A Quick Guide To EMC Engineering

A compendium of basic design concepts that can help make a non-compliant device compliant

Why is it people walk into a testing laboratory with all the confidence in the world that their equipment is going to pass, only to have all their hopes and dreams dashed upon the rocks? Now, they are under a number of pressures: (1) Someone already told the board manufacturer to start making production quantities of circuit boards; (2) the budget will allow for $0.13 more components and, beyond that, the budget is shot; (3) shipping starts the middle of next week; and (4) the test lab, the one they are standing in the center of while all this is going through their heads, is asking them what to do next and reminds them that the clock is running. This is a common situation. It is helpful at this time to remember the basics of EMC design.

Here are the basics, assembled in a brief overview. Even though this is only a thumbnail sketch of EMC design rules, I hope that it will reduce some of the pressure you might feel.

The Four Modes Of Noise Propagation

Conductive noise is the simplest to understand. This is unwanted electrical energy on wires or other conductive media. Noise on wires is broken down into two major categories: differential mode (also known as normal, metallic, and odd mode); and common mode (also known as longitudinal, even, voltage to ground mode). Differential mode is when currents flow out one wire and return on one or more associated lines. Common mode exists when currents flow out two or more wires, more or less in phase, and return by another path.

Patrick Andre, Andre Consulting, Inc.

Differential mode tends to be a low frequency problem, while common mode is high frequency. For example, a switching power supply fundamental switching frequency plus the first dozen or so harmonics will be mainly differential mode noise. Noise above the 20th harmonic is usually mostly common mode.

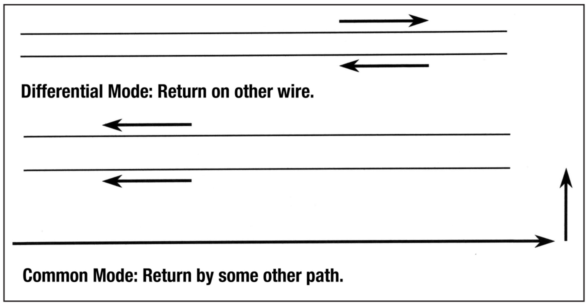

Figure 1: The difference between differential mode and common mode noise

Radiated coupling (or far field radiation) can originate from radio frequency voltages on the equipment case and the antenna of course. But usually it comes from the wires, such as power lines, interconnecting cables, antenna cables, and so forth. If the radiated noise is from the wires, it is likely due to common mode noise (see above) with the return path being the case or other wires, the ground plane or shielded enclosure, or Earth itself. The energy coupled to these return paths

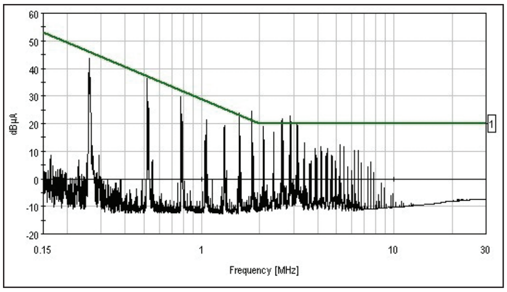

Figure 2: Emissions when using an electrolytic capacitor

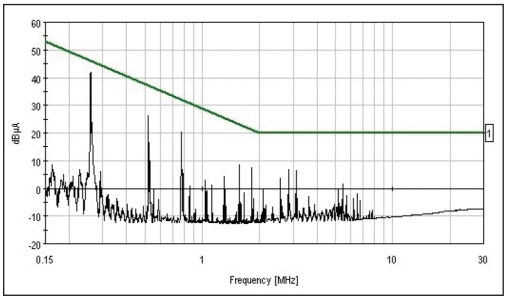

Figure 3: Emissions when using a ceramic capacitor

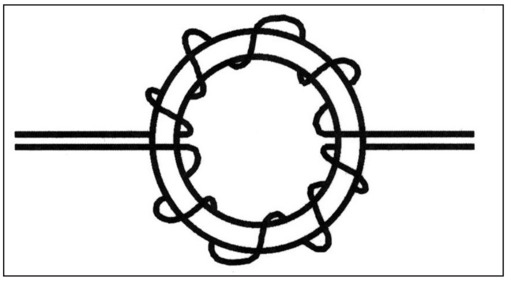

Figure 4: Toroid with two lines wound in opposite directions (differential mode)

