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On the Cover: A CV-22 Osprey hangs in the anechoic chamber at the Joint Preflight Integration of Munitions and Electronic Systems hangar at Eglin Air Force Base, Fla., March 6, 2012. The chamber is designed to stop internal reflections of electromagnetic waves, as well as insulate from exterior sources of electromagnetic noise to facilitate testing air-to-air and air-to-surface munitions and electronics systems on full-scale aircraft and land vehicles prior to open-air testing. U.S. Air Force photo by Tech. Sgt. Samuel King

# Disruptive Technologies

**Kenneth Wyatt**
Sr. Technical Editor, Interference Technology

I've been fortunate to have lived through several disruptive technologies in my lifetime:

- Vacuum tubes to transistors to integrated circuits - to entire systems on a chip
- Early B&W television to color CRTs to all solid state flat panel displays
- Vinyl records to 1/4-inch tape (including 4- and 8-track tape) to cassettes to CDs to MP3 players to streaming audio
- Wired telephones on party lines (remember those?) to individual mobile communicators and as of December 2015, 40% of Americans have terminated their landline phones.

Today, we're witnessing new disruptive technologies. Two of the biggest involve the automobile. For decades, automobile engines have been driven by explosive gasses in cylinders, which push mechanical crankshafts.

Electric Vehicles - While some major auto manufacturers have tested the waters of hybrid and all-electric vehicle production, it wasn't until Tesla started making big moves and investing in an extensive worldwide system of charging stations that the major manufacturers finally took notice. Now every manufacturer is rapidly developing production electric vehicles.

Autonomous Vehicles - Google is well advanced in their developmental self-driving vehicle. Other major automobile manufacturers are looking seriously at this technology. Experimental projects including self-driving trucks and farm equipment are also under consideration.

Other areas of disruptive technology include low cost test and measurement instruments, with Asian companies starting to produce excellent quality products that are forcing the major manufacturers to follow suit. The result is a big advantage for smaller companies to afford equipment that has so far, been out of reach.

You're probably sick of hearing about "5G" communications, along with all the early hype. Well, in fact the technology has been advancing to the point where standards are just beginning to evolve. The result will be vastly increased bandwidth and data rates for future communications and mobile devices.

The military and associated contractors have also been developing communications up in the mm-wave frequencies (30 to 300 GHz); partly for security, but primarily for increased capacity for data and communications for battlefield management.

Lastly, the medical field has exploded with new technologies; not only in the hospitals, but for affordable home care products. If you take a look at the variety of home care technologies available, it's incredible. This has also extended out to numerous fitness products and applications.

With all this new technology under development, the demand for EMC engineers will only increase. Exciting times ahead!

# Mitigating EMI Issues in Servo Motors and Variable Frequency Drives

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Servo motors and variable frequency drives are wide-spread in the industry. Industrial automation cannot be imagined without these motors. This article deals with certain EMI-related issues inherent to these motors, specifically high-frequency drive signals.

## BACKGROUND

Servo motors and Variable Frequency Drives (VFD) are typically comprised of two parts - the motor itself and a controller (also called "amplifier," "servo pack" or "inverter") which drives the motor and is connected to it by cable. Controller receives power from AC mains. Servo motors have a feedback circuit that allows it to maintain specific position with high accuracy. This also means that servo motors work even when they are not moving. Variable frequency drives (VFD) work in a different way - their speed is controlled by the frequency of the drive signal. What is common between these two different types of drives is that both are driven by a pulse-width modulated (PWM) signal. *Figure 1* depicts block diagram of a typical VFD arrangement. AC mains power enters variable frequency controller, which converts it into a pulsed signal driving the motor. Servo motors (*Figure 2*) add feedback position control. A typical manufacturing and robotic tool may have as little as one and as many as 20 such drives.

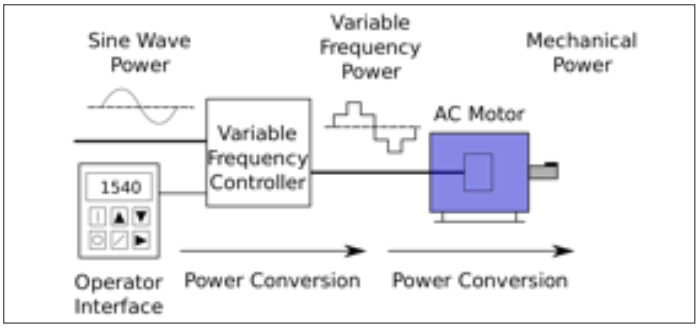


Figure 1. Block diagram of a typical VFD arrangement (Source: Psemdel/Wikipedia)

There are plenty of issues associated with VFD and servo motors. We will be focusing only on some of them. Readers can simply look up on search engines for VFD, bearings, overvoltage and EMI to see the entire scope of problems and attempted solutions to them.

## CHARACTERISTICS OF THE PULSE DRIVE SIGNAL

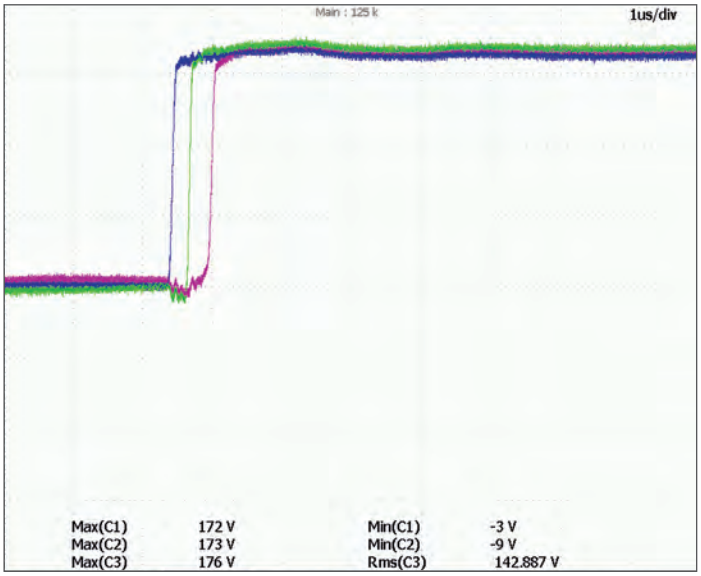


Figure 2. Pulse edges of servo drive signal - three phases shown

In order to reduce cost of equipment, inverters that generate drive pulses (also called carrier signals) use rapid switching causing drive pulses to have rise and fall times to be as short as few nanoseconds (*Figure 2*), extending the spectrum of these edges to several Megahertz. It is much easier, less expensive and thermally more efficient to simply turn on and off current to the motor than to create a gradual ramp up and ramp down of the output voltage. Such short edges of drive pulses are the main culprits of the variety of problems. If the connection between a controller and a motor was done as a proper a RF connection, i.e. matching input and output impedances, proper RF-grade cable and the like, many of the problems wouldn't exist. However, the main purpose of a

motor is not proper propagation of signal but rather to perform mechanical work, so there is seldom a consideration for the high-frequency nature of signals. Here are just some of the problems caused by and/or associated with sharp-pulsed drive signals (in no particular order of importance):

- motor bearing damage
- overvoltage and associated insulation damage
- high levels of conducted EMI in power lines and ground
- high level of EMI current in ground causing electrical overstress (EOS) problems
- high levels of radiated EMI from the cables
- mechanical noise
- motor overheating

In the following sections we will consider each of them and discuss mitigation of these problems.

## MOTOR BEARING DAMAGE

Let's consider a motor as an electronic circuit. Drive pulses with sharp edges are applied to the stator, i.e. inductors on a motor frame. The stator has strong capacitive coupling to the rotor (large metal surfaces of rotor and stator located very close to each other).

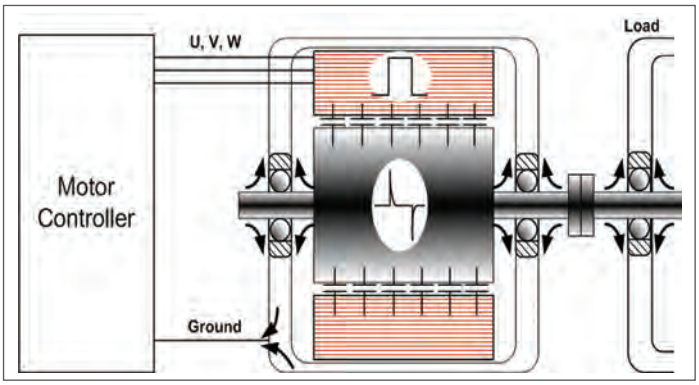


Figure 3. Parasitic current path in a motor

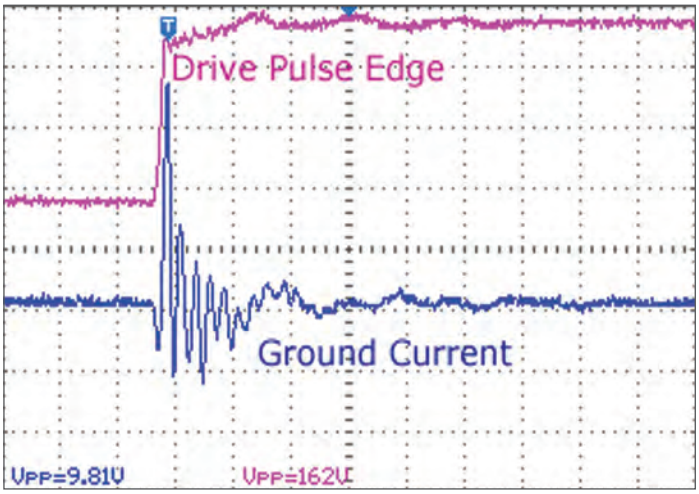


Figure 4. Ground current and drive pulse edge. Ground current is measured with Tektronix' CT1 probe 5mV/ma. Current shown is 1.96A

While the frequency of the drive pulses themselves is fairly low - typically no more than 20 kHz, and is not a concern - the high frequency component of sharp edges of drive pulses experiences little impedance from this capacitive coupling and now the rotor has a high-frequency voltage which is synchronized with drive pulse edges. This voltage, in turn, causes current flow to ground through the only path it can flow from the rotor - motor's bearings. Figure 4 shows how ground current is perfectly synchronized with the edges of the drive pulse.

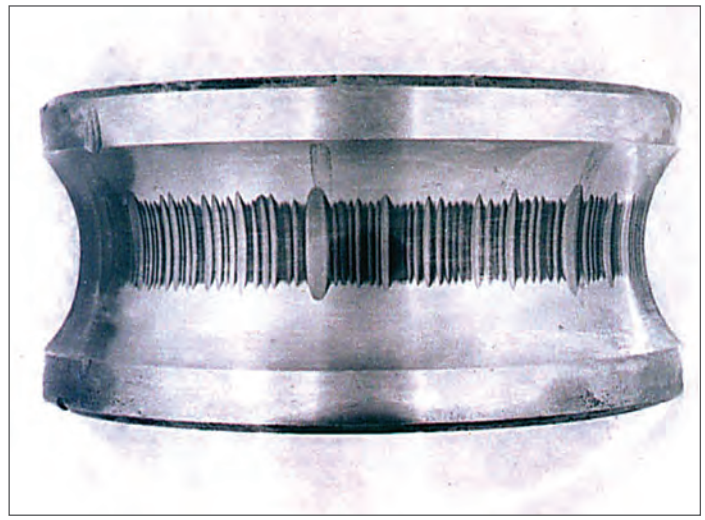

Figure 5. Bearing "fluting" (NEMA Application Guide)

The contact between the bearing's balls and bearing races is highly intermittent, exacerbated by presence of insulated lubricant[1]. The resulting current in bearings is arcing which, in turn, leads to a phenomenon called EDM - electrical discharge machining[2]. In essence, sparks "eat" metal in small pieces at a time. This phenomenon is widely used for work on otherwise hard-to-machine metal partsWith the ball bearings the mechanism of machining the metal is essentially the same; the purpose and the outcome, however, are vastly different. Sparks-caused EDM in bearings starts with tiny craters, or pockmarks, creating discontinuities, which cause further discharges and further damage[3]. Voltages on the shaft as low as 200 mV are capable of causing sparking[4], although induced voltage on the rotor can be quite high - up to tens of volts[5]. Once a pockmark is created, it becomes a focus point of further discharges. Since the drive pulses and resulting discharges occur several thousand times per second every second of motor's operation (see *Figure 5*), it doesn't take long to create a permanent damage to the bearing. One of the most common problems is "bearing fluting," or, so called "racetrack" - see *Figure X* (ABB). The problem propagates, eventually resulting in permanent damage to the motor due to the bearing's failure. This problem is widespread and does not show any signs of diminishing by itself.

## PULSE EDGE OVERVOLTAGE

If the output impedance of the motor controller, input impedance of the motor and the impedance of the connecting cable were perfectly matched, the drive pulses would be perfect square wave pulses. Alas, motors are not RF devices, no one attempts to match the impedance, plus should anyone attempt this it wouldn't work anyway. Mismatched impedance causes

ringing and overshoot.

Figure 6. Pulse edge overvoltage

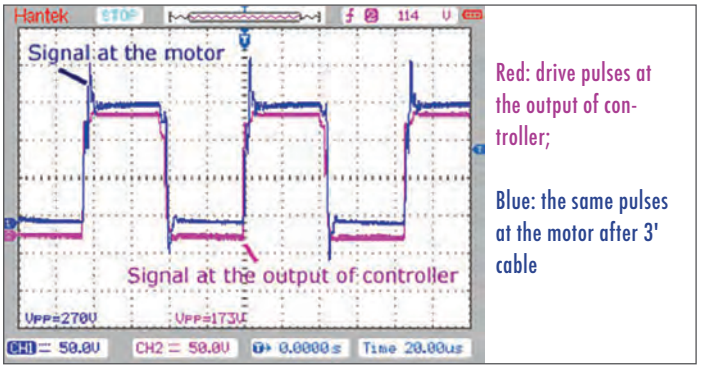


*Figure 6* shows rather mild cases of ringing and overvoltage, although in many cases the overvoltage may easily exceed 60% of the normal pulse amplitude[6]. The red trace is the drive signal directly at the output of a controller; blue trace is the same signal at the motor after 3' (~1m) of cable. Needless to state that such overvoltage and ringing only increase ground current through the bearings. According to U.S. Department of Energy[7], "The fast rise time pulses from a PWM VFD can ... "create a potentially harmful current flow in bearings even when overvoltage is not significant." Overvoltage not only causes further beading damage, but also stresses insulation of the cables and of the internal wiring of the motor, in addition to other problems, including potential controller drive circuit damage, motor overheating and acoustical noise, not counting less grave effects. This problem is widely recognized. IEC/TS 60034-25[8] (merged with IEC/TS60034-17) states that the pulse voltages at the terminals must not exceed 1,350 V on motors with standard insulation. In case of pulse voltage rise times of less than 0.8 µs at the motor terminals, the permissible pulse voltage is reduced to ~900V for pulses with 50nS rise/fall times shown in *Figure 3*. NEMA MG1-2014[9] also addresses the issue with EMI-caused bearing damage and associated problems.

## EMI IN EQUIPMENT

It would be incomplete to focus only on motor damage or overvoltage aspects of high-frequency drive signals in VFD/servo motors. The motors do not work in isolation - they are installed in equipment, which may be susceptible to EMI caused by operation of the motor(s). High-frequency interference from drive's operation is capable of:

- non-compliance with EMC regulations
- interference with operation of electronics
- errors in measurements and in sensors' outputs
- electrical overstress (EOS) to sensitive components

Generation of drive pulses causes sharp changes in current consumption from the mains, which, in turn, causes high-frequency conducted emission flowing back into these mains. Compliance efforts largely consist in utilizing power line EMI filter on mains, which is recommended by most servo/VFD manufacturers. This may help with electromagnetic compliance. However, there are no current EMC regulations governing EMI inside the tools, because most regulations concern themselves with how particular equipment may possibly affect operation of other equipment. Failure to manage EMI inside the tool causes it to interfere with itself, especially in cases of a composite tool where the user or integrator combines motion equipment with other electronics. In such cases interoperation of different pieces of equipment is not as rigorously checked as if just one company manufactured the tool.

Most of internal EMI problems from drives are caused by drive pulses and manifest themselves as radiated emission from sharp edges of drive pulses, noise on the tool's ground, including tool's frame, and induced conducted emission on tool's wiring which is seldom filtered inside the tool. The ground current going through the bearings in the motor as was described above pollutes the entire ground system of the equipment, reducing signal-to-noise ratio in data lines, altering signal from sensors, resulting in process variations, sometimes causing life-threatening situations, such as false readings in MRI[10]. Some studies indicate that voltage as low as 1V between neutral and ground may cause equipment malfunction[11]. To a smaller degree, capacitive coupling between the drive cables and the equipment's ground[12] also contribute to noise on ground.

