ELECTROMAGNETIC COMPLIANCE: A VIEW FROM THE FIELD

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By Vladimir Kraz

When we hear "EMC," or its longer version, "electromagnetic compatibility," it suggests elaborate anechoic chambers with pretty tiles, highly-specialized antennae, sophisticated EMI receivers, copper and more copper, and a thicket of regulations. This magazine, as well as other technical publications, extoll the finesse of intricate details of measurements and expert techniques of getting the last decibel right. What is not discussed, or even mentioned, is why these regulations are in place to begin with, and whether current regulations help to resolve electromagnetic interference (EMI) issues satisfactorily. This article addresses these whys and whethers.

Why are there regulations for EMC? Everyone knows it – to assure that regulated equipment doesn't emit anything that would interfere with normal operation of other equipment, and not fall victim to emission from other equipment. Let's then look at what actually causes harmful interference and how EMC regulations address them. We will examine three typical and largely encompassing cases that can be extrapolated to many other applications.

DIGITAL CIRCUITS AND TRANSIENTS

Let's consider an example of the simplest element of any digital circuitry – a gate. Today's circuits operate on much lower voltages than before – down to 0.7V[1] – to reduce current consumption and overheating. With such low supply levels, it is only logical (pun intended) to have low threshold levels as well – with V_{CC} of 0.75V threshold level from 0 to 1 could be just 200mV (same reference). Even at conservative 1.8V supply common in notebook computers and just about elsewhere all it takes is 360mV to alter logic level of the gate.[2] Such low logic levels make it easy to have even previously-insignificant noise on data lines to cause false level switching (Figure 1). Noise on VCC and ground can momentarily alter threshold levels accordingly, contributing to false logic level switching.

Another twist is that, due to many factors, including higher operating frequencies and silicon die shrinkage which lowers internal capacitance on chip, logic circuits are more susceptible to very short transients which they used to simply ignore before. Similarly, they themselves produce much sharper pulse edges than before (in a range of 0.2 nanoseconds),[3] causing

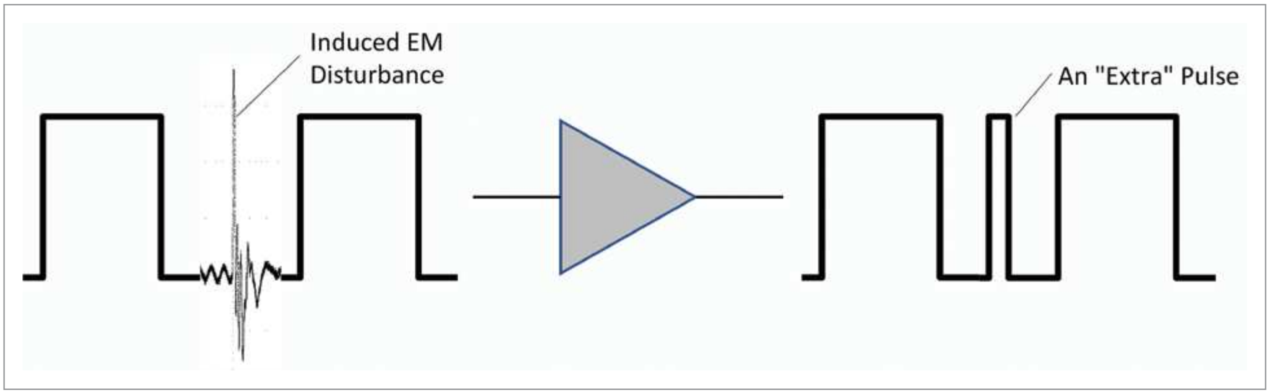


Figure 1: EMI transient causing an "extra" pulse in a digital circuit

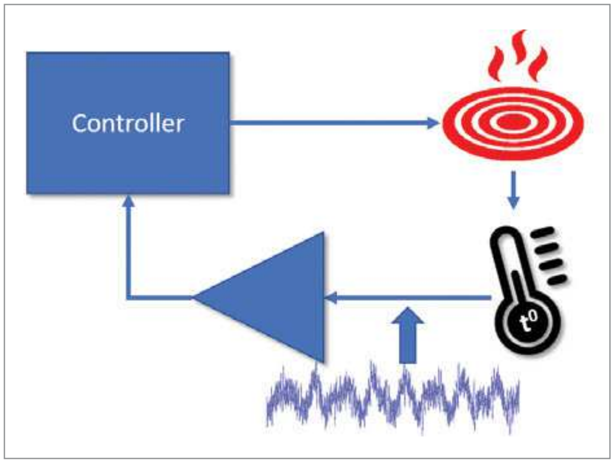


Figure 2: EMI causing sensor misreading

Figure 3: Robotic arm of a typical IC handler

interference elsewhere. At this short rise/fall times even a short trace on PCB would be quite effective antenna, both receiving and transmitting. And at that speed capacitive coupling between data or ground lines/ traces to nearby ones becomes equivalent to a wired connection. It would not take much noise to make a circuit do something that it was never intended to do.