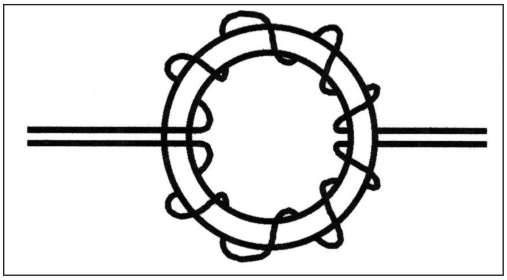

Figure 5: Toroid with two lines wrapped on opposite sides (common mode)

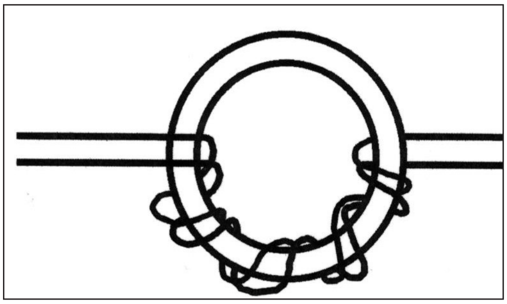

Figure 6: Toroid with two lines wound together (common mode)

is by propagation of radio wave. The problem occurs when the measurement antenna gets into the coupling path. Radiated coupling below a few hundred MegaHertz requires significant distance to couple well, thus the term “far field.”

Inductive coupling (or magnetic field coupling) is caused by the movement of current in a wire, on the chassis, or on other metal members of the equipment. As in transformer theory, moving currents generate magnetic fields, which create other moving currents in adjacent wires or conductors. The greater the current is, the more intense the effect. This can be used to our advantage by returning the noise back to the source before it radiates out of control. The problem starts when currents are coupled in an unintended manner onto lines or case members, which then radiate. In addition, look for inductive coupling on power lines during conducted emissions testing. Unless the filter components are mounted directly at the connector of the unit, any exposed lines between the filter and the connector are susceptible to cross coupling.

Capacitive coupling (or electric field coupling) is caused by voltages in a wire, on the chassis, or on other metal members of the equipment. Voltages create electric fields, which couple charges in adjacent metal surfaces and wires. This creates current flow and voltages which appear in these adjacent metal surfaces and wires. The greater the voltage is, the more intense the effect found.

Both capacitive and inductive coupling are considered “near field” effects, requiring close proximity between source and receptive circuits.

Using Capacitors Appropriately

The formula for impedance is:

$X_C = 1/(2\pi fC)$,

Where:
X_C is the impedance of the capacitor,
f is the frequency in Hertz, and
C is the value of capacitance in Farads.

For noise problems up to 1 MHz, aluminum electrolytic and tantalum capacitors work well. Above 250 kHz, ESR and ESL (electrical series resistance and electrical series inductance) become dominant in capacitors. Use ceramic, polystyrene, glass or other high frequency capacitors. Figures 2 and 3 show how emissions are reduced by changing from an electrolytic capacitor (Figure 2) to a ceramic capacitor (Figure 3), even though the actual capacitance was lowered from 10 µF to 2.2 µF. Both parts were SMT components.

The inductance of the leads will also limit the frequency these capacitors can be used. Keep leads very short (e.g. 1/4”), or use SMT (surface mount technology) capacitors. A leaded ceramic capacitor may not have the same quality and benefit as the SMT part used. When using SMT capacitors, solder them directly between the traces or from the trace to the chassis. If this is not practical, use some type of wide and flat conductor, such as copper tape.

Do not neglect the vias used by the capacitors. Vias can be very inductive. To minimize via inductance, use multiple vias for each bypass capacitor.

Using Inductors Appropriately

The formula for impedance is:

$X_L = 2\pi fL$

Where:
X_L is the impedance of the inductor
f is the frequency in Hertz, and
L is the value of inductance in Henries.

Some inductor core manufacturers will supply values of A_L, which is the inductance per turn of wire. If the A_L value is known, the formula for inductance $L = A_L * N^2$, where N is the number of turns on the inductor. Remember that a wire passing through the center of a toroid, wrapping around the outside, and back through the toroid is two turns, not one.