Electrical overstress (EOS) can also be caused by EMI from servo motors[13] and VFD. Substantial voltage difference between grounded parts in the semiconductor and PCB assembly equipment can expose sensitive devices to electrical overstress, often causing either instant or latent damage where the

device passes the test in manufacturing but soon fails in the field. The particular problem is that EMI voltage on ground has very low output impedance and resulting strong current capacity, damaging devices at very low voltage differential. The most fundamental standard in PCB assembly - IPC-A-610[14] - limits the voltage applied to sensitive devices, especially transient voltage characteristic for EMI from the motors to as low as 300mV. EOS is becoming increasingly important in yield and reliability considerations for electronic devices.

## MEASUREMENTS OF EMI CAUSED BY VFD/ SERVO MOTORS

"You cannot control what you cannot measure," goes a profound saying. Conducted emission measurements on AC mains done solely for the purpose of electromagnetic compliance are well-known, are thoroughly documented elsewhere, and don't need to be repeated again. Rather, this section points to measurements not normally covered by EMC regulations but are rather important for reliability and operability of equipment.

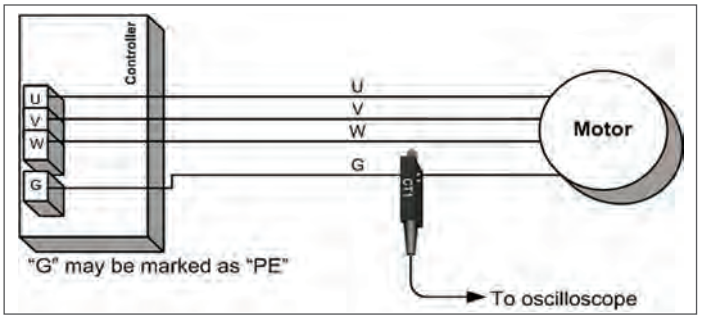


Figure 7. Measurements of ground current

### MEASUREMENTS OF BEARING CURRENT

Needless to say, direct measurements of current through rotating bearings is not a practical endeavor at the least. However, reasonably relevant measurements can be made by measuring current in the return path of the drive signal, i.e. current in the ground wire between the controller and the motor, as shown in *Figure 7.*

The basic premise is that the current through the bearings must return to its origin – the motor controller. The return path is via the ground wire (sometimes designated as PE - "power earth"). While there is some purely capacitive high-frequency current path between the stator windings and a grounded motor enclosure, it is insignificant in comparison with the current through bearings, making measurements of high-frequency current in the ground wire sufficient for estimate of current through bearings. *Figure 7* shows the basic setup, which is applicable for both servo motors and VFD. These motors have three drive lines commonly, but not exclusively, designated U, V and W, and ground wire G, or sometimes designated PE. A broadband current probe on this ground wire carries return current passed via the bearings.

*Figure 8* shows typical current through the ground wire as measured with Tektronix' current probe CT1[15]. This probe has 5mV/mA sensitivity. All measurements of current in this paper were done using this method. As seen, peak current is 1.72A - quite a significant value. This peak current is applied to the bearings 10,000 times per second. Note that the servo motor is working even then it is not moving – simply maintaining its position. Not surprisingly, the damage to bearings is likely, as well as other undesirable effects - interference with operation of tool and electrical overstress.

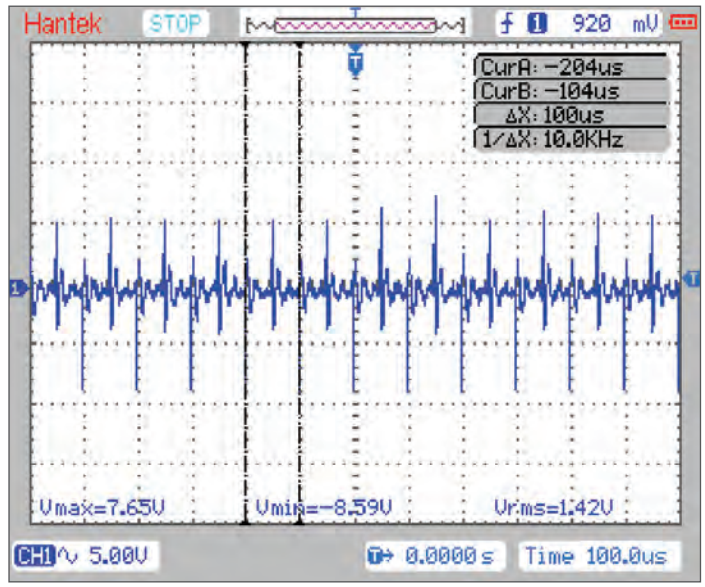


Figure 8. High-frequency current through shaft of the motor

### MEASUREMENTS OF DRIVE SIGNAL - OVERVOLTAGE AND RINGING

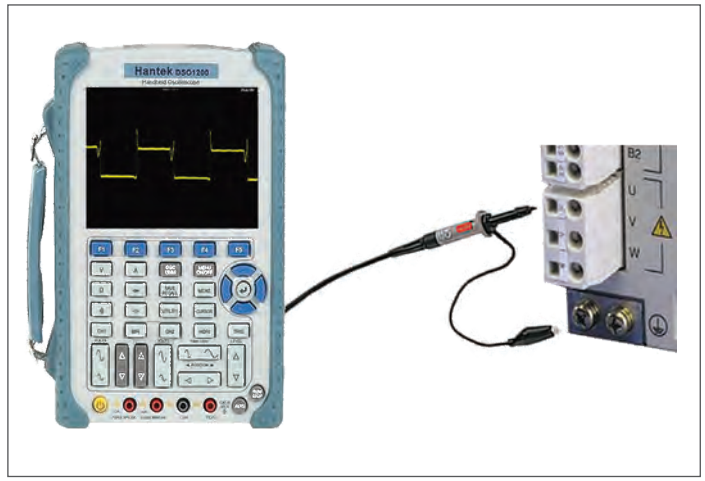


Figure 9. Measuring drive signal voltage

Here we are entering territory where the reader must pay attention to safety si nce drive signals may have high voltage (up to 480V) with strong current capability. Exposure to such voltages may cause injury or death. If you are not accustomed with working on live high voltage lines you should defer test, or at least, its "connecting" part, to a properly trained and experienced specialist.

You would need a battery-powered oscilloscope with the bandwidth of at least 200MHz (a higher bandwidth won't offer any advantage) and 100:1 high voltage oscilloscope probes. Note that a spectrum analyzer won't do and the AC-powered oscilloscope would create ground loop due to its connection to a facility's ground. Also, note that regular 10:1 probes won't attenuate drive

signal sufficiently enough to prevent clipping the signal. Very important: if you value your oscilloscope, you will set its input to 1 MOhm rather than 50 Ohms, as high voltage and low impedance don't play well together. This may add some small ringing artifact to the signal, but this is better than a damaged oscilloscope.

At most motor controllers you would find terminals labeled U, V and W - these are the outputs to the motor. Connect ground of the probe to the controller's ground and the tip of the probe, perhaps with some extension, depending on the terminals' construction, to any of U, V or W terminals (*Figure 9*). Ground of the scope's probe should go to the controller's ground terminal, which is located in the immediate proximity to the U, V and W terminals. It would be helpful to make several measurements setting time base of the oscilloscope to capture several drive pulses, rise edge of a pulse and a fall edge of a pulse.
You should expect nearly square wave drive signal at the good-quality motor controller terminals. Measurements at the motor are much more tricky and often seem nearly impossible due to termination and hard-to-get issues, but with the help of equipment specialist it may be possible. Make sure that ground clip of an oscilloscope probe is connected to ground terminal at the motor itself, not anywhere else, otherwise the test results are severely compromised.

## MITIGATION OF EMI PROBLEMS IN VFD/ SERVO MOTORS

Ultimately, all the problems described above are caused by and/or related to sharp edges of drive pulses. Therefore, the solution to these problems would be to modify pulse edges so that the rise and fall times are slow enough for the capacitive coupling between the stator and the rotor not to be a strong conductive path; all while maintaining operability of the motor. There are partial solutions involving optimized cabling and altering the path of current through the bearings or blocking this path altogether. The problem with PWM-driven motors is not a new one and is quite widespread - there are a number of solutions, which we will examine, in further chapters. Given the wide spread of this problem and its financial impact, there are a number of solutions available to motor users, performing with various degrees of success. The field of preventive measures for VFD and servo motor problems is very competitive - a user is advised to pay attention to factual technical analysis versus the intensity of sales hype in selecting a solution to the motor's problems.

### OPTIMIZED CABLING

Needless to say, a shorter motor cable offers less ringing and less emissions than a longer one. A cable to the motor routed separately from other cables induces less voltage and currents into other conductors. Good properly connected shield (copper braided) helps with reducing electromagnetic field from the pulse edges.

There are special cables manufactured for VFD and servo drivers. A better cable between the controller and the motor is properly shielded one (copper braided shield) with sufficient gauge. Some cables have separate ground wires for each phase[16] which further reducing ringing. The user is discouraged from using regular cables not specifically intended for VFD applications since they may exacerbate the problems.

Importantly, better cabling does not by itself change how sharp the pulse edges are. Ringing, of course, affects pulse edges but not to the degree where this becomes noticeably effective.

### INSULATED BEARINGS

One approach to prevent high-frequency current going through bearings is to make bearings non-conductive. Ceramic-coated bearings[17] electrically isolate the rotor and offer no galvanic connection from rotor to ground. Capacitive coupling across ceramic coating still remains, however, providing some significantly smaller current than it would be otherwise. The coated bearings focus narrowly on the bearing damage problem, leaving most of other problems, such as EMI from the cables and others, intact. Another challenge with coated bearings is that they need to be designed for each type of shaft and two of them have to be uses on each side of the motor, affecting cost and installation. High frequency voltage residing on the rotor will still be shared with motor's load via conductive coupling, subjecting its bearings to destructive current.

### SHAFT GROUNDING

Another mechanical solution is grounding of the rotor's shaft using special brushes[18] or other electrical contacts that essentially short-circuit high-frequency currents to ground bypassing bearings. Just like insulated bearings, these solutions are narrowly focused on reducing damage to bearings and reducing voltage on conductively-connected load. However, they still leave high-frequency currents in equipment ground intact, as well as preserving EMI problems associated with drive signal pulses. Any mechanical solution requires periodic checks and, if needed, repair or replacement. Naturally, the bypass contacts must be installed on both ends of the rotor's shaft and they have to be tailored to the specific motor type. When using shaft grounding contacts or brush you must connect motor's case/ground to the load's ground in order to protect equipment[19].

### FERRITE CORE RING

A simple ferrite core put over three motor drive wires (U, V and W) provides limited common mode rejection similar to typical ferrite core applications. However, given simplicity of installation and relatively low cost, sometimes just a little bit of improvement may be sufficient. The ferrite cores for this purpose are usually oval to accommodate three drive wires. They may be either split-core or solid. Important considerations are saturation - if the core isn't "beefy" enough, it will saturate just when it is needed the most. The frequency response of the core should be geared more towards the lower frequencies. Just like any filtering solutions described further in this article, the ferrite core shall be positioned close to the drive controller, not to the motor, to lessen emission coming from the cable.

### LOAD REACTORS

An output (or load) reactor connects between the controller and the motor. It is simply three separate inductors on a common core connected in series with the phases of the drive signal of the motor. The reactor's main function is to extend dV/dt

time of rise and fall edges of drive signals. Increased dV/dt time "spreads" drive pulse edges, typically 3 to 5 times[20,21]. Reactors are installed close to the motor controller in order to reduce emission from the cables. Reactor benefits include:

- lower current through the bearings
- overall reduction of EMI in equipment
- lower "ringing" of drive pulses, allowing for longer cables between the controller and the motor
- lower temperature of motor

Unlike mechanical solutions, reactors are selected solely on the basis of their electrical performance and do not need to be either fitted to a particular motor nor need to be checked or maintained. Reactors can be added after installation without much effort and with no mechanical work on a motor. Reactors not only help with the bearing damage and overvoltage, they also reduce ground current and overall EMI in equipment. On a flip side, they provide very marginal performance improvement - both in increasing dV/dt (i.e. "slowing down") of pulse edges. Wherever just a small improvement is required, a reactor may be a reasonable choice.

### MOTOR FILTERS

There are two basic types of motor filters – sine wave and dV/dt. Both are enhanced versions of reactors, adding more filter stages and other enhancements.

### SINE WAVE FILTERS

Sine wave filter[22] is essentially a low-pass LC filter in each phase of the motor, which converts the PWM signal into corresponding sine waves with approximately the same RMS voltage as the original PWM signal. Sine wave filters offer the advantage of greatly reduced EMI in all aspects. They also can be retrofitted in existing installations. Just like a reactor they need no periodic test or maintenance. Sine wave filters, though, work only with certain types of motors (i.e. they cannot be used with servo motors); cannot be used at lower switched frequencies due to possible internal capacitor damage, and are bulky.

### DV/DT FILTERS


Figure 10. OnFILTER' SF series VFD/Servo Motor dV/dT filters

These are arguably the most versatile filters, which perform quite well with both VFD and servo motors. The dV/dt filters "stretch" the rise and fall times of the drive pulses thus reducing high-frequency spectral content of the drive signal which, in turn, reduces capacitive coupling between

the stator and the rotor and resulting current through the bearings and ground current, as well as overall EMI levels in host equipment. Just like sine wave filters and reactors, they require no periodic test or maintenance and can be installed "after the fact." Due to their versatility and wide range of applications, we will examine their performance more closely. We will do so on example of SF series servo/VFD dV/dt filters manufactured by OnFILTER (*Figure 10*), as the ones on which the author performed most of the tests.

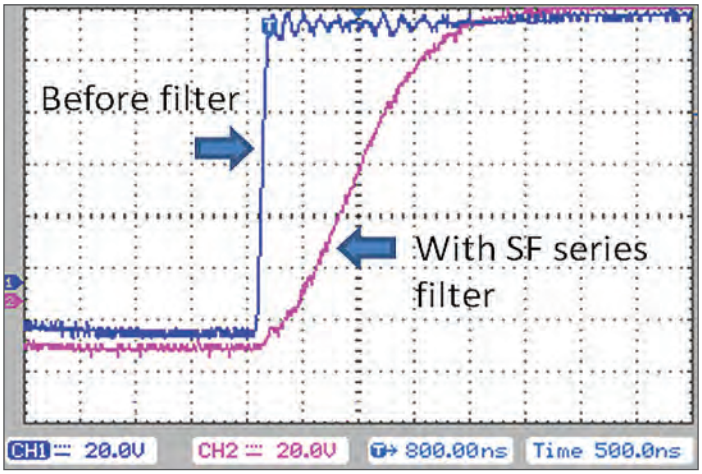


Figure 11. Modification of drive pulse edge with OnFILTER's SF series filte

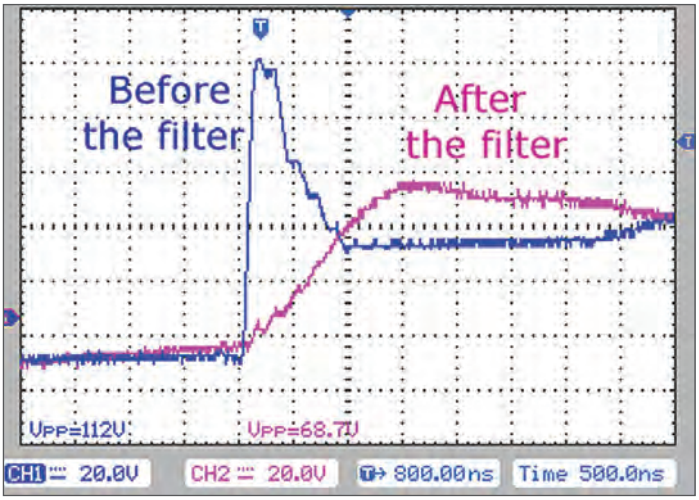


Figure 12. An example of reduction of overvoltage with OnFILTER's SF filter

*Figure 11* shows typical pulse edge "stretch" with VFD/servo motor filter SF series[23]. As seen, the rise time increased from under 100nS to almost 2μS. How significant is it? Let's consider *Figure 12*, which shows how this filter removes overvoltage caused by sharp rising edge of the pulse. When a filter is placed right at the output of the motor controller, the drive signal on cable is largely free of sharp edges which reduces overshoots and resonances, as well as radiated and coupled EMI in the tool.

What about ground noise? *Figure 13* shows how to measure ground current; *Figure 14* shows the results. The measurements were done using Tektronix' CT1 current probe. As seen, SF series filter is capable to substantially resolve ground current situation. Unlike reactors and regular VFD/servo filters, SF-series motor filters utilize proprietary additional filtering stages, which allow for reduction of ground current down to a negligible level.

