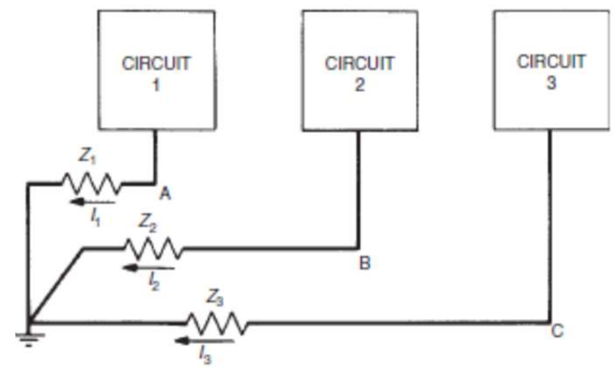
- All ground systems have their own pros and cons, so be aware!
- Finally, remember that grounding is hierarchical. It is done at the IC level, at the board level, as well as the system or equipment level.
- Signal grounds can be divided into:
  1. single-point grounds
  2. Multipoint grounds
  3. Hybrid grounds

- **Single point grounds**:
  - effective for low frequencies up to 20KHz
  - We direct the current Ig to reduce its effect in sensitive ground locations
  - This technique can be effective against ground loops
  - Used for its simplicity
  - Careful about the voltage drops within stages and the reference ground



$$V_A = (I_1 + I_2 + I_3) Z_1$$
$$V_C = (I_1 + I_2 + I_3) Z_1 + (I_2 + I_3) Z_2 + (I_3) Z_3$$

  - Point A is the most critical as it has all three currents for all circuits!
  - To reduce this current, we can use the parallel configuration of the single point ground.
  - Potentials now are only functions on the own circuit current.
  - Sometimes we use a combination of series and parallel (application specific)



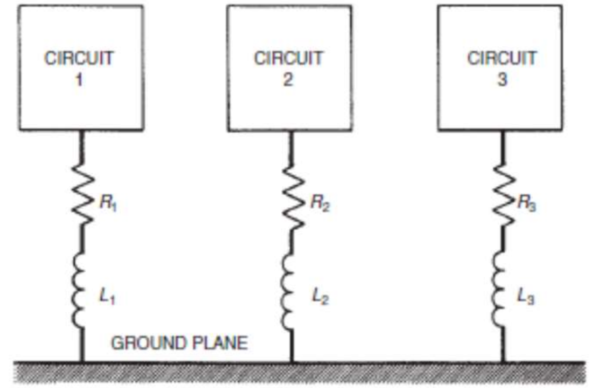
$$V_A = (I_1) Z_1$$
$$V_C = (I_3) Z_3$$

  - Ground leads should be less than $\lambda/20$ to avoid acting as antennas

- **Multi-point grounds**:
  - used at high frequency (above 100KHz) and in digital circuits and systems
  - They minimize ground noise voltage via the minimization of the ground impedance (i.e. minimizing ground inductance)
  - Ground planes and grids minimize ground inductance
  - Note that, increasing the thickness of the ground plane has no effect on its high frequency impedance:

    (1) it is the inductance not the resistance of the ground plane that determines its impedance

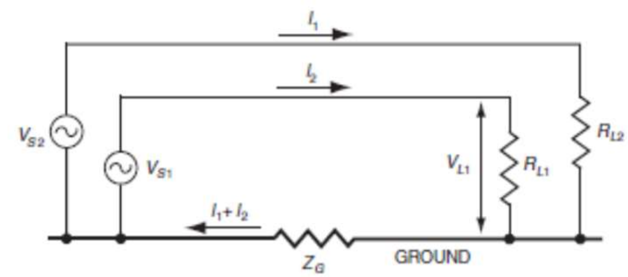
    (2) high frequency currents only flow on the surface of the plane due to the skin effect