Inductors used for differential mode noise are often wound on separate cores (toroid, E-cores, and the like). When winding two lines on the same core, they are wound in the opposite direction (see Figure 4). This means that the current through the inductor is equal to the total current of *both* windings. Since the core will see a great deal of total current, the core material typically used is powdered iron, molypermalloy, or other powdered magnetic materials.

Common mode style inductors have both conductors wrapped around the core in the same direction. On the toroid shown in Figure 5, the two lines are wrapped on opposite sides of the core. The advantages of winding an inductor in this manner are: (1) there is no wasted core material; (2) the capacitance of the wires from input to output is minimized; and (3) it is less likely to cross wire the core. The disadvantages are: (1) a minimum of line-to-line capacitance, which is helpful for rejecting differential mode noise; and (2) there is more leakage inductance in this layout. Leakage inductance is caused by having each half of the core wound with an unopposed current. Even with these shortcomings, this is the best general method of winding a toroid.

For very high current devices, and for very high permeability core materials, toroids can have the problem of micro saturation. This is to say the currents on the half core have enough leakage inductance to saturate the core under the windings. To avoid this, the core can be wound with both lines together (see Figure 6). Of course, this will have the disadvantage of having half the core unused, and the danger that, during manufacturing, the core will be wound with the input and output near each other (to make use of the whole core). In doing so, you will lose some common mode rejection from capacitive cross coupling from the input side to the output side.

Often, E cores are used for ease of manufacturing. One danger with these cores is the generation of uncontrolled magnetic fields (see notes about Inductive Coupling above). This is due to the core gapping and other construction issues. Attempt to keep the core as closed as possible. Placing the core in a steal cup can help shield the inductor from magnetic field leakage.

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Wires And Lead Lengths

Remember that inductance values are best determined using complete current paths, or loops. Use the following information as a guideline for approximate values of inductance due to leads and ground wires, and as a demonstration of the need for short wire lengths.

$L = 0.0002*\text{Length}*(\ln(4*\text{Length}/\text{Diameter})-0.75)$ with length and diameter in millimeters. (From IEEE Std. 518-1982)
where L is inductance of the wire, and ln is the natural logarithm.

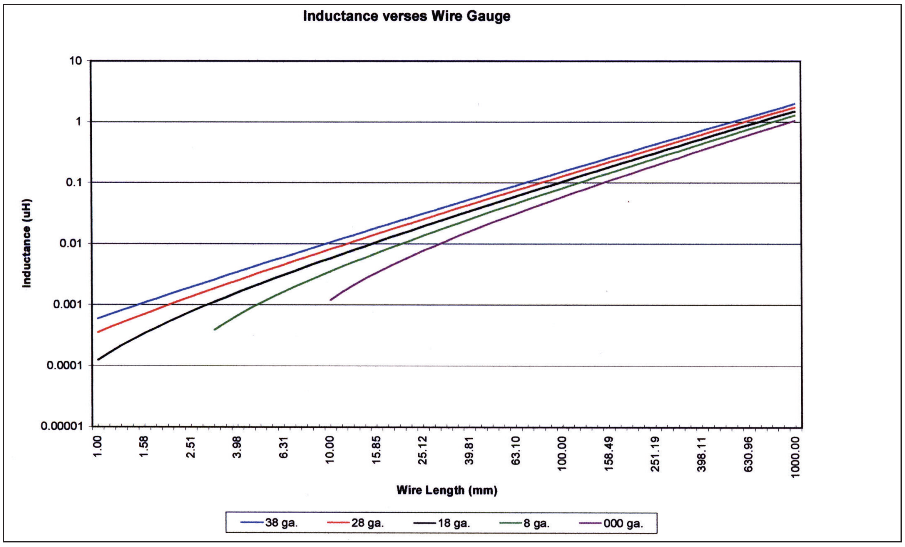

Figure 7: Inductance versus wire gauge

Now those of you with sharp eyes will notice that the inductance of the wire is strongly associated with length, but only weakly associated with diameter (or wire gauge, if you prefer). Figure 7 is a graphical representation of the inductance of a wire with respect to length. Notice that the top line is a 38 ga. wire, while the bottom is a 000 ga. wire.