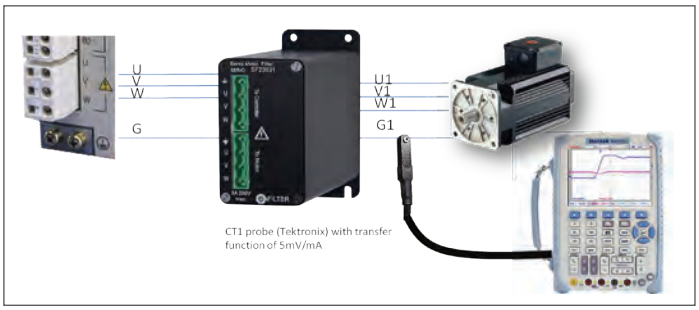


Figure 13. Measurements of ground current with filter

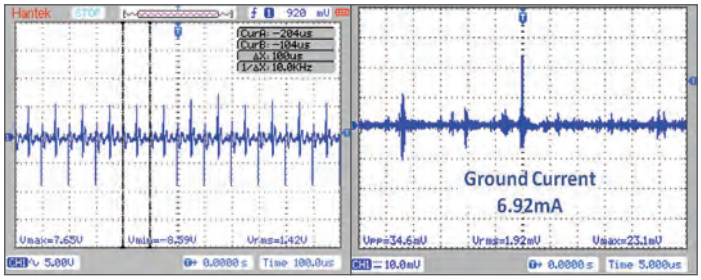


Figure 14. Ground current without the filter (left), and with SF series filter (right) Current measurements per Figure 13.

Some filter models, such as model SF20032 (*Figure 10*) uniquely combines filtering of load and filtering of AC noise in one small package, providing complete EMI coverage for a drive. This saves cost and precious real estate inside equipment - all filters and/or reactors must be located as close to drive controller as possible in order to maximize their effectiveness.

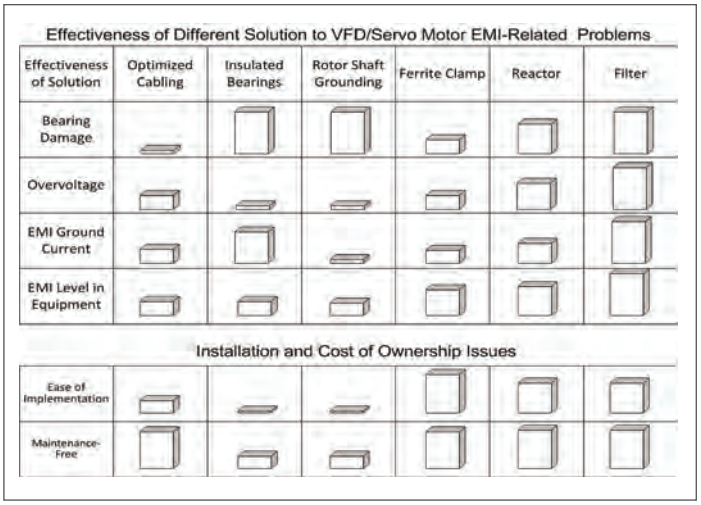


Figure 15. Summary of different solutions for VFD and servo motors

*Figure 15* shows the summary of different methods of reducing EMI and its effect on the drives, cables and host equipment.

## CONCLUSION

The inherent problems with PWM motors - VFD and servo

- are not going away and with increase of automation and associated motor use, they are only going to increase. EMI mitigation solutions address these issues at their core and are capable of help the whole industry to improve reliability of equipment, increase its up time and reduce cost of operation.

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# IMMUNITY TESTING BELOW 150 kHz:
# THE UNIVERSAL SOLUTION – NSG 4060 GENERATOR

New requirements for EMC immunity testing in the lower frequency range can now be tested with a complete test generator solution. A large number of current product standards such as EN 61326-3-1, IEC 61850-3, IEC 60255-26, IEC 60533 and IEC 60945 are supported on the basis of the standards IEC 61000-4-16 and IEC 61000-4-19. The key to the test solution is a generator with a unique operator interface and intuitive menu design, with output signal and impedance determined by the coupling device selected. Time-saving analysis options to monitor the testing are available through comprehensive interfaces.

**NSG 4060 Highlights:**

- **Signal generator with built-in-amplifier for the 15 Hz to 150 kHz frequency range**
- **NSG 4060-1 extension unit for IEC / EN 61000-4-16, to cover DC and short-term testing up to 330 V**
- **IEC / EN 61000-4-19 voltage testing with CDND M316-2 and current testing with CT 419-5**
- **5.7" colour display with intuitive user interface**
- **Comprehensive interfaces for test monitoring**
- **Client-specific test reporting via auto-report function**

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# Assembling Your Own EMI Troubleshooting Kit – Part 2 (Miscellaneous Additions and Immunity)

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Part 1 can be found at
http://www.interferencetechnology.com/assembling-low-cost-emi-troubleshooting-kit-part-1-radiated-emissions/

This article concludes the two-part series, ***Assembling Your Own EMI Troubleshooting Kit – Part 1***, which included a listing of the major components of a complete EMI troubleshooting kit that can be easily transported where needed. Most of the probes and tools listed in Part 1 were useful for troubleshooting radiated emissions. In Part 2, we'll discuss several other useful additions to your kit, including low cost tools for evaluating the most common immunity issues, such as radiated immunity and ESD. As a bonus, we'll also describe how to use an oscilloscope for EMI troubleshooting.

## USEFUL ADDITIONS TO YOUR KIT

Sometimes the signal level from near field probes needs a boost – especially from the smaller-diameter H-field probes. For this, I recommend a broadband preamplifier, such as those available from Mini-Circuits (Figure 1), Beehive Electronics, Tekbox, or Aaronia AG. There are many other manufacturers of these from the larger test and measurement companies.

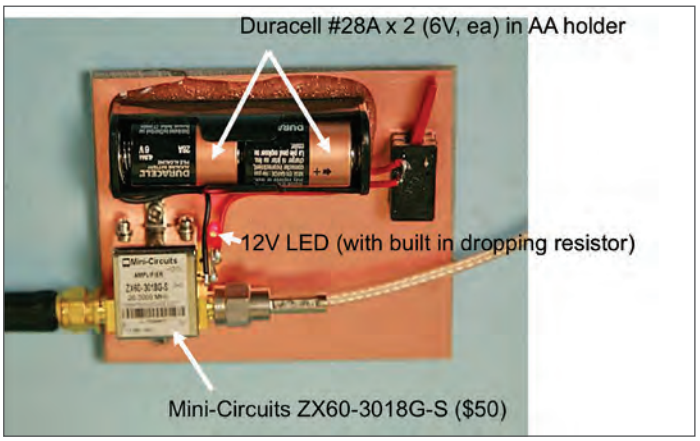


Figure 1. The Mini-Circuits model ZX60-3018G-S broadband 20 - 3,000 MHz preamplifier mounted on a PC board has a 20 dB gain and 2.4 dB noise figure. It's powered by two 6 V batteries mounted in a single AA holder. The price is about $50 through their web site (http://www.minicircuits.com).

Beehive Electronics also has a nice preamplifier that can be powered from an exterior 9V battery plugged into the power input jack (*Figure 2*). This makes the unit portable with one less line cord to deal with. The unit has 30 dB of gain from 100 kHz to 6 GHz, which covers all the commercial frequency ranges of interest. The cost is $525 through their web site (http://www.beehive-electronics.com).

Figure 2. Beehive Electronics makes a $525 30 dB gain broadband preamp that is useful from 100 kHz to 6 GHz.

Figure 3. Metal and plastic knitting needles may be used to test for RF energy on connector pins. Plastic crochet hooks can manipulate cables without having to touch them.

Metal knitting needles may be used as antennas by touching to the circuit board or pins of a connector. Being metal, they will act as an extended antenna. If the circuit connector pin is a source of RF, this may increase when touched with the metal knitting needles. Be sure to insulate the handle end of needle for safety reasons and take care to avoid shorting out circuits.

Plastic knitting needles, crochet hooks, or probes may be used to manipulate wires or press on chassis without having to touch the equipment, which can change its effective radiation (*Figure 3*).

## USEFUL RADIATED IMMUNITY ITEMS

One of the more frequent product failures I see is radiated immunity. That is, the product under test is susceptible to outside RF transmitters. There are a number of low cost solutions to help check the sensitivity of your product to external RF energy.

One of the simplest is a small handheld Family Radio Service (FRS) license-free walkie-talkie (*Figure 4*). These produce about 1/2-watt in the 465 MHz band and may be used to quickly check the susceptibility to RF, in general. Best of all, they sell for about $30 a pair. Just press the transmit button briefly and hold it near your product to see if it induces any upset or instrument lockup. I've resolved many radiated immunity problems with nothing more than one of these radios.


Figure 4. A typical 0.5W 465 MHz Family Radio Service two-way radio. Some other countries have similar license-free radios that may be used for simple radiated immunity testing.

For a more elegant and controlled test, I find the PC-controlled RF synthesizer; model SynthNV, from Windfreak Technologies to be ideal (*Figure 5*). It will produce up to +19 dBm (90 mW) into 50 Ohms. The unit tunes from 34 MHz to 4.4 GHz in user-defined steps as low as 1 kHz. It can also modulate the RF with AM or pulse modulation, which is useful for commercial or military immunity testing according to the respective standards. The price is $599 from their web site (https://windfreaktech.com).

To perform a quick immunity test with the SynthNV, simply attach the larger size H-field probe to the output and scan the probe around on your circuit board and any interconnecting or I/O cables. Adjust the frequency to step every 50 MHz, or so, for each scan throughout the desired frequency band. For more details, refer to the article, Inexpensive Radiated Immunity Pre-Compliance Testing[1].

Another very effective source of broadband RF emissions is a "chattering relay". This is actually specified in certain MIL-STD-461 and DO-160 standards. A chattering relay is merely a line or DC-operated relay with the normally closed contacts wired through the coil. When powered, the relay coil opens the contacts, which then deactivate the coil, allowing the contacts to close again. This continues with a loud buzzing sound as the contacts continuously open and close. The inductance of the coil creates a 600 to 800 volt repeated arcing across the contacts. This produces a broadband RF noise spectrum as high as 1 GHz. According the standards, closely coupling the cable of the chattering relay to the product's power cable, is a rather rigorous immunity test. I find that simply holding the relay near your product circuitry should reveal any issues pretty quickly.


Figure 5 – The Windfreak Technologies RF synthesizer is small and can produce up to +19 dBm from 34 MHz to 4.4 GHz. It can also modulate the RF with AM or pulse.

## TESTING FOR ELECTROSTATIC DISCHARGE (ESD)

The other frequently encountered EMC issue I find is due to susceptibility to ESD. With the trend towards lower power supply voltages (5V to 3.3V to 1.8V to 1.2V, and lower) is the overall reduction in noise margin for digital circuits. There are a number of low cost tools we can use to evaluate our products for ESD immunity.

Figure 6 - The Keytek Mini-Zap is a handy handheld ESD simulator that can test up to 15 kV. The contact discharge tip is shown.

Normally, ESD current pulses of up to 8 or 15 kV are applied

to any external metal that could be touched by the equipment operator. This would include front panel controls, displays, connector ground shells, metal enclosures, and the like. Exceptions under most ESD standards would preclude testing directly into I/O pins or internal circuitry. I must caution you that this test is potentially destructive, so I usually try to test less sensitive points first and with lower test voltages.

Of course, the best approach would be to use a commercial ESD simulator. I like the KeyTek MiniZap (*Figure 6*). While new ones can cost about $20k, these may be commonly found in the used market for under $3,000. However, to fit within our $5,000 maximum budget, here are some alternatives that will help characterize the ESD immunity of your product.


Figure 7 - The Coleman brand lighter is unique that the butane has a separate control switch with no need to empty the reservoir. Cut the metal shroud back with a Dremel tool to expose the tip and connect a length of grounding wire. It produces about 4 to 6 kV from the piezoelectric element when the trigger is pulled.

There are various piezoelectric spark sources, such as BBQ lighters, that will produce several kV of electricity. One I like is the Coleman brand butane lighter, because you don't need to open the gas valve in order to trigger a spark (*Figure 7*). By carefully removing part of the outer metal shroud with a Dremel tool, you'll expose the center tip where the arcs originate. Connecting a ground return wire to the metal shroud will complete the circuit. Just place the product under test on a metal-top table (or lay out some aluminum foil to cover the table top as a conductive plane). You'll need a way for the electrostatic charges to bleed off the metal plane, and you can connect a 1 Megohm resistor from the metal plane to earth. Then, connect the ground return wire to the metal plane, hold the lighter tip within 1/4-inch and start triggering the arcs. This lighter will produce from 4 to 6 kV discharges.

The problem with ESD susceptibility is that it usually occurs infrequently. Therefore, you'll also want a way to detect ESD discharges to help indicate when an event occurred. An inexpensive AM broadcast receiver (*Figure 8*) will make a simple ESD detector. Just tune the radio off-station, so you just hear the background hissing. You'll be able to hear ESD events as "clicks" in the static. If you're handy with electronic projects, you can also make the DIY ESD detector and counter found on my personal web site. It is based on a popular lightning detector circuit. The construction article may be found under "Technical Articles" at http://www.emc-seminars.com. The basic circuit includes the detector and a pulse-stretcher circuit. By adding extra switch transistors, you can add various indicators. Mine will blink a light, beep a buzzer, and also has a digital event counter.


Figure 8 - An AM broadcast band radio tuned off-station is useful for detecting the "clicks" of ESD events.


Figure 9 - A typical commercial ESD detector. This one is the model "ESD Pro" from Static Control Systems (Courtesy Static Control Systems).

A better commercial tool would include the "ESD Pro" ESD detector (*Figure 9*), manufactured and sold by Static Control Systems (http://staticcontrol.descoindustries.com). It is extremely sensitive and will detect ESD from hundreds of feet away.

One very useful tool is a SmartTweezer RLC meter from Advance Devices (*Figure 10*). This small tweezer can help you identify surface mount (or leaded) resistors, capacitors, or inductors. The calculation is fast and because it measures both the real and imaginary parts, can also read out ESR or ESL of components. The accuracy is comparable to lab-grade analyzers, and will easily fit in your kit.

## OSCILLOSCOPES

I'd like to discuss one last piece of recommended equipment -

oscilloscopes. While a good oscilloscope won't fit in your transit case, they do prove to be handy for troubleshooting EMI issues, but in the time domain, rather than in the frequency domain. For example, oscilloscopes can measure transient events, whereas most swept spectrum analyzers are limited to periodic waveforms that are continuous. An oscilloscope is a very useful troubleshooting tool that may be used to examine digital waveforms for ringing and measuring rise times. Many digital models have a wide enough bandwidth to capture ESD and other impulsive signals, enabling you to track the signals through your circuitry.

Figure 10 - The SmartTweezer RLC meter is helpful for measuring surface- mount components. Pictured is the Advance Devices model ST5, that costs $387 through their web site (http://www.advancedevices.com).

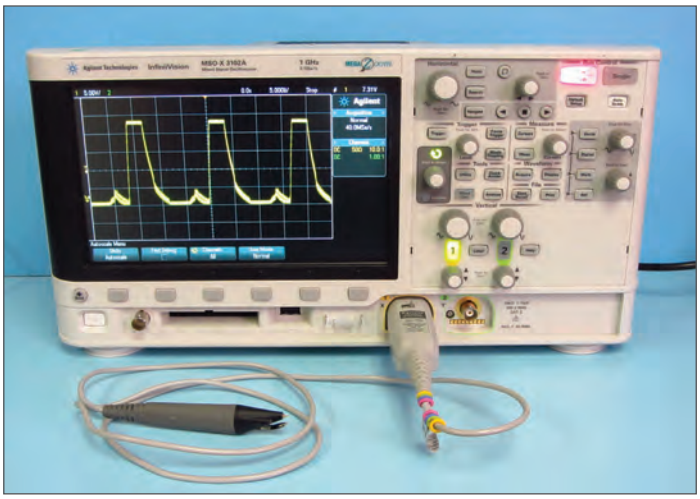

Figure 11 - A useful EMC troubleshooting tool is a digitizing oscilloscope, such as the Keysight MSO-X 3102A with N2976A 2 GHz active probe pictured here.

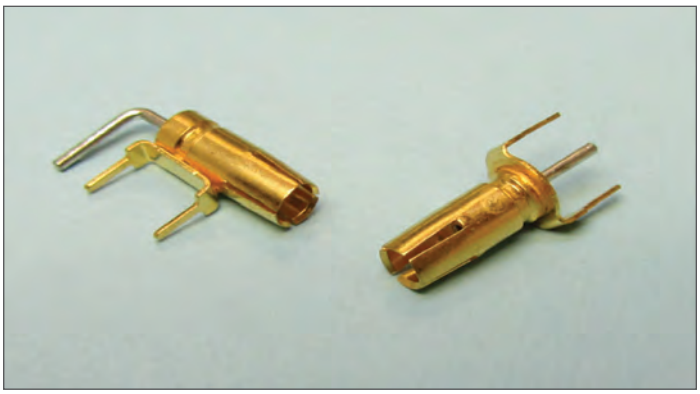

Figure 12 - An example of miniature oscilloscope probe sockets for high-frequency measurements. These eliminate the issue of long ground leads that can compromise the signal measurement and cause ringing. They are typically soldered directly to the PC board under test. The spring-loaded oscilloscope probe tip is pulled off and the tip is inserted directly into the socket.