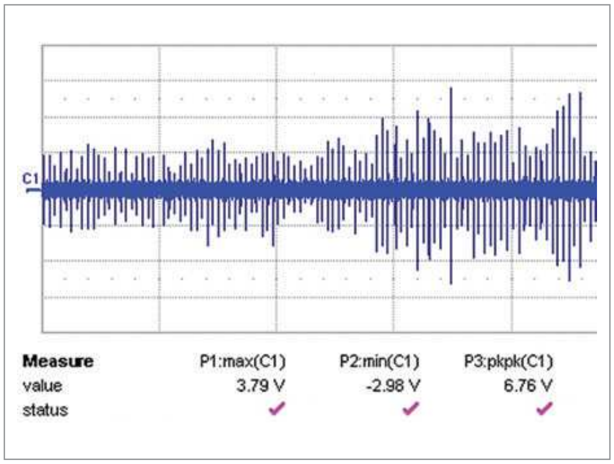
AUTOMATED PROCESSES

In an automated process, much is left to unattended control circuits which change process parameters based on the feedback from various sensors. Figure 2 shows perhaps the most ubiquitous block diagram of a temperature control – other types of control are fundamentally similar. A controller provides signal to a heater; the heater "warms up" temperature sensor which sends signal to a signal conditioner telling the controller what that temperature is. If the temperature is too high, the controller will typically turn off the power to the heater until the measured temperature gets below the set lowest limit and then turn it back on again. There are variations where the controller would adjust pulse, width and modulation (PWM) parameters or the firing angle of thyristor control; however, in either case it would still be a temperature sensor that would govern the entire process.

We covered digital signals in the previous section – let's assume that the signal from the temperature sensor is analog (i.e., thermocouple). External signals, would they be picked up as radiated emission, or induced into the wires by conducted emission from nearby cabling, may be rectified by the circuit and would "add" to the temperature readings. In this case, the controller would act based on the information received and will still maintain the temperature, but lower than that to which it was set. This may result in a defective product (such as a chemical, a food product, or a semiconductor wafer) and the worst part of it is that it will go completely undetected and untraceable – after all, the signal from the temperature sensor that the controller receives is "authentic."

INSIDE OUT

EMC regulations specify emission coming out of equipment to the outside – what about emission inside equipment? Would it matter? Not for most equipment, but very much for some.



Measure	P1:max(C1)	P2:min(C1)	P3:pkpk(C1)
value	3.79 V	-2.98 V	6.76 V
status	✓	✓	✓

Figure 4: High frequency voltage between robotic arm and the frame in the IC handler

Why would there be a need to worry about EMI inside equipment? Several reasons:

Internal Interference with its Own Electronics

Real-life example: SMT pick-and-place machines use several servo motors for their operation. Servo motors are one the strongest EMI "polluters" in the industrial environment.[4,5] Positioning of fine-pitch components on the PCB is critical and requires great precision. Occasionally, however, a component is dropped by robotic arm in a wrong location instead of being placed correctly on the board. The root cause – noise from a particular servo motor controlling the movement of the arm, which causes the system to conclude that the component is where it needs to be, while placing it nowhere near it, often outside of the board. A specialized servo motor filter[5] placed between the servo amplifier and the motor resolved the problem.[6,7]