Values of inductance were not plotted for wire lengths that were shorter than the diameter of the wire. Please note:

000 ga. = 10.4 mm
8 ga. = 3.26 mm
18 ga. = 1.02 mm
28 ga. = 0.326 mm
38 ga. = 0.1 mm

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What this chart shows is how little the gauge of a wire affects the inductance. Changing a wire that is as fine as a hair with one the power utility would be proud of does not significantly reduce the inductance of the cable. In fact, for 10 cm long wires, the difference in inductance of a 38 ga. wire to a 000 ga. cable is about 3:1. However, the reduction of inductance with respect to length is approximately a linear relationship. For an 18 ga., one-inch (1”) wire, expect about 20 nH, and 1.5 µF for a one-meter cable.

When using leaded capacitors, the inductance of the leads can overwhelm the benefit of the capacitance. Keeping leads short will keep the impedance low and the frequency of resonance higher.

When dealing with wires and cables, remember that these will function as antennas. The area of the loop from the signal to its return path is critical. The larger the loop area, the more it can radiate, and the more likely it is to receive radiation. Always minimize the size of these loops. Keep cables and their returns very closely coupled and, if possible, against the metal chassis. Route any loose wires away from sources of noise, especially inductors and transformers.

Chassis Considerations

If you are fortunate enough to have a metal case for the equipment, ensure that the bonds between each case piece are *very tight*. What is meant by *tight* can vary. Two wide overlapping surfaces with bonding screws (or other tie points) at distances of 1/20th the wavelength of the highest clock frequency can be tight. Using conductive gaskets can make a bond tight. Many screws, close together, with pressure bonds is very likely tight and will overcome a number of problems.

With metal chassis, problems occur under the following conditions (in other words, **DO NOT DO THIS**):

- One or both surfaces are painted
- One or both surfaces are treated (e.g. anodized, improper chromate coatings)
- The two metal pieces are gapped
- The two metal pieces are connected by a thin tab of metal
- Open frame chassis
- Screws are relied on for electrical bonds (applies to connectors and shields)
- Using long thin holes for ventilation (round is best)
- Unfiltered wires penetrate the shield
- Unterminated shields penetrate the shield
- Pigtail style terminations of the shield to the chassis are used

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Although having a small round hole will have a higher shielding effectiveness than a long thin hole (when both are exposed to the same frequency), many small round holes will be needed in order to maintain airflow. The addition of many holes will degrade the quality of shielding effectiveness to a value near that of the long thin hole.

Avoid unfiltered wires and unterminated shields. Remember that you are trying to create an RF barrier. Every penetration through this barrier will need to be filtered at the barrier, or the shield will need to be properly terminated at the barrier. Not doing so will allow fields on the inside of the case to couple back onto these wires and propagate outside the box.

Be careful terminating shields to the chassis. In Figure 8, you will notice how noise is coupled to the chassis, wires, and case. This can radiate outside the chassis and couple back into the case through all the seams. Figure 9 shows the same signals coupling back locally at the connector by using a capacitor, before they are allowed to leave the case and radiate.

When dealing with EMI reducing coatings, such as paints, DAG coating, and so forth, look for the following trouble spots:

- Poor contacts between case halves
- How does the coating of one case half make contact to the other case half?
- Is there a wide overlap between case halves?
- Are there several bond points between case halves?
- Was the coating brought to the edge of the case in order to make contact possible?
- Stiffening ribs in the case - Does the coating cover the ribs?
- Are the ribs rounded or are they sharp? (If sharp, the coating might not maintain a constant thickness over the corner, and may actually not cover at all)
- Is the radiated noise polarized in the opposite direction of the ribs? (This indicates the ribs are not conducting properly and a voltage exists across the gap)
- Contacts from the circuit to the case
- How does the noise return from the case to the circuit?
- Do several low impedance bonds exist from case to chassis coating?

Troubleshooting

If the product does not pass, what are ways to narrow down the problem area(s)? First, find out the source of the noise. Is it a harmonic of a clock or some other source (e.g., diode or rectifier noise)? Do not neglect the fact that the noise might be a very high harmonic of the clock, even the 100th or higher.