For general-purpose troubleshooting, the minimum recommended model would be a 500 MHz to 1 GHz bandwidth and at least 4GSa/s, or more. Examples might include the Keysight Technologies MSO-X 3000 series (*Figure 11*). There are many equivalent models from Rhode & Schwarz, Rigol Electronics, Siglent, Tektronix, and Teledyne-LeCroy.

When measuring high-frequency clock signals, be sure the bandwidth of the oscilloscope and probe exceed the measurement you're making. Minimize the length of the signal return lead of the probe. Using the typical 4 to 6 inch probe ground wire will just accentuate ringing due to the high self-inductance created by the measurement loop area. I advise using the small solder-in probe sockets sold by the top oscilloscope manufacturers (*Figure 12*). An alternative would be to solder the probe right into the circuitry or to use a 1/4-inch (or shorter) probe ground or signal return connection. An alternative would be to use one of the high frequency active probes, such as the Keysight Technologies model N2976A 2 GHz probe or Rohde & Schwarz 1.5 GHz model RT-ZS20 probe, or equivalent.

Most oscilloscopes today have a fast Fourier transform (FFT) math function that converts time domain signals to the frequency domain. While this could be potentially helpful in troubleshooting, one of the issues is lack of dynamic range and input sensitivity. Most low-cost oscilloscopes can capture only eight bits of data, so very small signals can be buried in the noise floor and may be difficult to observe.

Some of the more expensive models, such as the Rohde & Schwarz RTO or RTE-series have 14-bit acquisition and are sensitive to 1 mV/division. These models are ideal for troubleshooting EMC issues in both the frequency and time domains. Other manufacturers also offer higher analog-to-digital resolution, better sensitivity, and lower noise, and thus are more useful.

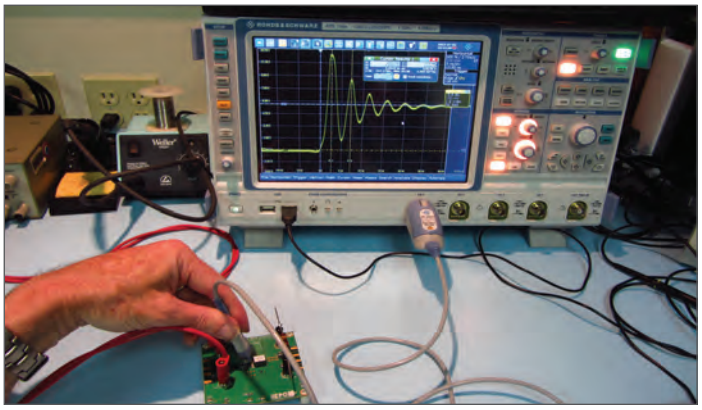

Figure 13 - A high-bandwidth digital oscilloscope is very useful for identifying ringing on clock traces and power buses, as shown here. In this example, we're measuring the ringing from a 1 MHz DC-DC buck converter. The large ring frequency is 217 MHz as measured witha Rohde & Schwarz RTE 1104 oscilloscope and RT-ZS20 1.5 GHz active probe.

As you can see, the large 217 MHz ringing in the example of *Figure 13* has potentially caused large broadband radiated emissions as measured by a current probe on the power supply input and output circuit (marker 1 and 2 in *Figure 14*).

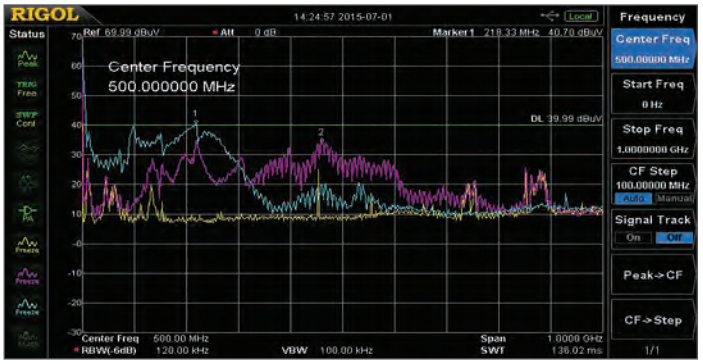


Figure 14 – Broadband noise peaking due to the large ring frequency on the main switch of the buck converter example of Figure 13 as measured by a current probe. The yellow trace is the ambient baseline signal, the aqua is the emission at the power input, and the violet is the emission at the power output. Notice the peak at marker 1 is at the ring frequency about 217 MHz and at marker 2 is the second harmonic about 460 MHz.

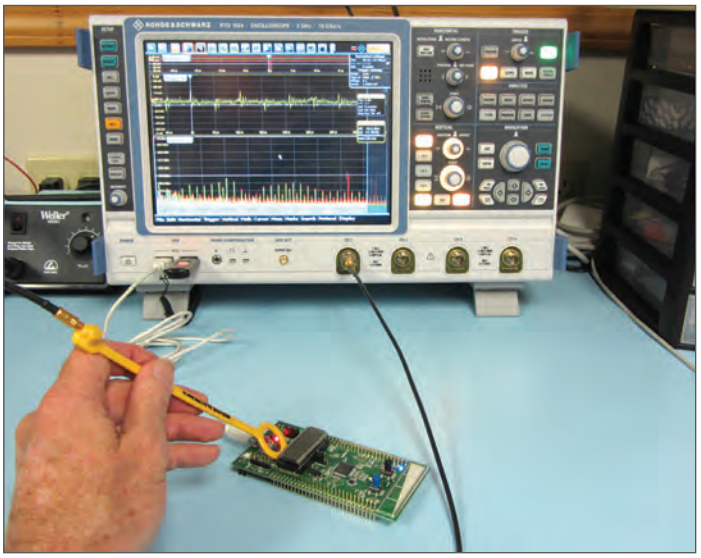

Figure 15 - Troubleshooting an embedded processor board for EMI using the FFT function (lower trace) using a Rohde & Schwarz RTO 1024 oscilloscope.

It's also possible to use near-field probes (H- or E-field) with oscilloscopes. In fact, using one channel as a reference, you can probe with the other to determine correlations between a known noise source and other signals (*Figure 15*).

## MISCELLANEOUS CONTENTS

The following is a list of "small stuff" that you might find very handy (in no particular order).

- Small digital multimeter
- Small driver kit (with an assortment of bits)
- Various hand tools
- Power screwdriver, such as the Ryobi Model HP53L ($30)
- SMA connector wrench
- Pencil soldering iron (Weller WM120, $40)
- Solder and solder-wick
- Dental inspection mirror (small mirror with long thin handle for probing in confined spots)
- Small flashlight
- Small magnifier

- ESD wrist strap
- Tape measure (English/metric)
- Tweezers
- X-Acto knife
- Emory cloth (for sanding away paint)
- Wire (miscellaneous sizes and lengths)
- 10 and 20dB attenuators (Mini-Circuits VAT-10W2,VAT-20W2 and HAT-10+, HAT-20+, $12 and $9, respectively, in SMA and/or BNC sizes)
- Various coaxial adapters
- Aluminum foil (1-2 foot square pieces folded)
- Copper tape (or "snail tape", available from hardware/gardening stores at less than $10)
- Insulating Kapton® tape
- EMI gaskets (ask manufacturers for a sample kit)
- Ferrite chokes (chip and leaded beads, clamp-on chokes, ask for a sample kit)
- Capacitors (various values, chip and leaded, in range of values: 100 pF, 1/10/100 nF, 1/10 uF)
- Resistors (various values, chip and leaded in range of values: 1/10/27/47/100/470/1k/10k/100k Ohms)
- Inductors (various values, chip and leaded in range of values: 1/10/100/1000 uH)
- Common-mode chokes (chip and leaded, ask for sample kit)
- External line filter with short line plug (used in-between line cord and product as additional external filtering)
- Small (5x5" bare) copper clad PC board (used for shield – place in a plastic sandwich bag for insulation)
- Clip leads (1m long)
- Various 1m long I/O cables (USB, RS-232,Video VGA, etc.)
- Various BNC and SMA coaxial cables
- Plastic bag with a few coins for generating ESD
- EMI gaskets (ask manufacturers for a sample kit
- Various BNC and SMA coaxial cables

## CONCLUSION

This wraps up the description of my EMC troubleshooting kit. As you have probably observed, not all the recommended equipment will fit inside the Pelican transit case. However, if you do need to travel light, most of the important troubleshooting components will fit, along with the recommended TTi PSA2702T spectrum analyzer or either the Tektronix RSA306 or Signal Hound BB60C real-time analyzers.

For more information, feel free to check my web site at http://www.emc-seminars.com, my EMC blog at http://www.design-4-emc.com, or Interference Technology at http://www.interferencetechnology.com.

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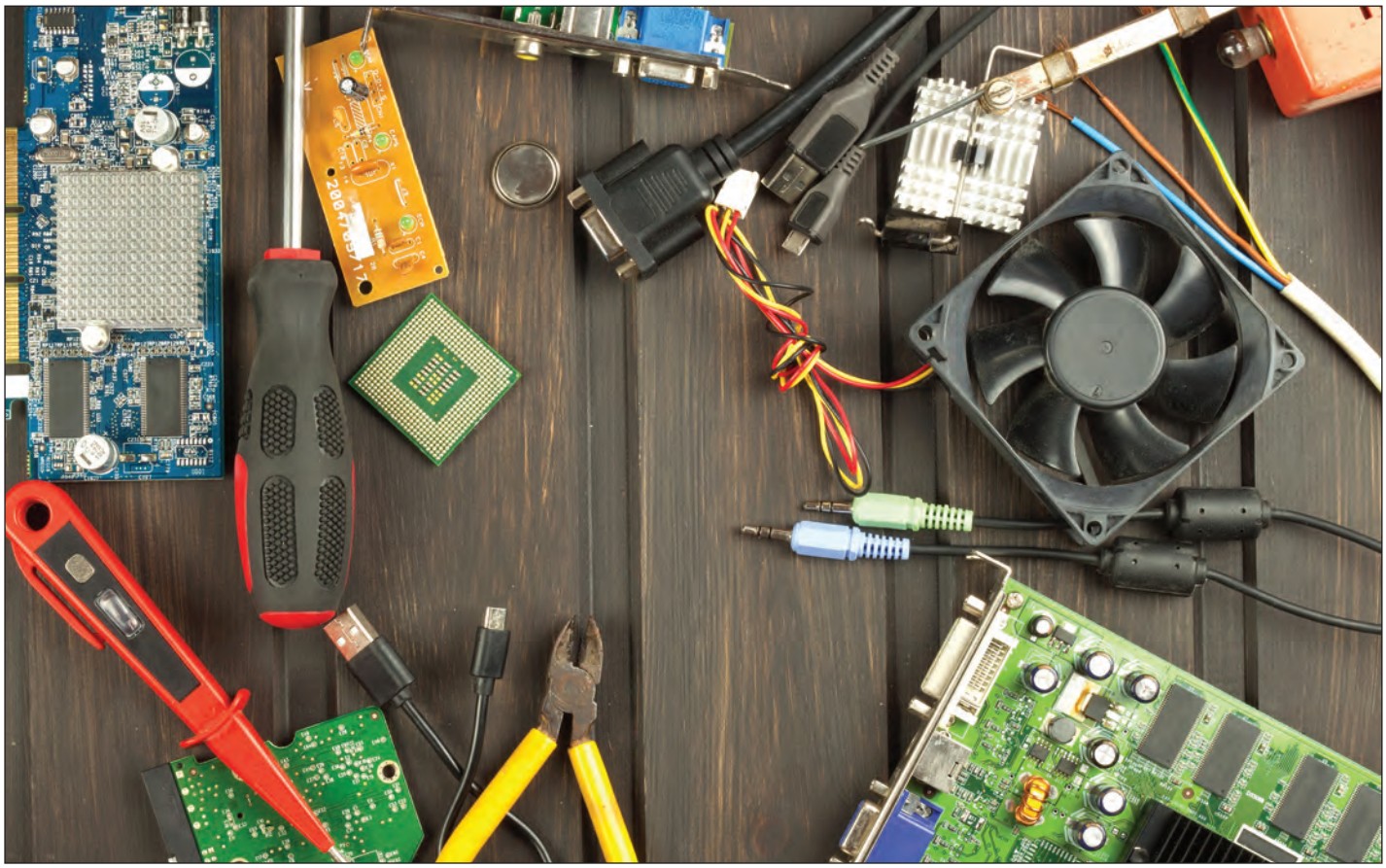

# The New CS117: Assessment of Pin Injection & Cable Induction Test Methods

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The new MIL-STD-461G standard, released in December 2015, includes requirements for lightning induced transients. Besides other fundamental differences to DO-160G Section 22, the decision to renounce Pin Injection method and Single Stroke tests requires an analysis. The standard committee established that these requirements are harmonized and covered by the test levels applied via Cable Induction method. This article will compare the mentioned test levels, and will provide a rationale for assessing the equivalence of Pin Injection method and Cable Induction method.

*Keywords—indirect lightning test; DO-160G Section 22, CS117, pin injection, cable induction.*

## INTRODUCTION

The new requirement CS117 from MIL-STD-461G refers to lightning induced transients, a set of tests that have been applied previously to commercial aircraft through DO-160G Section 22 standard. However, requirements for military aircraft and surface ships are slightly different from the ones in Section 22. Both standards specify 6 pulse waveforms to be applied during test. The waveforms appear as part of 3 event types in Section 22: Single Stroke (SS), Multiple Stroke (MS) and Multiple Burst (MB). Requirements in CS117 refer only to MS and MB, excluding thus SS. Section 22 specifies three application methods for disturbances: Pin Injection (PIN), Cable Induction (CI) and Ground Injection (GI), whereas CS117 requires application of pulses with CI method.

The rationale for previously mentioned modifications in comparison to Section 22 is consistent with the prescriptive approach utilized in MIL standards generally, aiming at a reduced and simplified decision-making process. Aircraft zoning, a procedure necessary for establishing applicable waveform sets and test levels, is relatively complex and time consuming. Furthermore, a standardized test setup is considered of major importance.

In the next section, an extensive comparison of test levels from the two standards will be performed.

## TEST LEVELS COMPARED: SECTION 22 VS CS117

Test levels are defined specifically for each waveform in both standards. In Section 22 there are five test levels for a waveform, whereas in CS117 only two test levels. Additionally, CS117 defines special (reduced) test levels for low count wire bundles or power leads. However, reduced test levels from CS117 do not have equivalents in Section 22 and will not be included in the comparison.

Finally, when comparing PIN test levels from Section 22 to CI test levels from CS117, an important difference in generator definition is to be mentioned: a PIN generator has a fixed virtual impedance, provided by the ratio of open circuit voltage and short circuit current, whereas in the case of CI testing, a voltage or current waveform is applied with no fixed impedance and a current or voltage limit is set in order to prevent overstressing equipment. In order to maintain a coherent approach, only test levels will be compared: WF1 as current waveform, WF2 as voltage waveform, WF3 as voltage waveform, WF4 as voltage waveform, WF5A as current waveform and WF6 as current waveform. Current or voltage limits established for Cable Bundle (CB) tests are not taken into consideration for this analysis.

## SECTION 22 PIN VS CS117 CI

In DO-160G Section 22, three waveforms are applied using the PIN method: WF3 (1 MHz), WF4 and WF5A. The PIN test levels are compared for each waveform with corresponding level (first stroke) of same waveform specified for CI in CS117.

### I. SECTION 22 PIN VS CS117 CI (WF3 1 MHZ)

| WF3 1 MHz | | | |
|---|---|---|---|
| DO160G S22 | | MIL-STD-461G CS117 | |
| PIN | | CI (First Stroke) | |
| L1 | 100 V | | - |
| L2 | 250 V | | - |
| L3 | 600 V | Internal | 600 V |
| L4 | 1500 V | External | 1500 V |
| L5 | 3200 V | | - |

Both test levels (first stroke) specified in CS117 for WF3 1 MHz (see *Table I*), CB tests with CI method, have amplitudes equal

to level 3 and level 4 PIN from Section 22. Since the 10 MHz waveform is not defined in Section 22 for PIN tests, no comparison has been considered in this section. The highest single stroke peak requirement for WF3 can be found in Section 22.

A similar comparison for WF4 is to be found in *Table II*. The test levels from CS117 are equivalent to level 3 and level 4 from Section 22. The highest single stroke peak requirement for WF4 can be found in Section 22.

## II. SECTION 22 PIN VS CS117 CI (WF4)

| WF4 | |
|---|---|
| DO160G S22 | MIL-STD-461G CS117 |
| PIN | CI (First Stroke) |
| L1 50 V | - |
| L2 125 V | - |
| L3 300 V | Internal 300 V |
| L4 750 V | External 750 V |
| L5 1600 V | - |

Table III introduces the comparison between peak level requirements concerning WF5A in Section 22 (PIN method) and CS117 (CI method). Unlike PIN test levels for WF3 and WF4, highest single stroke peak requirement in the case of WF5A is specified in CS117. Since the waveform has a relatively long rise time, and cable inductance has less influence in propagation of disturbance from coupler to EUT input connector, it can be asserted that CS117 requirement for CI might cover all PIN requirements for WF5A from Section 22.