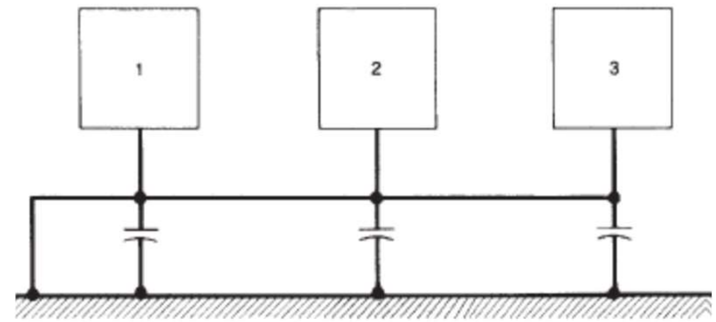
- **Common Impedance coupling**:
  - common when circuits (1) share the same ground, (2) high impedance ground (3) large ground current (4) high sensitive low noise margin circuit
  - Load voltage is a function of the other circuit current:

$$V_{L1} = V_{S1} + Z_g \left(I_1 + I_2 \right)$$

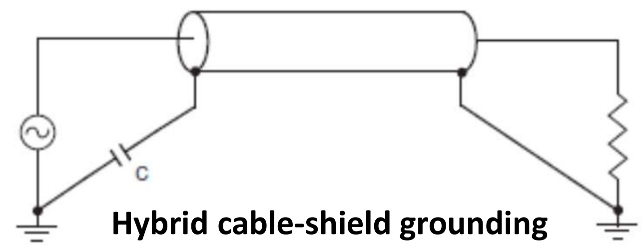
  - I1 creates the noise voltage component ($I_1 Z_g$)
  - Solved by multi-point ground techniques



- **Hybrid grounds**:
  - Signals with wide bandwidth that cover below and above 100KHz might need a hybrid grounding scheme (i.e. video signals)
  - Acts a single point ground at low-frequencies, and multi-point ground at high frequency ones
  - This can be also applied to cable-shielding configurations (as we saw before), at low-frequency the capacitor is open circuit, and thus we will have single side grounding for minimum loop area. At higher frequencies, the capacitor is a low impedance, thus we have double side grounding of the shield.

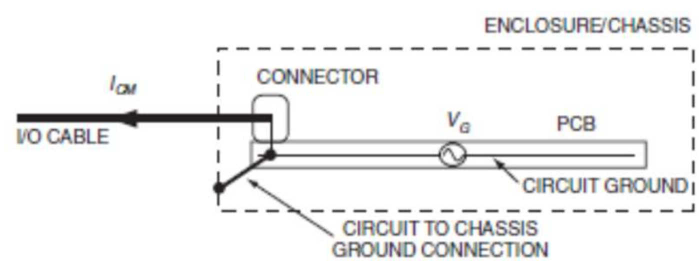


Hybrid grounding



Hybrid cable-shield grounding

- **Chassis Ground**:
  - Any conductor that is connected to the equipment metal enclosure
  - Chassis and signal ground are usually connected at multiple points, to reduce noise and interference and radiated emissions
  - Vg appears at the circuit ground due to its finite Z. This will drive a CM current on the cable and will cause radiated emissions.
  - If the circuit ground is connected to chassis at opposite side of cable, the full Vg will drive the current to the cable
  - If the circuit ground is connected to the chassis at the I/O connector, Vg will be almost zero!



→ Chassis connections next to cable outs! Always maintain low Z between PCB and chassis connection.

Equipment/System Grounding

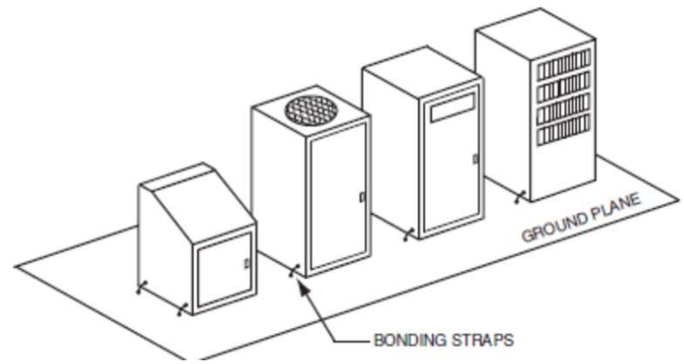
- The objective of equipment grounding includes electrical safety, lightning protection, EMC control and signal integrity.
- We will consider three types of systems
  (1) Isolated systems
  (2) Clustered systems
  (3) Distributed systems