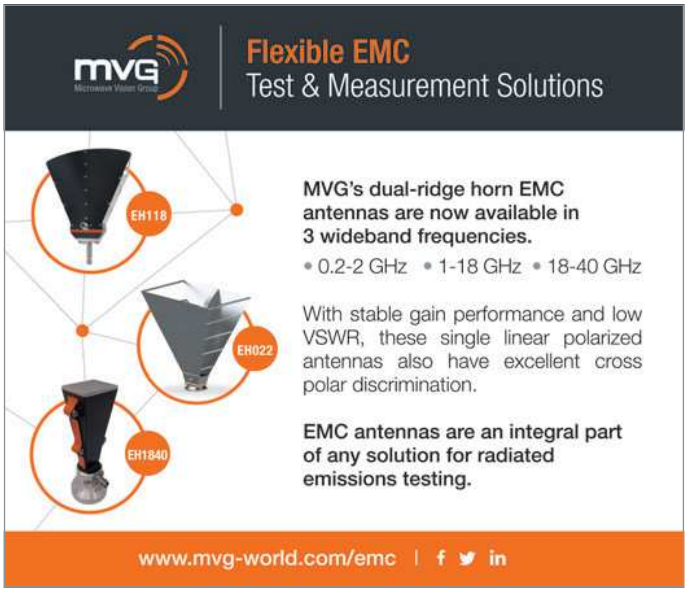
Electrical Overstress to Sensitive Components

Production equipment often handles sensitive components which, when exposed to EMI, can be damaged via electrical overstress (EOS).[8,9] In short, while grounded surfaces within the equipment are assumed to be "equipotential" and thus safe for handling sensitive devices, high-frequency signals cause difference in voltage between such grounded surfaces due to distributed inductance and capacitance of grounding cables, as well as parasitic coupling with power and signal wires.

An example of such would be robotic arm of a common IC handler used in manufacturing of semiconductors. Figure 3 shows a robotic arm that has three degrees of freedom - at least three servo motors and perhaps more, depending whether each individual nozzle at the end of the arm is controlled by a motor or pneumatically. The black "ribbon" seen coming from the top of the arm is a special flex cable assembly containing multiple wires for power, data and, most importantly for us, grounding. Typical DC ground resistance between the chassis and the end of the robotic arm is less than 1 Ohm.

According to all safety and ESD standards and recommendations,[10] this tool should be safe for handling sensitive devices. However, due to noisy nature of servo motors and other equipment in the handler, as well as a long run of closely-placed parallel wires in the long flex cable going to the arm, the ground wire at the end of the cable on the robotic arm contains substantial high-frequency voltage vs. much "quieter" chassis. Figure 4 shows actual voltage measured between the nozzle of the arm of one of such handlers and its chassis (an example is in Figure 3). As seen, peak voltage reaches 3.79V. Is such a seemingly low voltage a problem? After all, ESD damage level for ICs is typically 100V or above. But we are not dealing with ESD – there is no static involved here – but rather electric overstress (EOS) which, according to Intel, was the "number one cause of damage to IC components." [11]

Most definitive requirements for EOS levels in electronic assembly are in IPC-A-610 document "Acceptability of Electronic Assemblies."[12] Its section 3.1.1 states that "…equipment must never generate spikes greater than 0.3 volt" for sensitive components. Note "spikes," not RMS or other value – this document recognizes that using artificially slow detectors won't help to protect devices against EOS. The International Roadmap for Devices and Systems (IRDS, now under the IEEE auspices and available at http://irds.ieee.org) also specifies similar peak levels of noise.



WHAT SIGNALS ARE THERE ON POWER LINES AND GROUND?

Figure 5 shows one of typical waveform on power line found in industrial environment. Let's examine it closely to see how it correlates with EMC regulations (at this point we won't be speculating about the origins of these signals). As seen, this is a waveform composite of at least three different signals. In order of diminishing magnitude, the first one is a short transient with some minor ringing. Its peak amplitude is 344 mV as shown. Second is low frequency signal, likely itself composed of several signals - the waveform is not quite sinusoidal. The frequency of that signal is ~22 kHz and the peak magnitude - ~100 mV (one large division is 100 mV). Finally, there is a smaller underlying signal with the frequency of ~1.1 MHz and peak amplitude of ~25 mV.

Which of these signals would pose more problems for operation of sensitive electronics? Of course, the transient signal – it is significantly larger than other components and its properties are just right to cause a false pulse in signal lines. The runner-up, the low frequency signal with a fairly high magnitude, is also quite troublesome. The least worrisome would be the small continuous signal.

Now that we sorted the signals by the probability of their interference abilities, let's see what the EMC regulations say. The most troublesome signal - the strong transient spike - would be ignored because the limits are set and the tests are typically conducted using an excruciatingly slow quasi-peak detector. A spike like this would dissipate in such detector without a trace. Should there be many such spikes at short intervals, it may move the "needle" of the quasi-peak detector a bit, but nowhere near the "red line" of non-compliance.