## III. SECTION 22 PIN VS CS117 CI (WF5A)

| WF5A | |
|---|---|
| DO160G S22 | MIL-STD-461G CS117 |
| PIN | CI (First Stroke) |
| L1 50 A | - |
| L2 125 A | - |
| L3 300 A | - |
| L4 750 A | Internal 1000 A |
| L5 1600 A | External 2000 A |

As a partial conclusion, PIN level 5 amplitudes from Section 22 are higher than the highest first stroke amplitude from CS117 in the case of WF3 and WF4, and lower in the case of WF5A. In the case of CI method, the effective test level at connector will be estimated for all 3 waveforms in section 3 of this article. This estimation is required in order to compare more precisely the test levels, as long as PIN disturbance is applied at connector and CI method from CS117 applies the disturbance on the cable bundle, i.e. at a certain distance from connector.

Following tables compare the test levels required in Section 22 for CB tests (both CI and GI) to the test levels required in CS117. In the case of MS events, only the amplitude of first stroke is considered.

## IV. SECTION 22 CI AND GI (SS, MS, MB) VS CS117 CI

| WF1 – current waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| CI | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[A] | 100 | 50 | - | - |
| L2[A] | 250 | 125 | - | - |
| L3[A] | 600 | 300 | - | Internal 600 |
| L4[A] | 1500 | 750 | - | External 1500 |
| L5[A] | 3200 | 1600 | - | - |

## V. SECTION 22 CB/CI VS CS117 CI (WF2)

| WF2 – voltage waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| CI | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[V] | 50 | 50 | - | - |
| L2[V] | 125 | 125 | - | - |
| L3[V] | 300 | 300 | - | Internal 300 |
| L4[V] | 750 | 750 | - | External 750 |
| L5[V] | 1600 | 1600 | - | - |

## VI. SECTION 22 CB/CI VS CS117 CI (WF3)

| WF3, 1 and 10 MHz – voltage waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| CI | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[V] | 100 | 100 | 60 | - |
| L2[V] | 250 | 250 | 150 | - |
| L3[V] | 600 | 600 | 360 | Internal 600 (MB 360V) |
| L4[V] | 1500 | 1500 | 900 | Ext. 1500 (MB 900V) |
| L5[V] | 3200 | 3200 | 1920 | - |

Tables VII and VIII refer to waveforms 4 and 5A, for which DO-160G Section 22 specifies GI as preferred injection method. However, it is allowed to use the CI method if more suitable in some cases and some products standards demand the exclusive use of CI method for injection of waveform 5A.

## VII. SECTION 22 CB/GI VS CS117 CI (WF4)

| WF4 – voltage waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| GI preferred | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[V] | 50 | 25 | - | - |
| L2[V] | 125 | 62.5 | - | - |
| L3[V] | 300 | 150 | - | Internal 300 |
| L4[V] | 750 | 375 | - | External 750 |
| L5[V] | 1600 | 800 | - | - |

## VIII. SECTION 22 CB/GI VS CS117 CI (WF5A)

| WF5A – current waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| GI preferred | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[A] | 150 | 60 | - | - |
| L2[A] | 400 | 160 | - | - |
| L3[A] | 1000 | 400 | - | Internal 1000 |
| L4[A] | 2000 | 800 | - | External 2000 |
| L5[A] | 5000 | 2000 | - | - |

## IX. SECTION 22 CB/CI VS CS117 CI (WF6)

| WF6 – current waveform | | | | |
|---|---|---|---|---|
| DO160G S22 | | | | MIL-STD-461G CS117 |
| CI | | | | CI (FS) |
| | SS | MS(FS) | MB | MS |
| L1[A] | - | - | 5 | - |
| L2[A] | - | - | 12.5 | - |
| L3[A] | - | - | 30 | Internal 30 |
| L4[A] | - | - | 75 | External 75 |
| L5[A] | - | - | 160 | - |

## THE ANALYSIS OF TABLES IV TO IX INDICATES THAT:

- For all waveforms, the amplitude of SS test level 3 from Section 22 corresponds to the amplitude of first stroke in the MS requirement for aircraft internal equipment and equipment below ships' deck (from CS117).
- For all waveforms, the amplitude of SS test level 4 from Section 22 corresponds to the amplitude of first stroke in the MS requirement for aircraft external equipment and equipment above ships' deck (from CS117).
- In the case of waveforms 2 and 3 specified in Section 22, the amplitude of SS events is equal to the one of first stroke from the MS events. Since CS117 specifies MS events as test requirements, it can be considered for these waveforms that test levels are equivalent in the two standards (at common test levels).
- In the case of waveforms 1, 4 and 5A specified in Section 22, the amplitude of SS events is higher than first stroke from MS events. Equivalence in the two standards at designated test levels cannot be established directly.
- As for MB requirements, the test levels and limits from CS117 are directly equivalent to the ones from Section 22 (levels 3 and 4 respectively).

## ANALYSIS OF TEST REQUIREMENTS AND TEST LEVELS

This section will approach two topics, i.e. relevant differences between PIN, CI and GI injection methods, and a case analysis respectively. The case study will compare the situation in which waveforms 3, 4, 5A are applied with PIN and CI methods.

### PIN INJECTION VS CABLE INDUCTION

Injection methods, or test types, specified in DO-160G Section 22 are basically divided in two categories: pin injection and cable bundle (tests).

**In the case of pin injection tests:**

- EUT must be "energized", pulses are applied on either powered or unpowered pins.
- Positive and negative pulses are applied between designated pins and case.
- The generator has a fixed impedance, i.e. 25 Ω for WF3, 10 Ω for WF4 and 1 Ω for WF5A.
- After calibrating the generator in OC and SC conditions at a certain level setting, pulses are applied without any adjustment during the test.
- Monitoring voltage and current while pulses are applied identifies whether changes in the waveform or dielectric breakdowns occurred.

Voltage calibration is carried out at the end of test tips, as shown in *Figure 1*, in order to make sure that during the test no additional impedance is added between calibrated point and EUT interface.

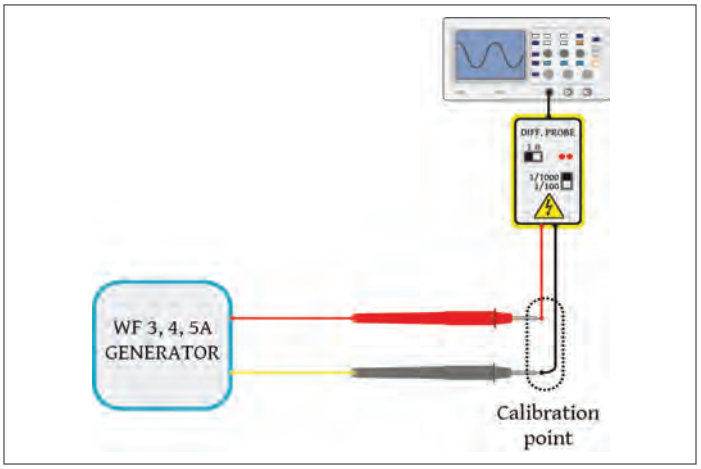


Figure 1. PIN voltage calibration.

With the same cables and tips connected to the generator, current calibration is performed using a short-circuit with the shortest shunt possible, as in *Figure 2*. Generator settings must remain unaltered from those required for the voltage calibration. Measurement of short-circuit current allows the calculation of generator's virtual impedance.

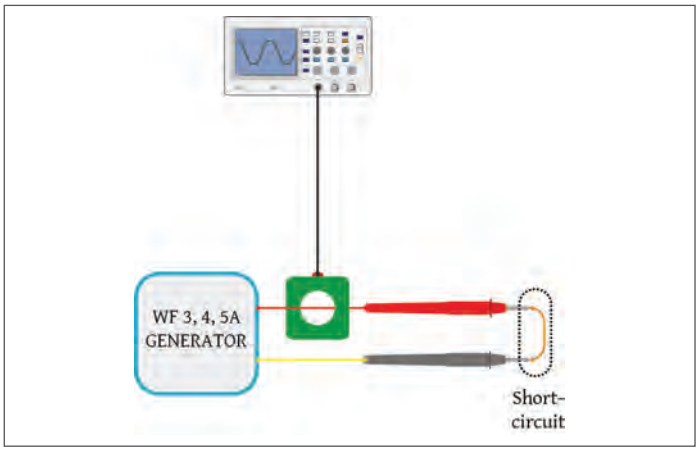


Figure 2. PIN current calibration.

When performing a test, the calibration point must be directly connected to EUT pins. The test is carried out in common mode only, as described in *Figure 3*.

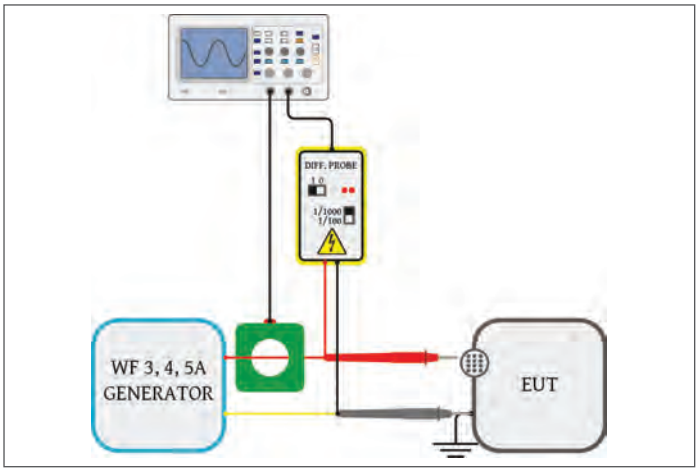


Figure 3. Simplified PIN test setup.

In the case of powered pins, additional protection elements are required to prevent EUT power damaging the generator. Likewise, protection elements would be required to decouple the power supply from test pulses. These elements are not included in diagrams, since their relevance for the comparison is relatively low.



An important aspect is the fact that a ground plane is not necessary for this injection method when compared to CI and GI methods.

In the case of cable bundle (CI and GI methods) tests:

- EUT must be fully functional and running during the test, with all sub-systems connected, powered and communicating.
- - Positive and negative pulses are either induced in cable bundles with couplers, or injected between the grounding point and case of the EUT.
- The generators are not necessarily supposed to have a fixed output impedance, current and voltage waveforms are monitored during the test.
- During the test, a specified test level must be reached and the injected waveform must be achieved at that test level. The generator setting can be increased in order to achieve established test level.
- Current must be monitored while increasing the generator setting when applying a voltage waveform for example. In order to avoid overstressing the EUT, a current limit is specified and in case this limit is reached before the voltage test level is achieved, test must be stopped and the voltage waveform test must be replaced with a current waveform test. The same principle is utilized when applying current waveforms.
- CI method is recommended for waveforms 1, 2, 3 and 6 while GI is the "preferred" method for waveforms 4 and 5A. An analysis will be performed in order to establish their equivalence for different configurations.

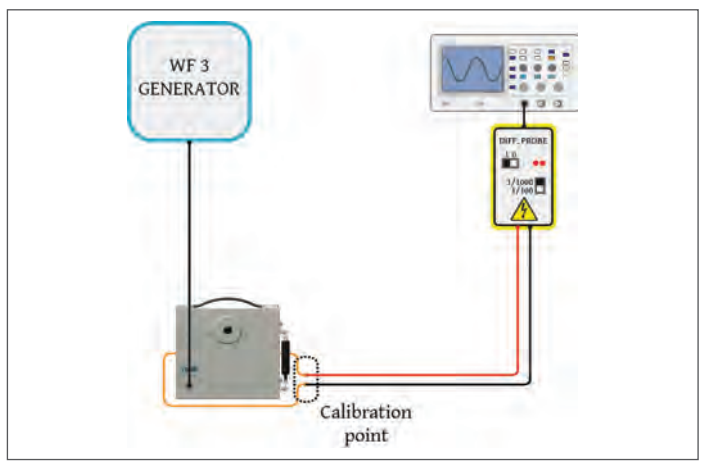


Figure 4. Simplified CI voltage calibration setup example.

Simplified calibration setups for CI method are presented in *Figure 4* and *Figure 5*, the example being taken for waveform 3. Calibration is performed at output of the coupler, it is thus considered that the entry point of a lightning strike could be situated somewhere on the cable bundle. This can be indeed the case in reality. Although Section 22 specifies a ground plane for the actual test setup, this is not regarded in calibration setups. The influence of ground plane during calibration would be more visible at waveforms with fast rise time, as the presence of a ground plane may impact the high frequency impedance of injection and calibration loops. However,

the same simplified calibration setups are present in CS117.

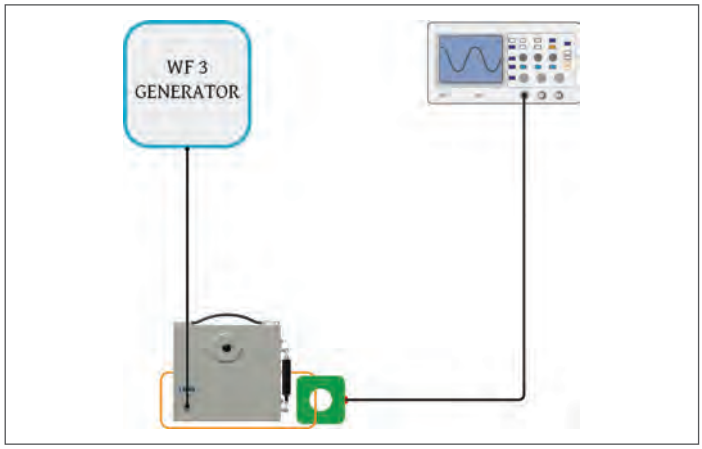


Figure 5. Simplified CI current calibration setup example.

In *Figure 6*, an example of test setup with CI method is presented. Section 22 requires voltage and current monitoring while applying the pulses. Furthermore, the insulation between ground plane and cable bundles should be minimum 5 cm unless otherwise specified. EUT, as well as auxiliary equipment or LISN, should be placed on the insulation support.

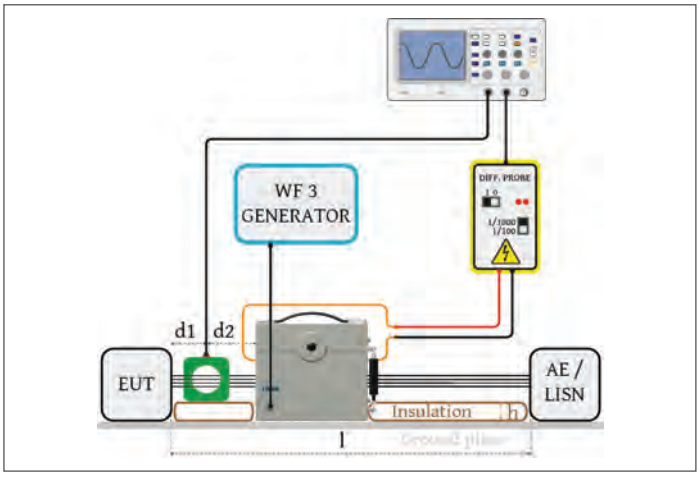


Figure 6. Simplified CI test setup example.

In comparison to a PIN test, where the calibrated point is applied to EUT interface directly, the CI test applies test signals to the interface through the cable bundle.

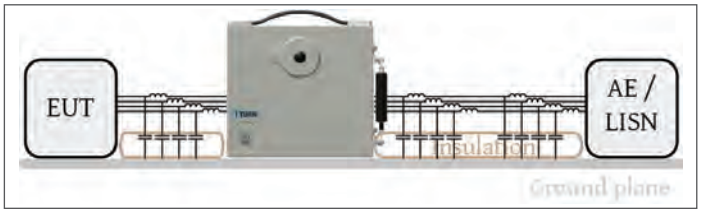


Figure 7. Simplified transmission line model for a cable bundle.

The distance between EUT and current monitoring probe (d1) should be in the range 5 – 15 cm, while distance between monitoring probe and injection transformer (d2) should be in the range 5 – 50 cm. Another important parameter in this context is cable bundle's length, Section 22 recommends a length not shorter than 3.3 m and not longer than 15 m. In order to better assess the difference between injection directly at interface and via the cable bundle, the transmission line model will be considered for cables in the bundle (*Figure 7*).

In order to simplify the demonstration of effects, only common mode capacitance and each conductor's serial inductance are considered (distributed parameters). Mutual inductance and differential mode capacitance are not considered.

A measurement of inductance and capacitance for the case wire on ground plane has been performed, in order to establish which effect is predominant. Results are presented in *Table X*. It is expected that cable bundle's inductance will be the predominant effect, but capacitive effect will also play a role in reducing voltage at EUT and AE ends of cable bundle.

## X. INDUCTANCE AND CAPACITANCE OF 1 WIRE OVER GROUND.

| Length | Section | Height | C(approx.) | L(approx.) |
|---|---|---|---|---|
| 3.3 m | 1.5 mm2 | 5 cm | 40 pF | 2 µH |
| 15 m | 1.5 mm2 | 5 cm | 120 pF | 14 µH |

Furthermore, capacitance to ground and series inductance of wires in a bundle are increasing with length of the cable between EUT and auxiliary equipment. As the voltage signal travels towards EUT or AE, voltage amplitude is expected to decrease. However, voltage amplitude at EUT side (situated closer to the coupler) is expected to be higher than the one at AE side (bundle's length to the coupler is higher).