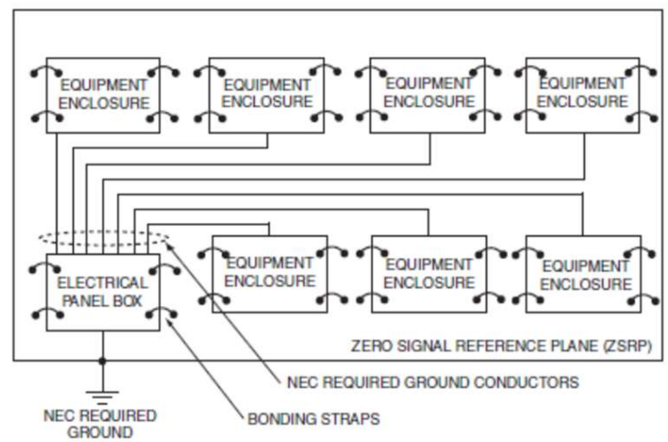
(1) Isolated Systems:

- Systems where all functions and connections are within a single enclosure with no external signal connections to other grounded systems. (vending machines, TVs, PCs)
- Optimum way to minimize potential difference between its interconnected electronics is to have them all contained within a 6-sided metallic enclosure which is as small as possible.
- NEC requires this enclosure to be connected to AC power ground
- Enclosure ground is provided by: (1) AC power ground (green wire) in single phase AC
  (2) separate ground wire run with power cable in 3-phase AC

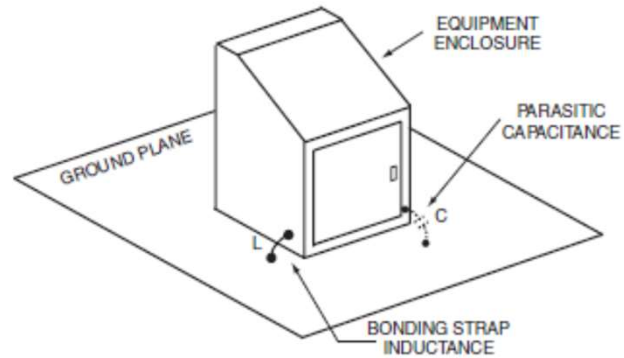
(2) Clustered systems:

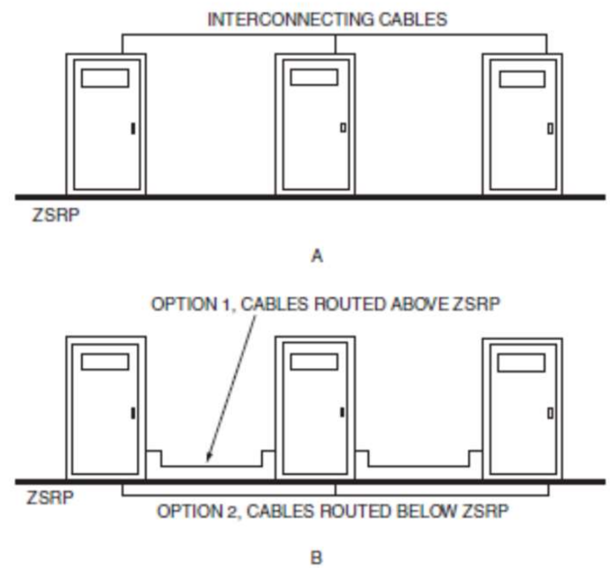
- Has multiple equipment enclosures located in a small area such as a closet or a room.
- Has multiple interconnecting I/O cables between individual elements but not with any other grounded system.
- Examples are data-processing centers, server-rooms, stereo system around a room
- For **safety grounding**, all equipment mush be connected to AC power ground. The racks can be single-point grounded or multi-point grounded. Parallel grounding is usually preferred.
- For **signal grounding**, multiple options exist. For example for multipoint grounding, metal straps to a common ground plane might be adopted (or a ground mesh) as shown in Figure.
- For sensitive equipment in a harsh environment, wide metal straps with ground planes are highly recommended. The best method is to use a **ZSRP** with wide metal straps.
- If a grid is to be considered instead of a solid ground plane, the holes should be small compared to the wavelength of the highest frequency component (< $\lambda/20$)