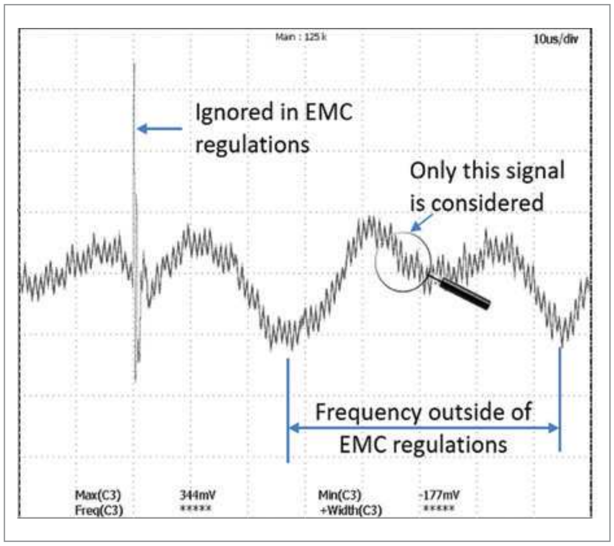


Figure 5: A waveform of EMI signal on power line

The second signal by magnitude may also be ignored, not due to the detector but due to its low frequency. Conducted emission limits in many locales and for many industries don't go below 150 kHz, and this notable signal will simply be discarded during compliance measurements. While some regulations extend the lower frequency limit to 9 kHz, most EMC-compliant equipment is tested and certified down to only 150 kHz.

What would be considered as part of EMC compliance is the least significant signal of 1.1 MHz. We observed peak amplitude of ~25 mV and with gross assumption of considering this signal a sinewave, RMS of it would be 17.7 mV, or 85 dBµV. This would also fail Class B of CISPR 22 but would barely pass Class A.

WHAT SIGNALS CAN BE FOUND "IN THE AIR" (RADIATED EMISSION)?

The shorter the antenna, the more its efficiency shifts to high frequencies. Since the edges of transients and pulsed signals in today's equipment are quite fast,

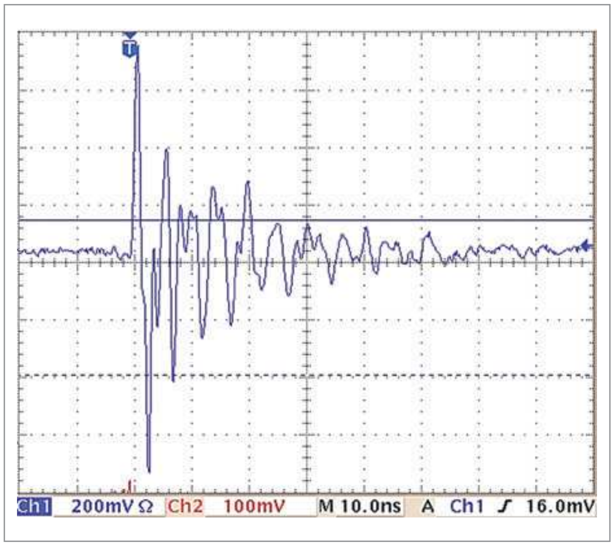


Figure 6: Typical radiated signal in the air picked up by a short antenna

even the shortest trace on a circuit board is now an efficient antenna. It is also a good receiving antenna, easily picking up such short transients. Figure 6 shows typical signal in the air in the industrial environment picked up by a small antenna. The ringing here is a result of inherent mismatch of impedance between short antenna and 50 Ohms input of an instrument. The peak signal is ~0.7V which would be enough to throw off logic level in a low-voltage gate. Seldom in an industrial environment do we observe a continuous signal in the air short of near obvious intentional radiators – WiFi access points, RF generators, RFID and alike – producing mostly transient emissions and not continuous emission.

HOW DO EMC REGULATIONS RELATE TO REAL-LIFE SIGNALS?

Quasi-Peak vs. Peak Detectors

Let's go back to Figure 5 What we see from this example is that in some cases EMC regulations address only the "least significant" emission and deliberately ignore signals with the potential to cause most interference. To further illustrate this point, consider Figure 7. A short but quite strong spike on power line has amplitude of 679mV – enough to wreck a havoc should it get onto a data line. Yet, the RMS value of it is only 25mV, largely reflecting the energy of the small continuous signal. Quasi-peak value would be even lower – perhaps enough to pass conducted emission test.