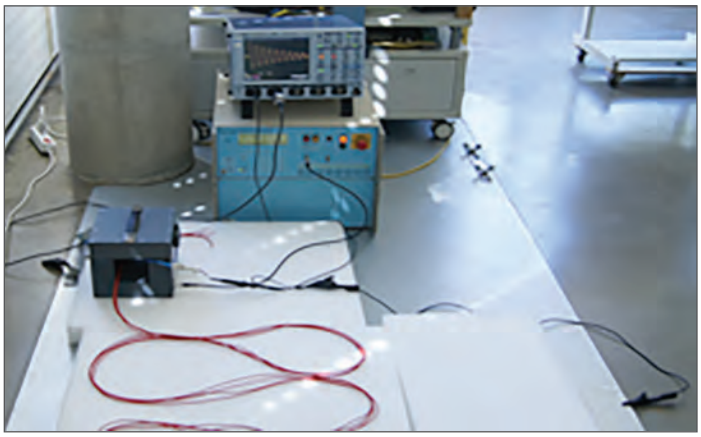

Figure 8. Test setup with 15 m cable bundle.

**Following cases will be considered:**

## XI. EXPERIMENTAL SETUP CASES.

| | d1 | d2 | l | h | ZT |
|---|---|---|---|---|---|
| Case 1 | 5 cm | 5 cm | 3.3 m | 5 cm | OC |
| Case 2 | 5 cm | 5 cm | 3.3 m | 5 cm | SC |
| Case 3 | 15 cm | 50 cm | 15 m | 5 cm | OC |
| Case 4 | 15 cm | 50 cm | 15 m | 5 cm | SC |

**Measurements have been performed as follows:**

- Calibration in open circuit and short circuit has been performed at test level 600 V.
- Waveform 3 1 MHz was applied at test level 1 from CS117, i.e. 600V.
- Generator has been calibrated in open circuit and short circuit conditions. Same generator setting has been maintained during the entire test.
- Insulation between cable bundle and ground plane was 5 cm, with μr ≈ 2.
- Tests and measurements have been carried out for two bundles. First bundle consisted of 4 wires, with Ø 1.8 mm, length 3.3 m, while the second had 15 m length. The lengths chosen reflect dimensions suggested by Section 22 as minimal and maximal.
- In cases 1 and 3 (*Figure 8*), the cable bundle's ends were open circuit (corresponding to high impedance to ground), whereas in cases 2 and 4, a short circuit to ground has been set (corresponding to low impedance to ground).

The results of measurements are presented in *Table XII*, as peak values.

### XII. RESULTS OF MEASUREMENTS FOR CASES 1 TO 4.

| | $V_{EUT\ END}$ | $I_{EUT}$ | $V_{AE\ END}$ |
|---|---|---|---|
| Case 1 | 519 V | n/a | 213 V |
| Case 2 | n/a | 30 A | n/a |
| Case 3 | ~ 505 V | n/a | ~ 107 V |
| Case 4 | n/a | 12.4 A | n/a |

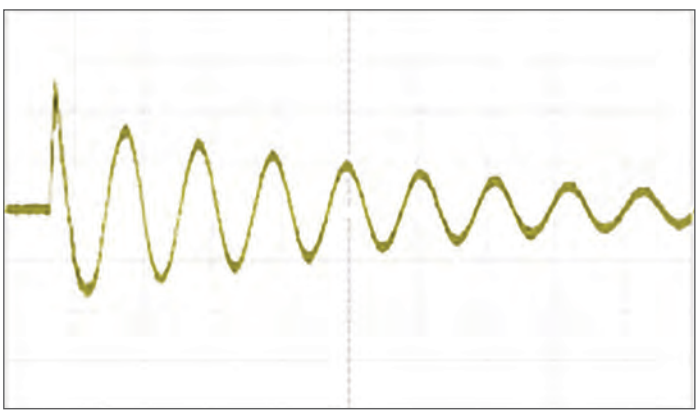

Figure 9. WF3 voltage measured in Case 1 at EUT side.

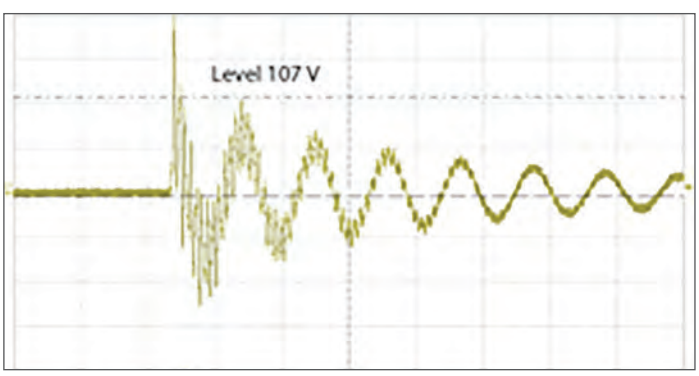


Figure 10. WF3 voltage measured in Case 3 at AE side.

**A set of partial conclusions can be drawn:**

- In the case of high input impedance EUTs, voltage applied to EUT terminals depends on length and mainly inductance of cable bundle.
- In the case of low input impedance EUTs, current in the cable bundle decreases with the increasing length of the bundle.
- In cases 2 and 4, the inductance of cable bundle prevents all the current delivered by the generator to flow, so voltage measured at output of the coupler may remain high. An interpretation of this phenomenon is not performed here, since it would require more detailed data.
- Current at both sides of the coupler has been measured in cases 1 and 3. Due to capacitive coupling to ground, currents up to 10 A were measured in cases 3, at the coupler output towards auxiliary equipment. The value represents more than 10 % of short circuit current measured during calibration, indicating that capacitive effect to ground is significant in the case of long cable bundles.
- Current measured at EUT end and AE/LISN end had similar waveforms and amplitudes. Thus, it is acceptable to include IEUT only in *Table XII*.
- In cases 1 and 2, both voltage (*Figure 9*) and current waveforms are similar to calibrated waveforms. However, in cases 3 (*Figure 10*) and 4, a significant superposed oscillation can be noticed, confirming that long cable bundles can form resonating circuits. The procedures from DO-357 (Section 22 User Guide) have been utilized in assessing peak values in all cases. Resonance phenomenon is common and requires no additional argumentation for the case of cable bundles.

## CONCLUSIONS

This article introduced two comparisons, i.e. between Section 22 PIN test levels and CS117 CI test levels, and between Section 22 CI test levels and CS117 CI test levels.

Generally, CS117 test levels represent level 3 and level 4 from Section 22 requirements for PIN or CI single stroke.

The CI requirements for waveforms 2 and 3 are similar for SS and first stroke of MS events at levels 3 and 4.

In the case of cable induction tests, lowest difference between injected (current) amplitude and the one present at EUT connector is achieved when distance between EUT and measurement probe is minimal (5 cm), and distance between injection probe and measurement probe is minimal (5 cm).

CS117 is focusing especially on current waveforms. This is demonstrated by specification of MS requirements and the fact that reduced test levels are always given as current (also for waveform 3 that is generally considered a voltage waveform).

The claim that PIN requirements are covered in CS117 by CI tests is mostly verifiable. However, measurements have demonstrated that voltage applied to EUT terminals in worst case (coupler 65 cm away from EUT input), is reduced with approx. 16 % (600 V applied at coupler, 505 V measured at EUT input). The phenomenon is normal, and reproduces the reality

of a lightning strike coupled into the cable bundle. However, if a certain test level must be validated at EUT input with CI method, generator setting must be increased to compensate cable bundle's impedance. The necessary increase in voltage and/or current depends on bundle's impedance. Increasing the test level may result in an over test if the limit level is exceeded.

For other waveforms, test levels and cable bundles, the necessary reserve of energy in the test generator may vary.

## AUTHOR AND AFFILIATION

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*EMC PARTNER AG is a worldwide leading supplier of impulse test generators with over 22 years experience in the field. Key domains are indirect lightning tests on aircraft components, CE mark / ANSI or UL tests, insulation tests, different impulse tests on electric/electronic components and related.*

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2. Department of Defense Interface Standard, "MIL-STD-461G: REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT", USA, 2015
3. RTCA Inc., "RTCA/DO-357 User guide: Supplement to DO-160G", Washington DC, 2014

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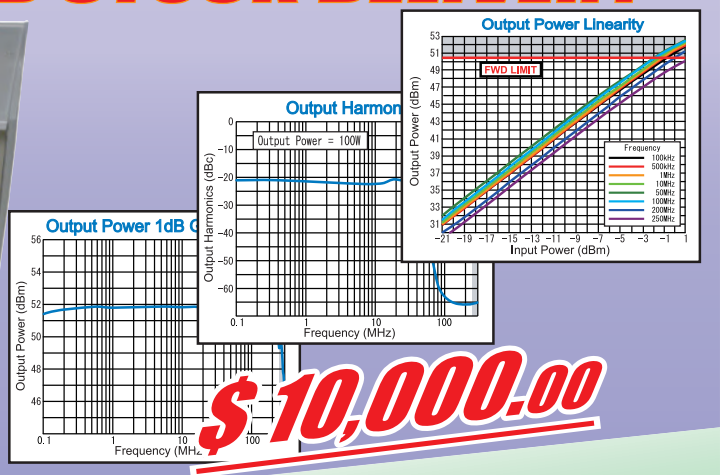


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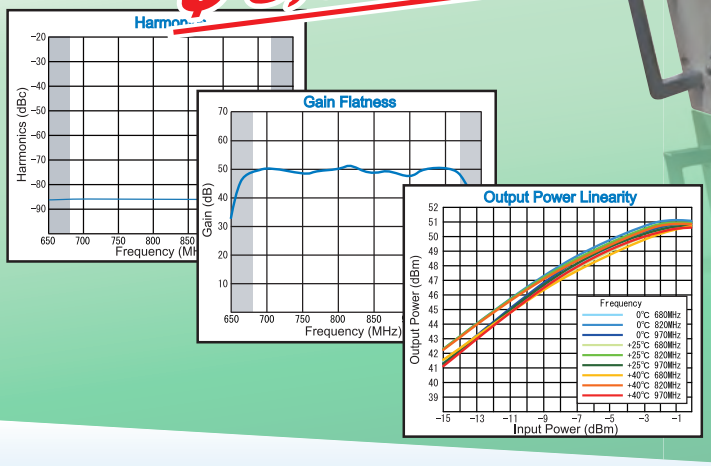


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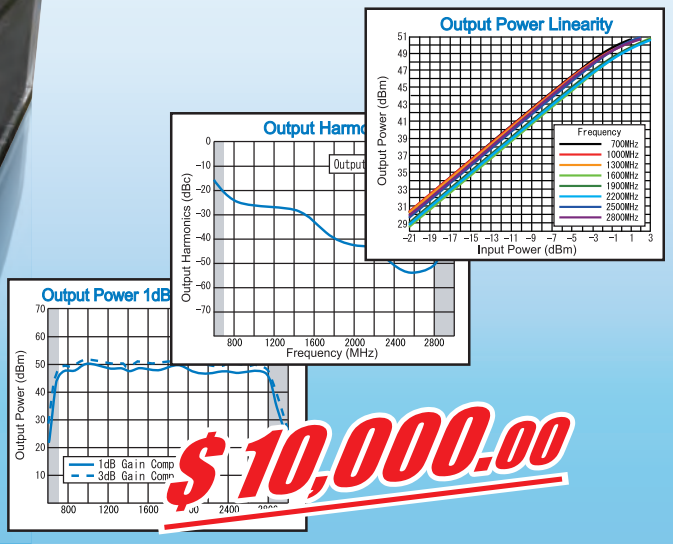


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# CISPR 35 – How does it compare with CISPR 24?

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*Ghery has written 8 papers and articles for publication and contributed a chapter for the 2nd Edition of the ARRL's Radio Frequency Interference Handbook. He is a member of the dB Society and serves as a Technical Advisor for the ARRL in the area of EMC. He holds an Amateur Extra class ham license (N6TPT) and is an instrument rated private pilot.*

***Editors Note:** table callouts refer to tables in the CISPR 35 standard

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After 15 years of work in CISPR Subcommittee I, the IEC Central Office published CISPR 35 Edition 1.0 on Tuesday, August 16, 2016. The IEC webstore link is https://webstore.iec.ch/publication/25667. In the US, ANSI has the standard available on their website as well. Go to www.ansi.org and type in CISPR 35 in the search window for standards. You must purchase a copy of the standard to see what the specific requirements are.

Regardless of whether you purchase the standard from the IEC web site or the ANSI website, have your credit card handy. The price shown on the IEC webstore is CHF 290, which, as of August 23, is about $300. On the ANSI site the price is $351 ($280.80 for ANSI members).

**Now that CISPR 35 is finally published, the questions that you want answered are: What is the same as CISPR 24? What has changed? What is new?**

The full title of the standard is, "CISPR 35:2016 Electromagnetic compatibility of multimedia equipment - Immunity requirements"

The abstract, from the IEC webstore page, states, "CISPR 35:2016 applies to multimedia equipment (MME) having a rated AC or DC supply voltage not exceeding 600 V. The objectives of this document are:

- to establish requirements which provide an adequate level of intrinsic immunity so that the MME will operate as intended in its environment in the frequency range 0 kHz to 400 GHz; and
- to specify procedures to ensure the reproducibility of tests and the repeatability of results."

Before going into any details, please note that CISPR 35, like other CISPR standards, uses dated references to other standards. Thus, the laboratory must use the version called out in the standard, even if a newer version is available. A particular example where this is necessary is in the use of IEC 61000-4-5:2005 for surge testing. A newer version is available on the IEC website, but CISPR Subcommittee I has determined that for the time being the 2005 version is the one to use.

**What does CISPR 35 cover? Where did it come from?**

CISPR 24 is specifically for information technology equipment (ITE). This is a fancy term for computers and their peripherals. CISPR 20 deals with broadcast receivers. For years the separation was fine. Then the digital television receiver came along. Both a broadcast receiver and a computer were now in the same box. Both requirements applied. Different test setups, different tests. Needless to say, the television manufacturers were not happy. CISPR SC E (broadcast receiver standards) and CISPR SC G (ITE) were merged in 2001 to form CISPR SC I (broadcast receivers, ITE and multimedia equipment). At first it was thought that it would be a simple task to merge CISPR 13 and CISPR 22 into a single emissions standard and CISPR 20 and CISPR 24 into a single immunity standard. Such was not the case. CISPR 32 (the multimedia equipment emissions standard) was first published in 2012. CISPR 35 has taken a bit longer, but has now finally been agreed and published.

**So, what is different between CISPR 24 (ITE immunity) and CISPR 35?**

A key difference is that CISPR 24 provides guidance on testing different types of devices while CISPR 35 focuses on "functions" of the EUT. For example, in the annexes of CISPR 24 there are annexes aimed at telephony terminal equipment,

data processing equipment, local area networks, printers and plotters, etc. The annexes in CISPR 35, on the other hand, deal with broadcast reception function, print function, scan function, display and display output functions, musical tone generating function, networking functions, audio output function and telephony function. Testing to CISPR 35 need only be performed for the primary function(s) of the product.

The general types of immunity tests are the same in both CISPR 24 and CISPR 35. There are a few key differences, however.

For continuous RF electromagnetic field disturbances CISPR 24 only calls out the use of IEC 61000-4-3 for performing the test. This is the traditional test in a fully anechoic chamber (or a semi-anechoic chamber with absorbers on part of the floor) with a uniform field established before the introduction of the EUT to the test area. CISPR 35, on the other hand, offers the user a choice of IEC 61000-4-3, IEC 61000-4-20 (TEM cell) or IEC 61000-4-21 (reverberation chamber). Thus, CISPR 35 offers more choice in testing environments. In addition, where CISPR 24 only requires testing to 1 GHz, CISPR 35 also adds spot frequencies of 1800 MHz, 2600 MHz, 3500 MHz and 5000 MHz to be tested. 3 V/m is the required test level for all these tests (swept from 80 MHz to 1000 MHz and spot frequencies as noted above). There is also guidance provided in Annex I on testing at spot frequencies at higher test levels (to as much as 30 V/m) to allow a user to have certain types of devices closer to the EUT. This annex is Informative, not Normative, so this information is not required to be followed, but is recommended. There are additional spot frequencies required in CISPR 35 for equipment with a primary function of telephony. Devices processing analog composite video signals (for example, PAL, NTSC or SECAM) have a relaxation from performance criteria A to performance criteria B test testing within +/- 1.5 MHz of a relevant subcarrier frequency. The key item to note in this is that laboratories that were equipped to test to CISPR 24 will now have to purchase new test equipment to allow performing radiated immunity testing above 1 GHz and manufacturers of equipment to be tested must be prepared for the addition test time and expense associated with this testing.

As a quick reminder, the field level stated is the level prior to turning on the modulation signal. This is the rms value of the field without modulation. Once the modulation is turned on more power will be required from the amplifier.