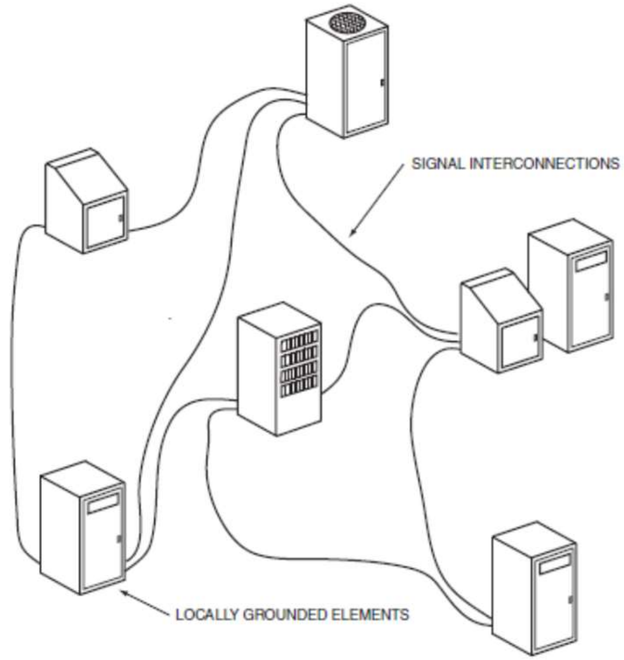
- A short flat rectangular strap should be used to bond enclosures to the ZSRP and not round ones, as the inductance of the rectangular strap is lower than the round one. Inductance decreases as strap width increases
- Also, placing multiple adjacent straps will have inductances add in parallel, thus half their values can be obtained if two are connected in parallel
- When the equipment are insulated from the ground they are sitting on (intentionally or un-intentionally introducing) a capacitance that will cause a resonance with the ground strap according to: $f_r = \frac{1}{\sqrt{2\pi LC}}$
- This is a parallel resonance, thus the impedance at resonance will be large (as compared to series resonance) thus effectively disconnecting the enclosure from the ground! This resonance is in the 10-50MHz range, thus make sure to keep this resonance FAR away from your operating frequencies.
- For the signal and power cables, make sure you place them as close as possible to your ground plane or ZSRP to minimize the area between them and the reference plane, thus minimizing CM noise coupling to the cables



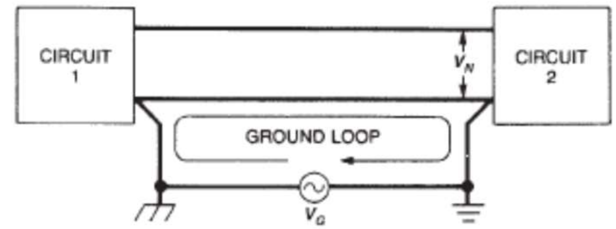


(3) Distributed Systems:

- Equipment/enclosures are physically separated
- Different elements/equipment have separate AC power, safety, and lightning protection. Elements within a close proximity can be treated as clustered.
- All signal ports should be considered as being in a harsh (noisy) environment and treated appropriately.
- Based on the signal type, characteristics, frequency, amplitude, being balanced or not, type of cable used, etc, we will choose proper grounding, filtering, balancing among other techniques to have good signal grounding, and minimize noise
- In such systems, ground loops might be an issue. We will discuss in the coming slides.
- A common battery distributed system (automobiles and aircraft) is one in which the structure (chassis, airframe, etc) is used as the DC power return. Thus the structure is the signal reference.
- Because all the ground currents flow on the structure, common impedance coupling can be a major problem. In such systems, we will consider balanced and differential signaling rather than single-ended (with reference to ground). Also, providing power using twisted pairs is better than using the chassis ground.