Would repeatable transients affect quasi-peak measurements? Of course they will, but not nearly enough to address the problem. Figure 8 shows current measurements on ground between a servo controller and a servo motor. Servo motors operate in pulses with the repetition rate of typically 6 to 20 kHz (this particular motor uses 10 kHz) and the sharp edges of these pulses cause leakage of current to ground. Should you be interested in how much current there is, it is 1.68A peak (measured with Tektronix' current probe CT1 with 5mV/mA sensitivity). However, look at the RMS value – it is six times less even though the pulses repeat every 100 μS. The RMS value of the signal here is that of underlying low-level continuous signal with very slight addition from the energy of the pulses.

Figure 9 illustrates how a quasi-peak detector can misrepresent peak values of signal. In essence. No wonder that otherwise fully-compliant equipment is "bursting on the seams" with high levels of transients. This is true for both conducted and radiated emission.

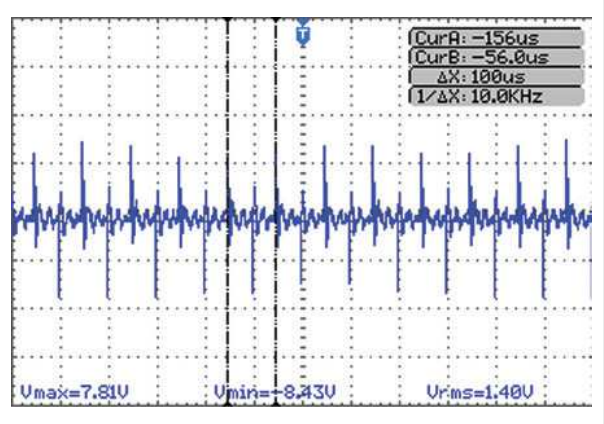


Figure 8: Repeatable transients and RMS value

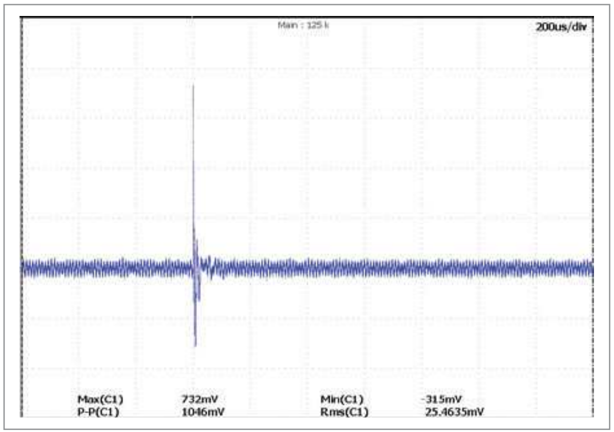


Figure 7: Typical transient signal on AC power lines

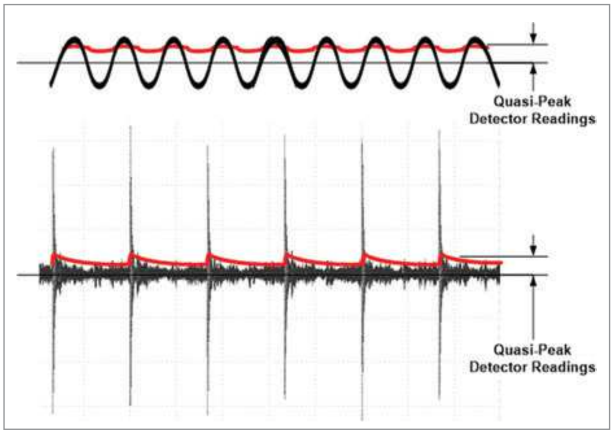


Figure 9: Readings of quasi-peak detector

Far Field vs. Near Field

Now let's consider issue with near and far fields in radiate emission. A summary of what it is can be found here.[13]

All radiated emissions are measured for compliance purposes in the far field - either at 3m or at 10m from the source, i.e., from the equipment undergoing EMC certification. CISPR 22 regulations require that radiated emissions measurements for Class A devices be measured at a distance of 30 m and Class B devices be measured at a distance of 10 m. Requirements of the U.S. Federal Communications Commission (FCC) specify 3 to 30 m test distance. However, since virtually all equipment manufactured today uses worldwide compliance, 10 to 30 m is the distance at which most measurements are done. Near/far field issues notwithstanding, at this distance the receiving antenna for radiated emission test will be fully illuminated from the entire equipment (short of trains, planes and ships), and the emission would be somewhat "averaged" which makes for repeatable measurements.

However, in practice, equipment at a factory is rarely placed at least 30 m from each other, and not all of us are so fortunate to be able to leave 10 m space between various gadgets at home. In many factories, equipment is co-located quite close to each other due to process requirements as well as expensive real estate.