The following table shows some key differences between CISPR 24 and CISPR 35 in the radiated RF area:

## TABLE A

| | CISPR 24 | CISPR 35 |
|---|---|---|
| Frequency range | 80 MHz to 1 GHz | 80 MHz to 5 GHz |
| Test method(s) | IEC 61000-4-3 | IEC 61000-4-3<br>-or-<br>IEC 61000-4-20<br>-or-<br>IEC 61000-4-21 |
| Test level | 3 V/m | 3 V/m with the option of going to as high as 30 V/m at certain spot frequencies |

*Table 2** providing immunity requirements for analogue/digital data ports is an expansion of the requirements contained in CISPR 24. Testing requirements unique to CPE (customer premise equipment) xDSL ports has been added. The test level for continuous induced RF disturbances has been changed. In CISPR 24 this was 3 V for the entire 0.15 MHz to 80 MHz frequency range. In CISPR 35 this remains at 3 V from 0.15 MHz to 10 MHz. From 10 MHz to 30 MHz this test level decreases with the logarithm of the frequency to 1 V and remains at 1 V from 30 MHz to 80 MHz. This was done as it is believed that signals induced by nearby radio transmitters decrease at higher frequencies and testing at 3 V to 80 MHz is not required. Note that in Claus 4.2.2.1 of CISPR 35, buried in the text, there is the notation that the test level (for level setting) is Vrms. And, this is before the modulation is turned on. This is not new (it was also the requirement in CISPR 24), but bears repeating here.

The following table shows the key differences between CISPR 24 and CISPR 35 in the conducted RF area:

## TABLE B

| | CISPR 24 | CISPR 35 |
|---|---|---|
| Test level | 3V | 3V - 0.15 MHz to 10 MHz<br>3V- decreasing to 1V<br>10 MHz to 30 MHz<br>1V- 30 MHz to 80 MHz |
| Testing for xDLS ports | Not called out | Specific tests called out. |

Immunity requirements in *Table 3** for DC network power ports are the same in CISPR 35 as they are in CISPR 24, except for the change in test level for continuous induced RF disturbances noted above.

There are some changes in *Table 4** for AC mains power ports, as well. The change noted above for test levels for continuous induced RF disturbances applies here, as well. For voltage dips and dropouts the voltage reduction is stated in terms of the residual voltage, rather than amount of reduction. For example, the first requirement was stated in CISPR 24 as a greater than 95% reduction, where in CISPR 35 it is stated that the residual voltage shall be less than 5% of the initial voltage. These requirements are the same, but are stated differently. In addition, CISPR 35 provides requirements for both 50 Hz and 60 Hz distribution systems for the remaining reductions, so that the 70% residual voltage test (dip) (30% reduction in CISPR 24) remains at 0.5 seconds for either power line frequency and the 5% residual voltage test (interruption) remains at 5 seconds for either power line frequency. In addition, CISPR 24 required that these reductions occur at the 0 degree crossover point on the voltage waveform. CISPR 35 allows the reductions to occur at the 90 degree and 270 degree points on the waveform as an alternative if the EUT fails at the 0 degree crossover point. Guidance is also provided in the table for surge testing relating to the number of surges and where these are to be applied in terms of the waveform of the power line voltage.

*Table 5** provided requirements on EUT arrangement with

respect to whether the EUT is intended for table top, floor standing, either table top or floor standing, rack mounting or "other" operational arrangement.

The following table shows the key differences between CISPR 24 and CISPR 35 in the voltage dips and dropouts area:

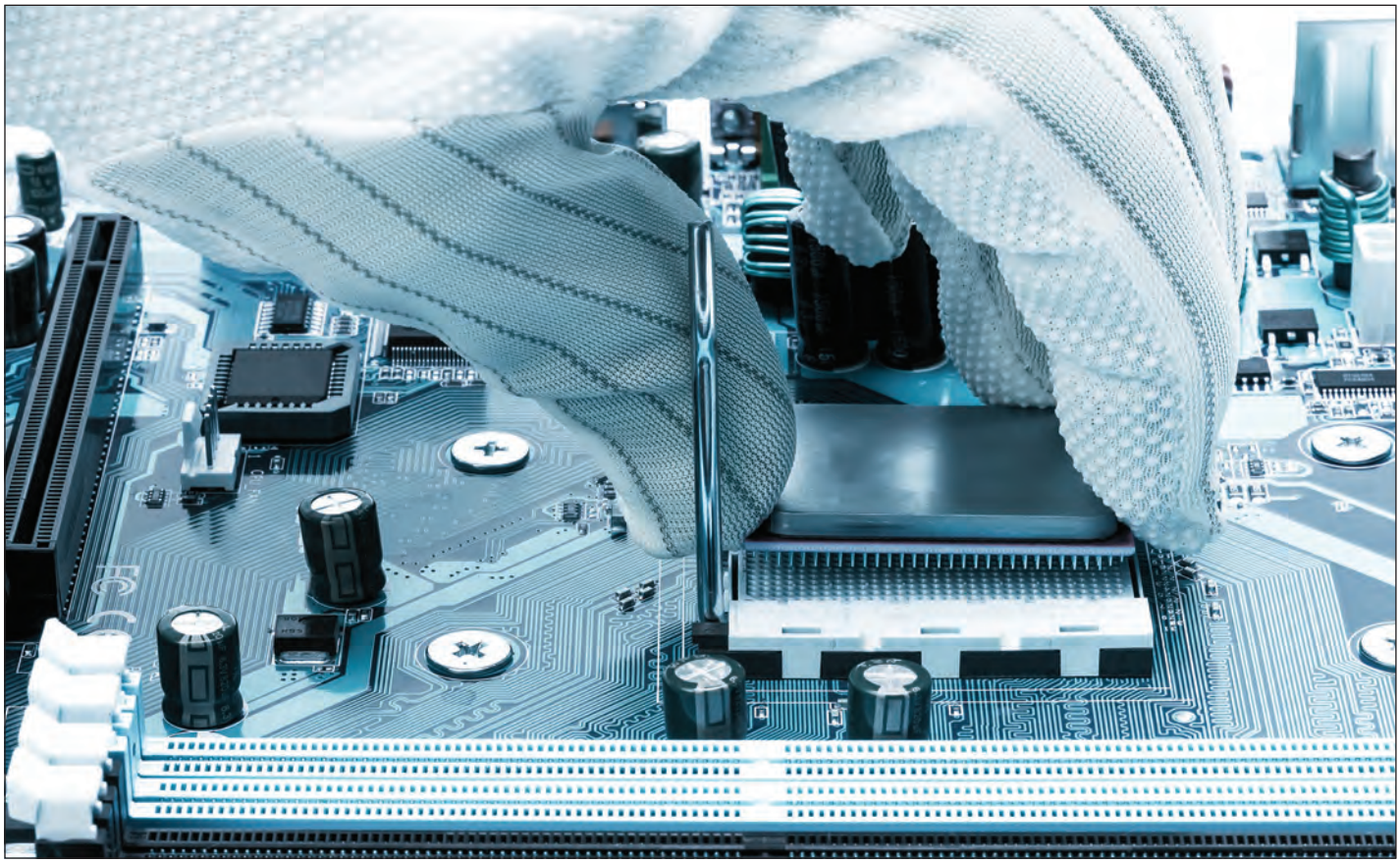
## TABLE C

| | CISPR 24 | CISPR 35 |
|---|---|---|
| Voltage dips | >95% reduction | <5% residual voltage |
| Voltage dips | 30% reduction | 70% residual voltage |
| Voltage dropouts | >95% reduction | <5% residual voltage |
| Line frequency for test | 50 Hz | 50 Hz or 60 Hz |
| Voltage change location on waveform | 0 degree crossover | 0 degree crossover<br>-or-<br>90 degree and 270 degree points if the EUT fails at 0 degrees |

The general performance criteria given in Article 8 of CISPR 35 is substantially the same as in CISPR 24. No surprises should be expected by laboratory personnel or manufacturers who are used to the criteria in CISPR 24. Specific information for the performance criteria for different functions is provided in the applicable annexes.

It is not the intention of this article to delve into the details of each annex for testing the different EUT functions called out. The user of the standard is commended to obtain a copy and read it in detail to ensure that their product is tested in accordance with the particular requirements for the functions contained in their product. An informative annex, Annex J, is provided in the standard to give examples of how to apply the document. Annex J provides a strategy based on the development of a test plan which details the EUT as a starting point and defines the applicable ports (enclosure, analogue/digital data, DC network power and/or AC mains power). Based on the ports the test plan would go on to list the relevant tests, EUT functions, mode(s) of operation and performance criteria for each test. Annex J.2 provides this information in a little more detail. Note that Annex J, while informative, states that only the primary functions of the EUT (as defined in 3.1.28) need to be exercised and assessed. Annex J provides 4 examples which should aid the reader in determining how to test their product. These examples are a multifunction printer, a flat panel television, a notebook computer and small key telephone systems or PABXs. Using these examples as a starting point the user of the standard should be able to come up with an appropriate way of testing other products.

CISPR 35 is very much like CISPR 24, except where the two standards are different. If you are familiar with CISPR 24 you have a good start on understanding CISPR 35. However, you must obtain and read CISPR 35 carefully to ensure that you test your product correctly to show compliance with the new standard. And don't forget, the laboratory needs new test equipment to perform radiated immunity testing up to 5 GHz.



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# Using a TEM Cell for Radiated Emissions and Immunity Troubleshooting

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Many companies would welcome a full EMC compliance test chamber if it weren't for budget and real estate considerations. Yet, they would like the opportunity to develop a low-cost troubleshooting solution for assessing radiated emissions and radiated immunity prior to going off for formal compliance testing. While I've written many articles (References 1 to 8) on how to perform your own emissions or immunity pre-compliance testing, a simple tabletop TEM cell may be just what you're looking for, if all you need is to try various fixes and make quick comparisons.

A TEM (or transverse electromagnetic field) cell is basically an expanded two-port 50-Ohm transmission line or strip line. The device under test (DUT) - usually a small circuit board or sub-assembly - is placed on an insulated spacer underneath, or on top of, the central septum. For radiated emissions testing, a spectrum analyzer is connected to one port and a 50-Ohm termination to the other (*Figure 1*). A DC block is a wise choice for protection of the spectrum analyzer in case some voltage from the DUT contacts the septum. For radiated immunity testing, the spectrum analyzer is replaced with an RF generator, with the 50-Ohm termination remaining (*Figure 2*).

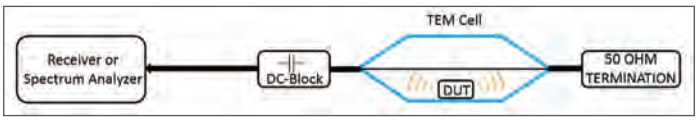


Figure 1 – Test configuration using a TEM cell for radiated emissions testing. Figure, courtesy Tekbox.

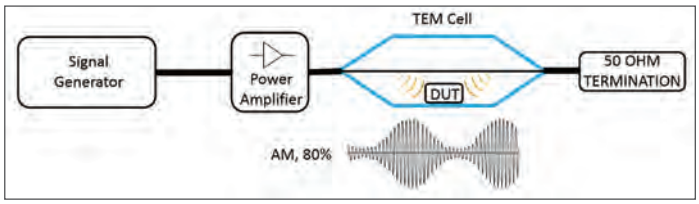


Figure 2 – Test configuration using a TEM cell for radiated immunity testing. Figure, courtesy Tekbox.

The TEM cell I'll use for this article is manufactured by Tekbox Technologies (http://tekbox.net). These are all available in the U.S. from Selig Electronics (http://www.saelig.com/category/tekbox-accessories.htm). Check the Tekbox web site for distributors in other parts of the world.

The Tekbox TEM cell design is quite robust, and uses heavy gauge stainless steel top and bottom plates and high quality hardware and "N" connectors. Most TEM cells suffer from higher order wave modes, which limit the usable bandwidth. The Tekbox design is unique in that the central FR4-based epoxy-fiberglass septum is designed as individual parallel strips with an array of distributed resistors connecting them together in parallel. Consequently higher order wave modes and resonances are suppressed. Each resistor is covered with a silicon-based protective bond, as seen in *Figure 5* below. This helps flatten and extend the frequency response. The TBTC2 model I used for this article was essentially flat out to 1 GHz.

Tekbox manufactures three sizes of TEM cells, TBTC1 (5 cm septum height), TBTC2 (10 cm septum height), and TBTC3 (15 cm septum height). I'll be using the mid-sized TBTC2 for the measurement examples in this article. This model will easily fit on top of your workbench. All TEM cells are provided with a 25-watt 50-Ohm termination, a wideband DC block, and short N-N coaxial cable.

The Tekbox design uses an "open" cell design, for ease of use in installing and evaluating DUTs. However, the open design also allows the reception of ambient signals, which can complicate the emissions measurements. Consequently, you'll want to characterize a baseline (ambient) measurement prior to measuring the DUT, so you can observe the difference emission profile.

These TEM cells are all designed for small DUTs, such as circuit boards or small subassemblies. Larger products could be tested in a similar – but larger - cell, called a GTEM. A GTEM is basically half of a TEM cell, but with RF absorber in one end. The larger models can easily fit a piece of tabletop equipment.

## TEM CELL EVALUATION

Before setting up the emissions or immunity tests, I wanted to pretest the performance of the 50-Ohm termination (*Figure 3 and 4*) and frequency response of the cell itself (*Figure 5*). The analyzer

used was the Rigol DSA815TG spectrum analyzer with tracking generator (http://www.rigolna.com/products/spectrum-analyzers/dsa800/). For the termination return loss test, I also used a Mini-Circuits ZFDC-25-5 20 dB (0.1 to 2000 MHz) directional coupler (http://www.minicircuits.com/pdfs/ZFDC-20-5+.pdf).

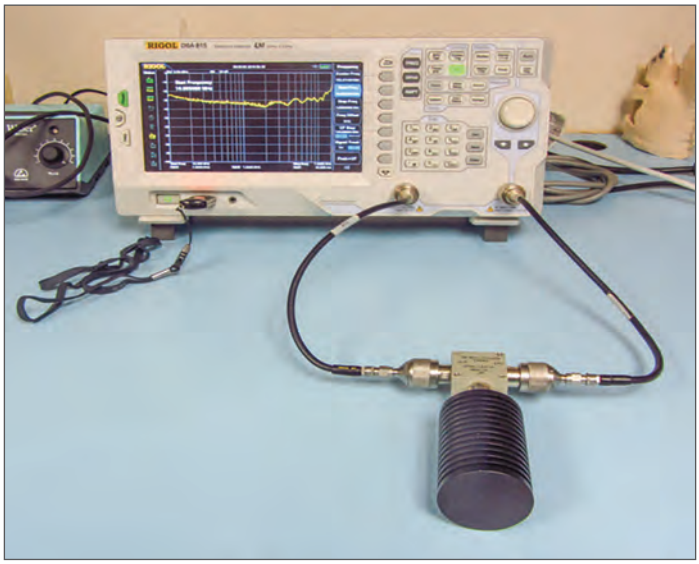

Figure 3 – Test of the 50-Ohm 25-watt termination provided with the TEM cell. See the screen capture of the results in Figure 4.

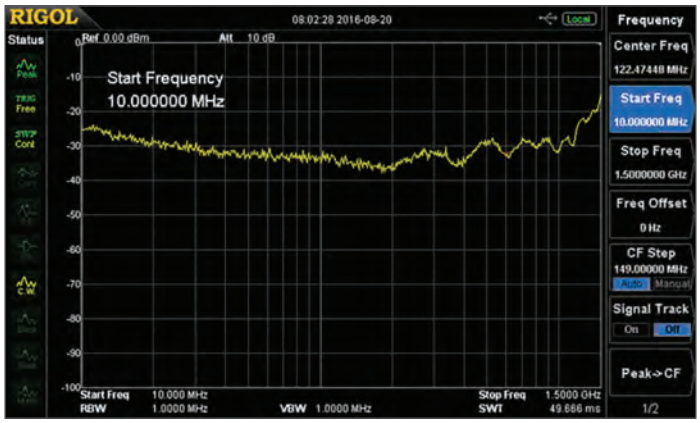


Figure 4 – the return loss measurement of the 50-Ohm termination varied from 25 dB (VSWR = 1.12) at 10 MHz to 17 dB (VSWR = 1.33) at 1.5 GHz. The best performance was 38 dB(VSWR = 1.03) at 200 MHz. The results were excellent.

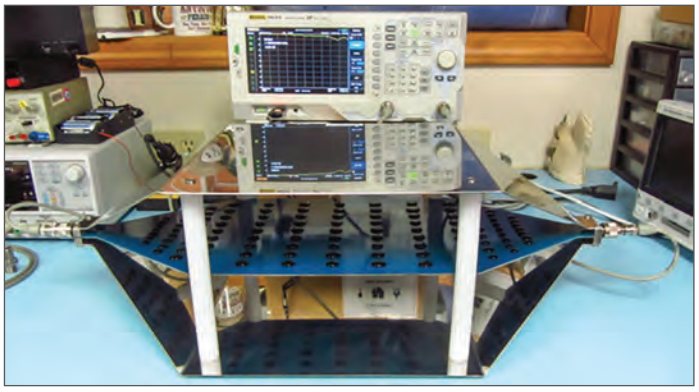

Figure 5 – Measurement of the transmission loss of the TEM cell using the Rigol DSA815TG spectrum analyzer with tracking generator. The measurement was made from 10 MHz to 1.5 GHz. Performance was excellent out to 1 GHz.