One way to determine the source is to zoom in on the frequency that is out of specification (and narrow the bandwidth as well). If the noise maintains a single frequency, then the source is a clock. If the noise spreads out, then the source is a broadband generator (diode, rectifier). If the clocks are dithered, then any harmonics seen will appear broadbanded, but have distinct upper and lower frequency bounds. Also look for broadband noise turning into narrowband noise. This will often happen with rectifier, diode, or switching power supply harmonics. And do not be surprised to see switch mode power supply noise well above 30 MHz, or even as high as 200 MHz.

Is the noise common mode or differential mode? The easiest way to determine this is by using a clamp-on current probe. First, clamp the probe onto a single line and take a reading,

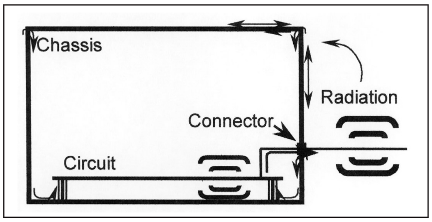

Figure 8: Poor or improper filtering of lines

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then clamp onto all lines (try with and without ground wires if possible). If the readings increase, the dominant effect is common mode noise. If there is a decrease in level, then the effect is differential noise.

If the problem is radiated, find out if the radiating element is the case or the cables. For conductive cases, try squeezing seams to improve contact. If the unit is small, wrap the whole thing in aluminum foil, and then slowly peel away pieces until the problem is found. For large equipment, cover seams with aluminum foil. Think of the foil as a capacitive coupling device from one case panel to another.

Most of the time, the cables are the source of radiated noise problems. To determine this, and if it is safe to do so, try grabbing the cables. To do this, stand on the side of the unit opposite of the antenna. Get into position to grab and release the cables with minimal movement. Remember that you are detuning the cables by doing so, but your movement will also change the radiation pattern of the unit, thus the reason to minimize movement. In addition, try bundling cables, stretching out cables, changing their polarization (lifting them vertically, then horizontal again), dropping them on the ground plane, or whatever else comes to mind.

If the cable or cables that are a problem are also shielded, then the shields may not be terminated properly. To check shields, try discharging to them with an ESD gun. If an ESD gun is not available, a piezoelectric lighter has a reasonable spark. I suggest using one that no longer has any fuel in it. If the shields are not accessible, try using an electrical fast transient (EFT) tester, or even a chattering relay (a normally closed relay wired to open its own contacts when energized – also known as a buzzer). Place the noise source around the cable with the shield in question and monitor the unit for upset.

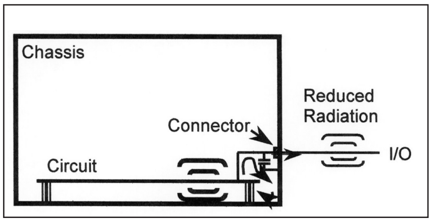

Figure 9: Improved filtering benefits

Look for filters that are not properly bonded to chassis (ground?), or are located several inches from the connector. Remember that three of the four methods to couple noise are often due to the wires (radiated, inductive, and capacitive). Just because a filter exists in a unit does not mean these filtered wires are immune to noise being coupled back onto them.

If you put a “fix” into a unit and it does not work, leave it in for the time being. Remember, we are dealing with a world of logarithms, and dBs do not add linearly. If a source is 20 dB out of specification, the source may be made up of several other sources, maybe some a few dB out of spec, and one that is 19 dB out of spec, all of which add up to 20 dB out of spec. Your fix may have cured one or more of the other noise sources. Leave all the fixes in the unit until the noise is eliminated, and then find out what can be removed.

Finally, what seems like the least likely thing to happen is often the very thing that happens. When given a unit where “nothing has been changed from last time,” assume that something has been changed inadvertently. All too often, the thing that changed is the thing that is causing the problem now. Never rule anything out. And good luck! ■

About The Author

Patrick Andre *is the founder of Andre Consulting, Inc., and can be reached at pat@andreconsulting.com. Andre’s* “Shirt-Pocket Guide to EMC Engineering,” *which summarizes the key points of this article in a portable format, is available at his web site, www.andreconsulting.com.*

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