So, what's wrong with locating equipment close to each other? To understand why, we need to remember that, at a distance of 10m or 30m, the receiving antenna "averages" emission from the entire product. However, emissions from equipment is rarely uniform over its surface. There are always "bright" spots, such as openings in enclosure, gaps on the edges of the lids, gaps around connectors, exposed wires and so on. Of course, there are also large "dead" spots emitting very little energy.

Imagine a car at night with its headlights on. While the headlights themselves appear quite bright, the rest of the car – a much larger area – is completely dark. A light sensor positioned at 10 m or at 30 m away will record very moderate total illumination; after all, the headlights are quite small and while they themselves appear bright, the total amount of light from them reaching antenna isn't that large. At night, the headlights can illuminate (and only to some degree) a narrow cone in front of the car, just enough to see the small length of the road ahead. A receiving antenna may similarly pick up very moderate total emission from equipment while some spots can be very "bright."

Why does this matter? Well, when equipment is placed close enough to "bright" spots emanating from neighboring equipment, it is essentially "staring right into the headlights," making its own operation difficult. In many situations equipment being tested works in conjunction with other equipment, often from a different manufacturer. As an example, IC tester is usually paired with IC handler. Together they perform critical function of fully automated test of integrated circuits. But they are often manufactured and tested for EMC compliance by different companies. Similarly, a wafer handler and die attach tool in the same semiconductor manufacturing facility operate in tandem, but may come from different manufacturers as well. A "bright" spot in any of these tools would pose a challenge to its "partner."

There are some initiatives to make measurements at closer distances[14] but no actual regulatory movements. And even these suggested measurements at closer distances do not focus on identifying "bright" spots in equipment.

The 50 Ohms Question

Life is quiet and predictable in the EMC test

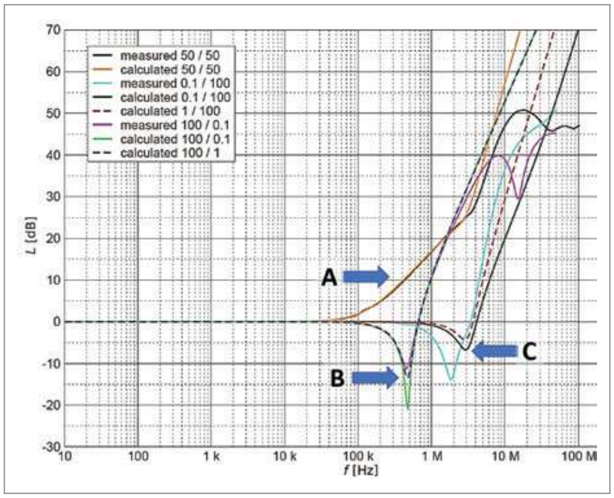


Figure 10: Insertion loss of a typical EMI filter at 50/50 and 0.1/100 Ohms (Source: J. Drinovsky, Z. Kejik, V. Ruzek, and J. Zachar, *International Journal of Circuits, Systems and Signal Processing*, Issue 3, Volume 5, 2011)

laboratory. Everything is nicely terminated with 50 Ohms - ins and outs. The cables are short (as short as the regulations allow it) and nothing else disturbs the test. Everything in this "bubble" is tranquil and steady. What could possibly go wrong by placing equipment under test out there in the real world?

As it happens, a number of thing can go wrong. Let's consider what happens when the impedance of a power line and ground is no longer 50 Ohms. There aren't many power lines out there with the impedance of 50 Ohms – their output impedance is very low, otherwise the voltage would dip significantly even with the weakest of the light bulb. Nor there are many "loads" with 50 Ohms impedance - only those consuming precisely 288 W at 120VAC or 1250 W at 250V would present such load to the power line. This is at 50/60 Hz, of course – impedance at high frequencies varies wildly. A much more realistic scenario for power line ("line side") output impedance is 0.1 Ohms. As for the "load" side (equipment itself) - anything goes. Industry has settled on 0.1/100 Ohms numbers - 0.1 Ohms for the "line" side and 100 Ohms for the "load" side.

Would the difference between 50/50 Ohms and 0.1/100 Ohms matter? Actually, quite a bit. The main method of control of conducted emission is use of power line EMI filter – almost every product that is plugged into power line has at least one, even if it is not immediately visible. A typical EMI filter contains some combination of L and C – inductors and capacitors, meaning that termination impedance would influence the filter's self-resonance performance and its transfer function.