Ground Loops



- This situation arises within a system when multiple physically separated grounds are used
- The figure shows a system grounded at two physically separated points, and are likely to have different potential (see the symbols used). This configuration has 3 issues:
  (1) A difference in ground potential Vg, might couple a noise voltage Vn to the circuits
  (2) Any strong magnetic fields can induce noise voltage into the ground loop
  (3) The signal will have multiple return paths, and at LF might flow through the ground connection and not the return on the signal conductor (not an issue at HF)
- The signal-to-noise ration (SNR) is important, and if this generated noise affects the required SNR levels, we need to reduce such noise effects
- Usually ground loops are not that bad, and you should not panic if you have some. Assess them properly before doing anything.
- Ground loops are seldom a problem at HF, why?

- If you identify problematic ground loops, you can:

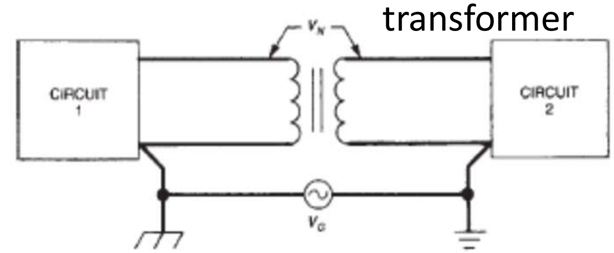
  (1) Avoid them by using single-point or hybrid grounds (effective at LF)

  (2) Tolerate them via the minimization of the group impedance (i.e. use ZSRP) or increase the circuit noise margin (use a balanced circuit, increase voltage level, use a different driver receiver technology, etc)

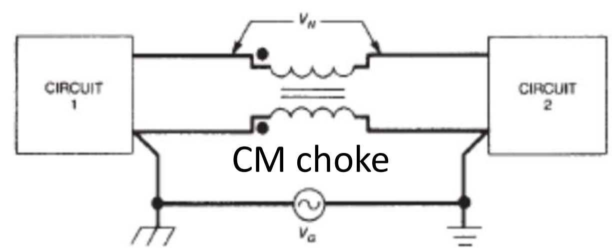
  (3) Break the ground loop by using transformers, common-mode chokes, or optical couplers

- When using the isolation methods, the noise voltage appears between the break points rather the input of the circuit, thus eliminating its effect on the electronics.
- Transforms are sometimes bulky and have limited frequency response, expensive and do not provide DC continuity.
- CM chokes will pass DC and differential signals while blocking CM ones, also they allow winding multiple signals on the same core, providing a cost effective solution.