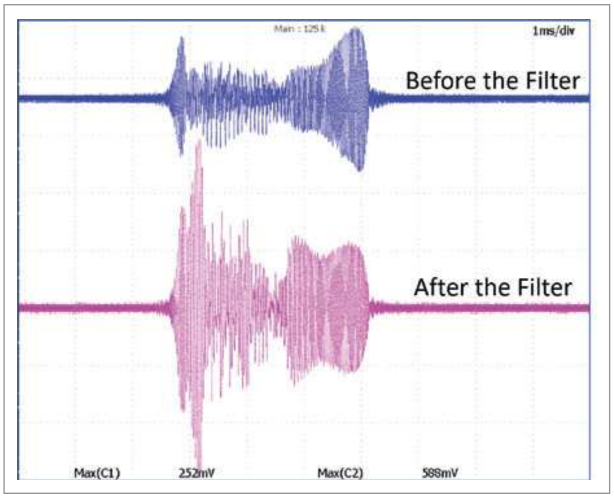


Figure 11a: Performance of a regular multi-stage EMI filter on actual power line.

Consider performance of a typical EMI filter in both 50/50 Ohms and in 0.1/100 Ohms scenarios. Figure 10 [15] shows that, in 50/50 Ohms termination, the attenuation of a filter steadily improves with the frequency (A). However, outside of the EMC testing laboratory and in real-life installation, the performance of the filter is quite different. Charts B and C show the transfer function of the same filter in 0.1/100 and 100/0.1 termination respectively. A most interesting thing happens – rather than attenuating the signal, the attenuation becomes "negative," which simply means amplification. At one frequency (~450kHz) measured "attenuation" is -12dB; in alternate termination at ~2MHz, it is -14dB. It simply means that noise at this frequency will be amplified ~4 times and ~5 times respectively.

Sounds surprising and incredulous – an EMI filter that would amplify noise? Not at all.[16] Figure 11a shows a fairly good-quality multi-stage EMI filter doing exactly that. For these and other measurements in this article, the 50/60Hz mains' frequency was blocked using power line EMI adapter.[17, 18]

Depending on a specific filter model, the "negative attenuation" frequency can be much lower, in the range of 50 to 100kHz, exactly in the frequency range of a switched mode power supply (SMPS).[19]

All this is not a defect of a particular filter – it is doing its job for the purpose it was designed for – test per EMC regulations. A filter manufacturer, just as any other product manufacturer, optimizes its product for the specific purpose, in this case, for very specific EMC requirements. Performance in an actual application is not regulated.

Is it possible to have a filter that would work well at impedances other than 50 Ohms? Yes, such filters do exist[20] – Figure 11b on page 50 shows performance of such filter under identical circumstances. Such filters are essentially impedance-independent, more complex and more expensive, but they do the job of suppressing EMI in real-life installations.

Cables: A Long and Winding Road

Once again, all is neat and orderly in the EMC test laboratory. Everything is known and predictable. The absolute minimum lengths of only-essential cables are properly laid out. No other cables are present and there is no possibility of them coupling to anything else. It could be called an "EMC cleanroom." But what a difference real-world installation and a few extra meters of cables can make.

At high frequencies, a power cable is a collection of distributed inductance (even a straight wire is an inductor), distributed capacitance (between internal wires in a cable and between all wires and any metal surfaces and other cables) and skin effect resistance (at 1MHz effective conductive depth of a regular wire is only 0.066mm) as shown in Figure 12.[21]

All this results in two signal-altering phenomena, with the cabling acting as both a low-pass filter and as a resonance circuit. Most of noise originating in the equipment consists of sharp transients caused by rapid transitions of voltage levels, whether it be in an SMPS, a PWM motor or another source. Such sharp transient will remain a sharp transient after short power cable, but as the length of the power cable increases, that sharp transient becomes "duller." You may also notice that that formerly sharp transient is now accompanied by some additional signal – ringing. Parasitic resonance of the complex cable RLC network "rings" just like a piano string would vibrate for a while after being hit by a hammer connected to a piano key. The longer the cable, the lower the ringing frequency. The result is that the signal, after some length of cable, looks nothing like how it looks at its origin (see Figure 13). Because of this obvious phenomenon, the spectrum of signals on power lines in a typical factory is well-contained within 2MHz, and often less than 1MHz. And we haven't even mentioned impedance mismatch and associated reflections.