transformer

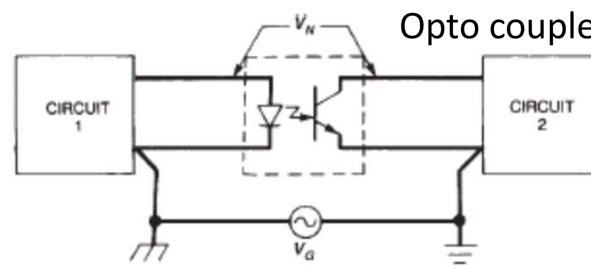


Audio transformer



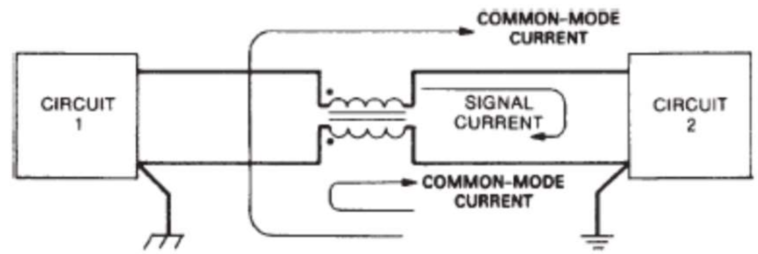
CM choke

Opto coupler

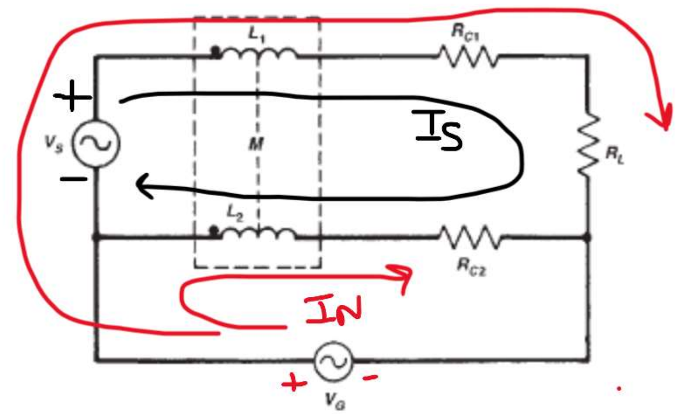


LF Analysis of CM chokes

- We can use a transformer as a CM choke (also called a balun, a neutralizing transformer and longitudinal choke) if we connect it as shown in the figure.
- It presents a low impedance path to the signal current at DC and it will provide a high impedance path to CM noise
- Signal current flows equally on the two conductors in opposite directions (DM current) (I_S)
- Noise currents flow in the same direction on both conductors and are called CM currents (I_N)
- Equivalent circuits shows the current directions as well as a function of the signal and noise sources
- Assume identical windings in CM choke, then L1=L2=M, also, Rc1 << RL, so neglect Rc1



PHYSICAL RELATIONSHIP



EQUIVALENT CIRCUIT

- Consider the **signal voltage** first, Vs, and at frequencies greater than ω=5 R_{c2}/L_2 , virtually all the current Is returned to the source will be via the second conductor and not the ground plane.
- Thus we can write KVL,

$$V_s = j\omega\left(L_1 + L_2\right)I_s - 2j\omega MI_s + \left(R_{c2} + R_L\right)I_s$$

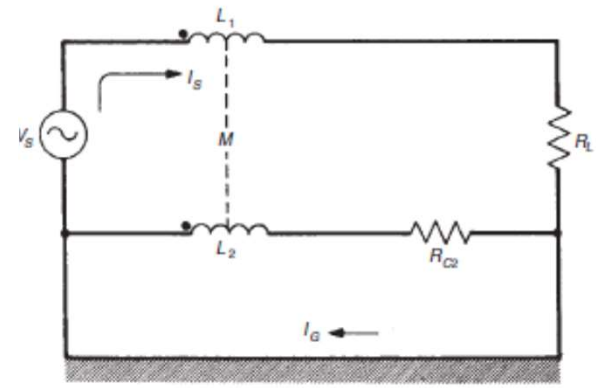
- Substituting L1=L2=M and solving for Is

$$I_s = \frac{V_s}{\left(R_{c2} + R_L\right)}$$

- Assuming the cable resistance is much smaller than the load, we get

$$I_s = \frac{V_s}{\left(R_L\right)}$$

- Meaning that there is no effect on the signal transmission from the CM choke as long as the choke inductance is large enough that the signal frequency is greater than 5 R_{c2}/L_2



- Consider the noise (CM) voltage now, the outside loop gives,

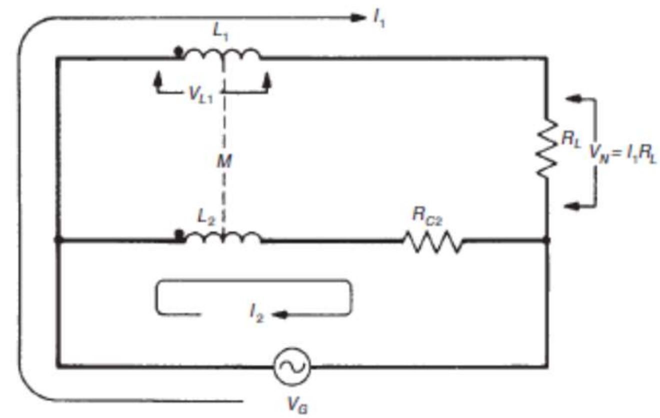
$$V_G = j\omega L_1 I_1 + j\omega M I_2 + I_1 R_L$$