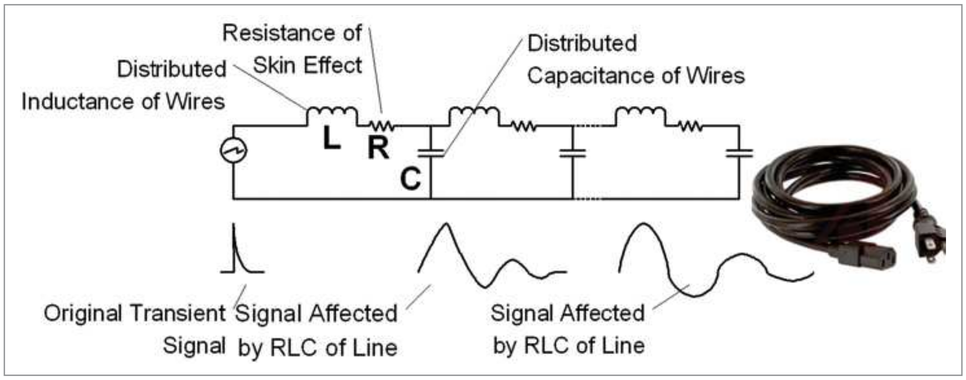


Figure 12: Power cables as a distributed network

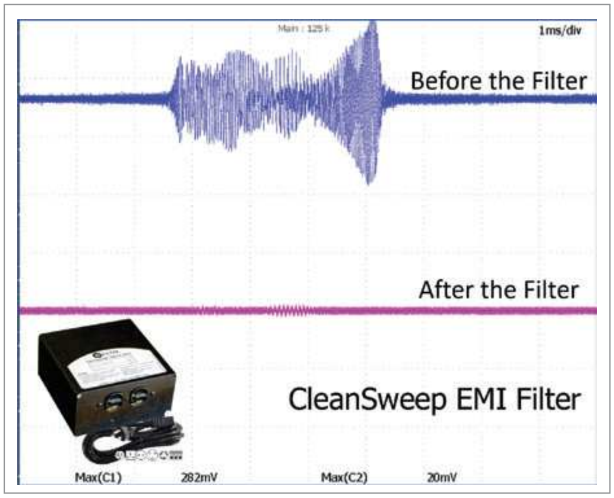


Figure 11b: Performance of a specialized EMI filter (OnFILTER CleanSweep® AFN515FG)

What difference does it make? Quite a significant one, actually. Equipment manufactures trying to comply with EMC regulations (both emission and immunity) see only sharp transients with mostly higher frequency content. Therefore, they select the filter with the best attenuation at the low end of the spectrum. As we now know (see Figure 10), the regular EMI filter would do decent job at the higher end of the spectrum, but would amplify noise at lower end of the spectrum or, at very least, won't attenuate it much. If such equipment is installed at the factory, it may be well equipped to block entry of high-frequency noise from power lines. Alas, it will almost invite lower frequency noise by amplifying it or, at best, not providing any reasonable attenuation. When this becomes the problem, an external EMI filter (Figure 11b)[22] specifically designed for such an application can solve the problem by blocking noise in the entire spectrum.

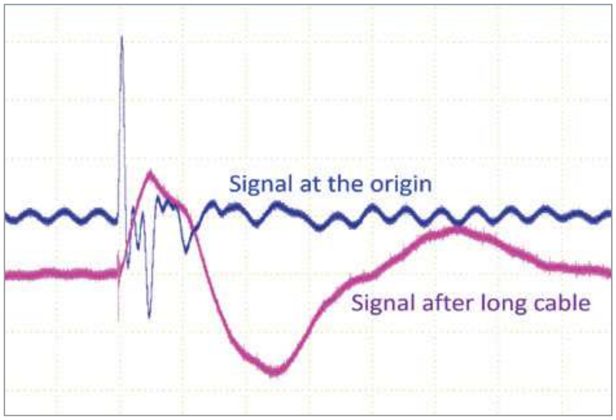


Figure 13: Transient signal at the origin and after long power cable

NOW WHAT?

In this article, we have examined several examples of substantial gaps between current EMC regulations and the needs of equipment users. Are current EMC regulations relevant at all? Of course they are, since without them there wouldn't be any EMI reduction at all. But, as we have seen, they are often not sufficient.

Since the needs are "fixed," shouldn't EMC regulations be changed to be accommodate the realities of real-life processes and equipment? Maybe, but don't hold your breath. In the meantime, the onus of reducing electromagnetic interference is on end users. Understanding the nature of EMI in real-life environment and how to deal with it can help users to make their processes and equipment much more effective and error-free, and their sensitive devices better protected from EMI-caused electrical overstress.

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