- The lower loop gives,

$$V_G = j\omega L_2 I_2 + j\omega M I_1 + I_2 R_{c2}$$

- I2 can be written as,

$$I_2 = \frac{V_G - j\omega M I_1}{j\omega L_2 + R_{c2}}$$



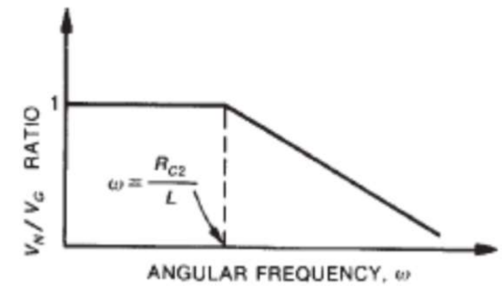
- Now, let L1=L2=M, and substitute I_2 in outer loop equation,

$$I_1 = \frac{V_G R_{c2}}{j\omega L\left(R_{c2} + R_L\right) + R_{c2} R_L}$$

- Thus, the noise voltage is equal to $V_N = I_1 R_L$, and assuming

$R_{c2} << R_L$, we can write

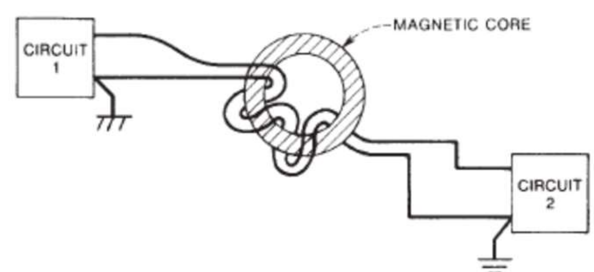
$$\boxed{V_N = \frac{V_G R_{c2} / L}{j\omega + R_{c2} / L}}$$



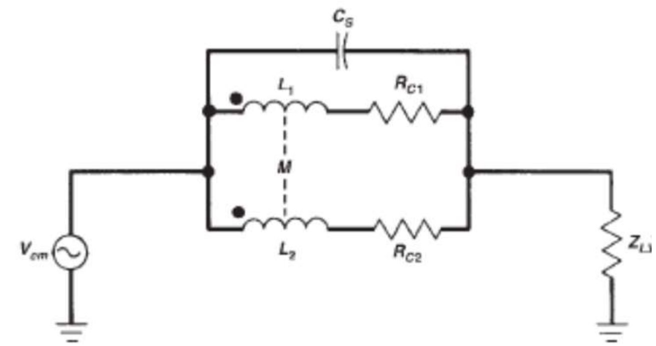
- To minimize V_N, R_{c2} should be kept as small as possible and

$L >> R_{c2}/\omega$

- The choke must be large enough to withstand any unbalanced DC current to avoid saturation



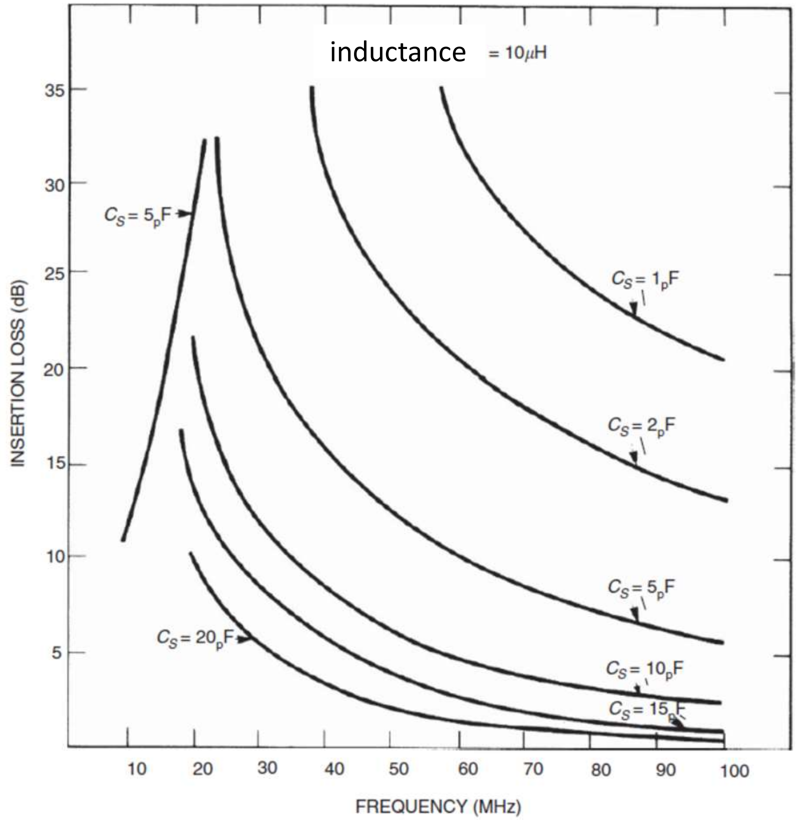
HF Analysis of the CM choke

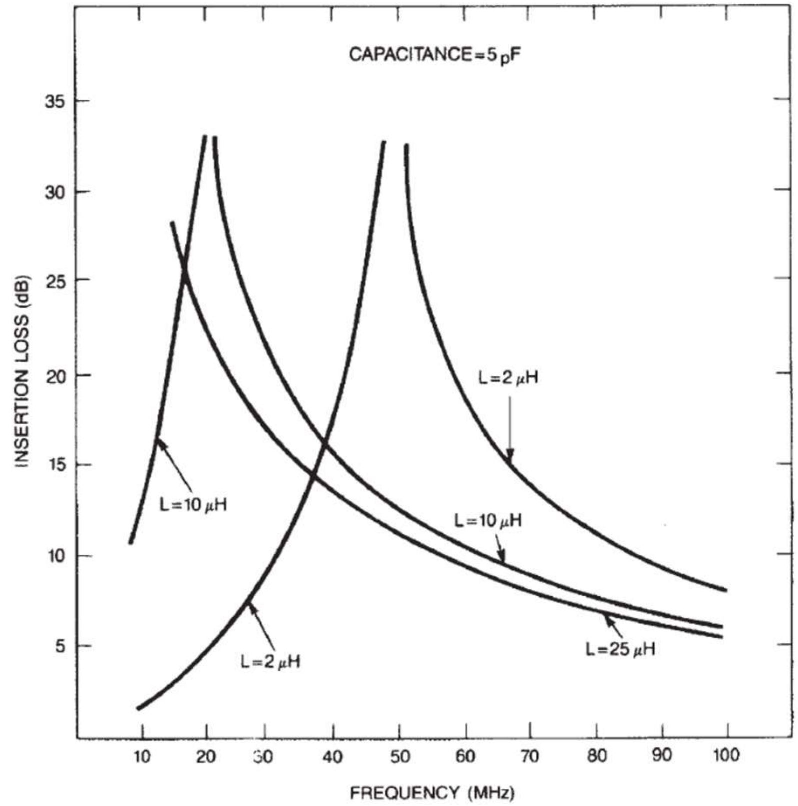


- At frequencies higher than 10MHz, parasitic capacitance of the CM choke should be considered.
- C_s is the stray capacitance between the two windings of the CM choke
- Z_L is the common mode impedance of the cable that might act as an antenna with variable impedance values ranging from 35-350 ohms
- The insertion loss (IL) of the choke is defined as the ratio between the CM current without the choke to the CM current with the choke. Let $R_{c1}=R_{c2}=R$, and L1=L2=L, then

$$IL = Z_L \sqrt{\frac{\left[2R\left(1-\omega^2 LC_s\right)\right]^2 + R^4\left(\omega C_s\right)^2}{\left[R^2 + 2R\left(Z_L - \omega^2 LC_s Z_L\right)\right]^2 + \left[2RL\omega + \omega C_s R^2 Z_L\right]^2}}$$

$R_{c1}=R_{c2}=5$ ohm
$Z_L = 200$ ohm





- Above 70 MHz, Cs is critical for the IL. Thus Cs is the parameter to check for HF performance of a CM choke
- At HF, the CM choke can be considered as open-circuit for CM noise currents, and the current values are determined by the parasitic capacitance of the choke.

→ In most cases, the system will perform better functionally and EMC wise with a single reference plane! So DO not split or have separate reference planes in your system (as much as possible!)

Next time …

- Balancing and Filters …