## RADIATED IMMUNITY TESTING

Testing radiated immunity simply requires connecting an RF source at one end of the TEM cell and terminating the other end in 50 Ohms. The E-field generated is 90-degrees to the plane of the interior septum and reasonably uniform.

It doesn't require much RF signal level to create rather large E-field levels within the cell. Tekbox provides a formula and chart for each model TEM cell (refer to their user manual for details). In the case of the TBTC2 used in this example, the calculated field levels are depicted in *Table 1*.

To calculate the power required for a given E-field level between septum and lower (or upper) wall of the TEM cell, you can use the formula: E = V/d where V is the RMS voltage of the applied signal and d is the distance between septum and lower (upper) wall. This is based on the simplified assumption that the E field would be perfectly homogeneous/evenly distributed.

A more practical formula is E = V*Cor/d where Cor is a correction factor for the average field strength over the volume of the DUT derived from the analysis of the field distribution over the cross section of the cell.

Assuming the DUT is placed in the center of the cell and in the middle between bottom wall and septum, we can use the simplified formula with sufficient accuracy.

For model TBTC1: d = 5 cm and E = (√(P*50Ω))*20

For model TBTC2: d = 10 cm and E = (√(P*50Ω))*10 (used for this article)

For model TBTC3: d = 15 cm and E = (√(P*50Ω))*6.66

| TBTC2, applied RF power | Maximum field strength between septum and wall |
|---|---|
| 10W (40 dBm) | 224 V/m |
| 1 W (30 dBm) | 71 V/m |
| 0.1 W (20 dBm) | 22 V/m |
| 0.01 W (10dBm) | 7 V/m |

*Table 1 – TBTC2, field strength vs. RF power*

Place the DUT on an insulated spacer if used in the lower septum area. In the example of Figure 6, I placed it in the upper chamber on top of the insulating pads. The important thing is to keep it some distance away from the top or bottom steel plates or from the inner septum.

Any connecting cables to the DUT will also be irradiated, which is a good thing, because many immunity issues are due to poorly terminated cables.

During troubleshooting, try to replace the DUT in the same physical location each time in order to reduce the number of variables. It might be a good idea to mark the placement of the EUT and tape down any connecting cables.

Most radiated immunity standards, such as IEC 61000-4-3, require either a 3 or 10 V/m field level. As you can see, you can easily achieve this with about 10 mW (+10 dBm). Levels

exceeding 200 V/m for military and automotive applications can be achieved with just 10 watts.

*One caution: When performing any radiated immunity test with an open TEM cell, such as the Tekbox design, it should be conducted inside a shielded chamber to avoid potential interference to existing communications or broadcast systems.*

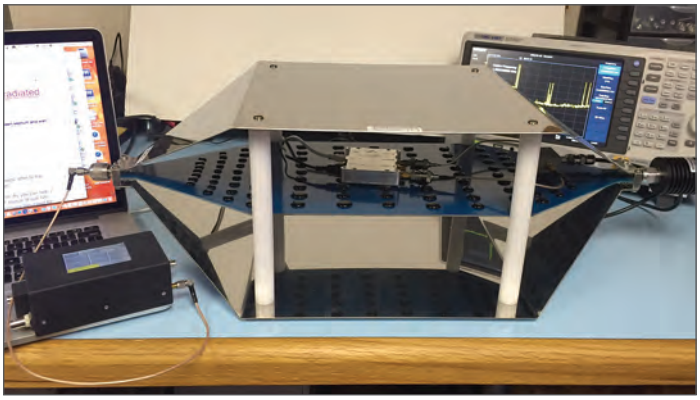

Figure 6 – Tekbox model TBTC2 being used to perform a radiated immunity test on a small product. The black dots are protective covers for an array of bandwidth-flattening resistors. A Red Oak Canyon RF sweep generator can be seen at one end and a 50-Ohm load is on the other. The DUT performance and is being monitored using a Rigol DSA815TG spectrum analyzer.

## RADIATED EMISSIONS TESTING

While measuring radiated emissions using a TEM cell will not necessarily compare with a measurement using a calibrated EMI antenna at a 3 or 10m test distance, it should provide a quick look at the overall emissions profile of the DUT and allow for quick troubleshooting. Remember, when troubleshooting radiated emissions, the important point is relative changes. Keep in mind, lowering the emission level of a harmonic by 10 dB does not necessarily equate to a 10 dB reduction when measured at a 3m or 10m test range.

Figure 7 – Radiated emissions test using the Tekbox TBTC2 TEM cell. The DUT is placed on an insulating block and centered in the lower septum area. Any attached cables will radiate, as well. If this is an issue, place a series of ferrite chokes around them to help decouple the common-mode currents from the measurement.

In this case, it is not required to perform the testing in a shielded chamber. However, if used outside of a chamber, you'll tend to receive ambient signals from various communications systems and broadcast transmitters. You'll want to save a baseline plot of the ambient signals prior to performing any emissions testing. I generally use Trace 1 to capture a minute, or so, of the ambients using Max Hold mode on the analyzer. Then I'll use Trace 2 for the actual emissions plot. See Figure 8 for an example.

For this example, I'm measuring the emissions from a ST Microelectronics STM32 F4 Discovery embedded processor board (http://www.st.com). The general-purpose board uses an ARM/Cortex-M4 core with LCD display and several I/O ports. The processor clock runs at 270 MHz.

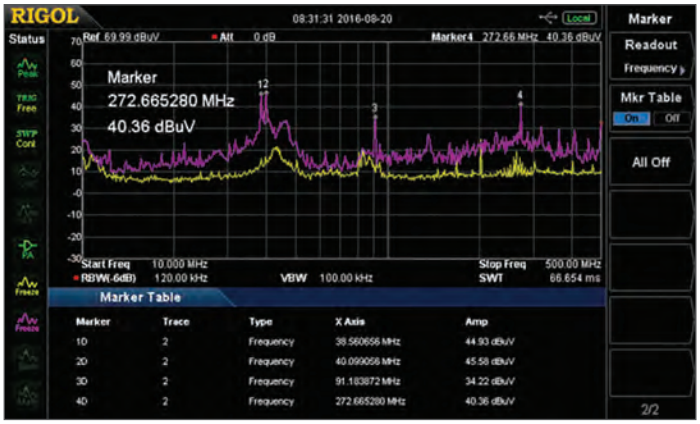


Figure 8 – The screen capture of the example embedded processor. You can observe several major narrow band emissions, including the processor clock running at 270 MHz. The yellow trace is the baseline showing the major ambient signals. The violet trace is the ambients, plus DUT emissions.

As you can see, the TEM cell can detect the entire emissions profile simultaneously – a marked improvement over performing the test in a regular EMI chamber – where harmonic emissions must be measured recorded one at a time.

I've placed markers at the peak harmonics and activated the marker table feature of the Rigol DSA815TG to aid in evaluating and troubleshooting the emissions. The processor clock at 270 MHz can easily be seen.

## SUMMARY

In summary, a TEM cell, such as the Tekbox model can be a useful tool for both radiated emissions and radiated immunity troubleshooting. The device under test must be physically small enough to fit with some room to spare, between either the top plate and septum or septum and bottom plate, so this is somewhat restrictive, depending on the product. In general, most small PC boards or subassemblies should work fine.

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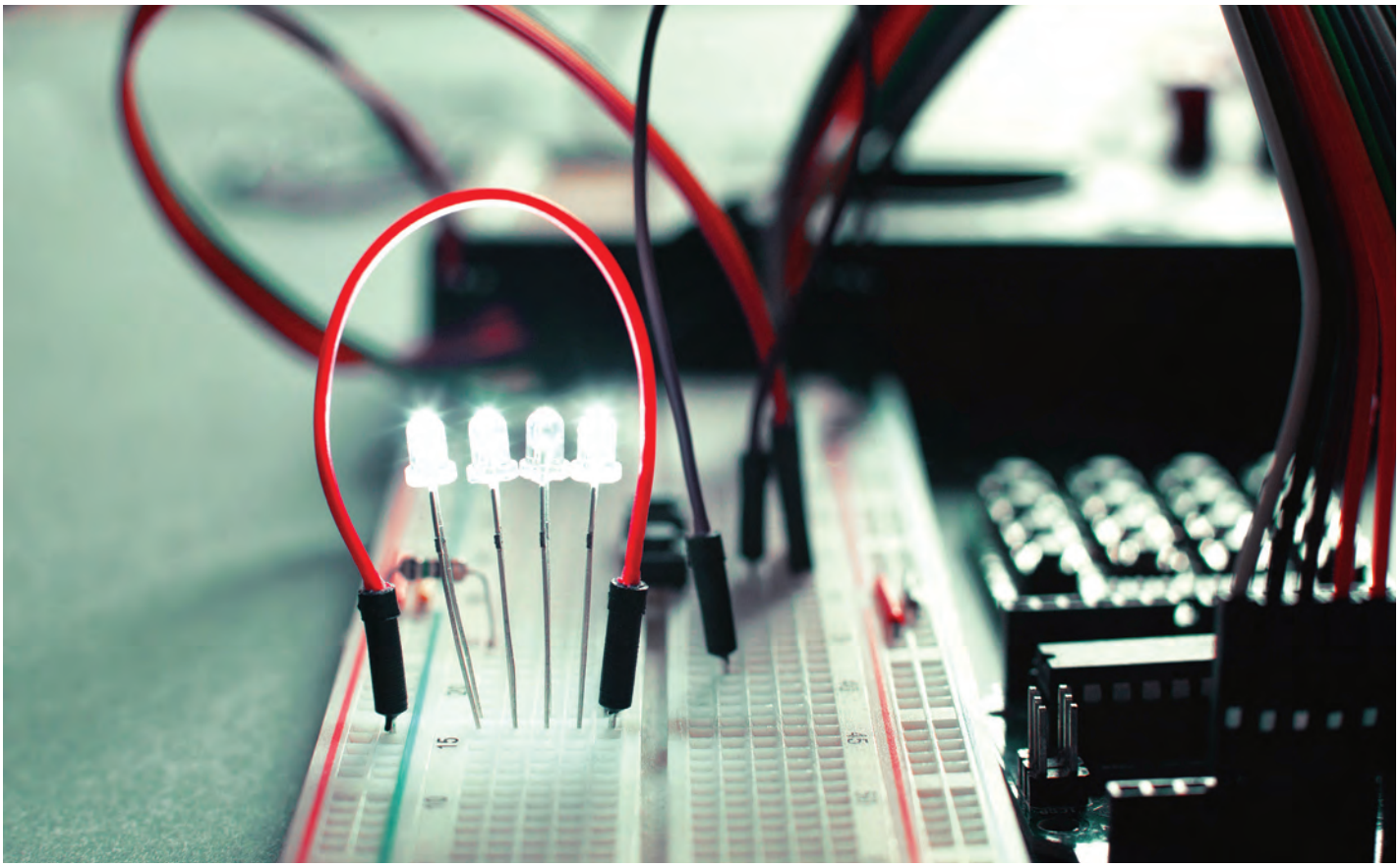

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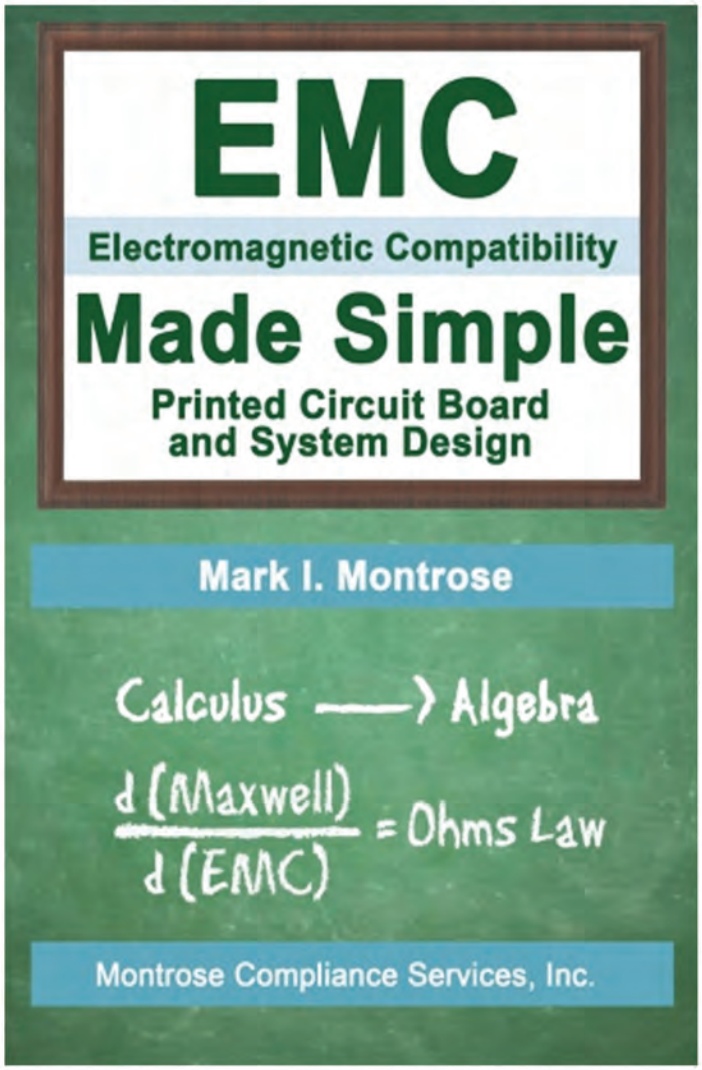


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| Wheeling | D.L.S. Electronic Systems, Inc.<br>www.dlsemc.com | (847) 537-6400 | • | • | • | • | • | • | • | | • | • | | • | • | • | | • | | • | • | |
| Wonder Lake | Midwest EMI Associates, Inc.<br>www.midemi.com | (847) 918-9886 | | | • | | • | | | | | | | | | | | | | | | |

# USA continued

| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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| Lexington | Lexmark International EMC Lab<br>www.lexmark.com | (859) 232-2000 | | | | | | | • | | | | | | | | | | | | | |
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| Columbia | DRS Advanced Programs<br>www.advprograms.com | (410) 312-5800 | | | | | | | | | | | | • | | | | | | • | | • |
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| Frederick | The American Association for<br>Lab Accreditation; www.a2la.org | (301) 644-3248 | | | | | | | | | | | | | • | | | | | | | |
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| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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| Billerica | Quest Engineering Solutions<br>www.qes.com | (978) 667-7000 | | | | | | | | | | | | | | | | | | | • | |
| Boxborough | Intertek (Boxborough)<br>www.intertek.com | (800) 967-5352 | | • | • | • | • | • | • | • | • | | | • | • | • | | • | | • | • | |
| Boxborough | National Technical Systems<br>www.nts.com | (978) 266-1001 | • | • | • | • | • | • | • | • | • | • | • | • | • | | | • | | • | • | |
| Lexington | Design Automation, Inc. | (781) 862-8998 | | | • | • | • | | • | • | • | • | | | | • | | | | | | |
| Littleton | Curtis-Straus LLC, subsidiary of Bureau Veritas<br>www.bureauveritas.com | (877) 277 8880 | • | • | • | | • | • | • | • | • | | | • | • | • | | | | • | • | |
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| Littleton | Compliance Management Group<br>www.cmgcorp.net | (978) 431-1985 | • | | • | | • | • | • | | • | | | | • | • | | | | | • | |
| Milford | Test Site Services, Inc.<br>www.testsiteservices.com | (508) 634-3444 | • | • | • | | • | • | • | • | • | • | | • | • | • | | • | | • | • | |
| Newton | EMC Test Design, LLC<br>www.emctd.com | (508) 292-1833 | | | | | | | | | | | | | | | • | | | | | |
| Peabody | TÜV SUD America Inc.<br>www.tuv-sud-america.com/us-en | (800) TUV-0123 | • | • | • | • | • | • | • | | • | • | | • | • | • | | • | | • | • | |
| Pittsfield | National Technical Systems<br>www.nts.com | (413) 499-2135 | | • | • | • | • | • | • | | • | • | | | • | | | | | • | | |
| Wilmington | Thermo Fisher Scientific<br>www.thermofisher.com | (978) 275-0800 | • | | | • | • | | • | • | • | • | | • | | | | | • | • | | |
| Woburn | Chomerics, Div. of Parker Hannifin Corp.<br>www.chomerics.com | (781) 935-4850 | | | • | • | • | • | • | | • | • | • | • | • | • | • | • | | • | • | |
| Woburn | NELCO<br>www.nelcoworldwide.com | (781) 933-1940 | | | | | | | | | | | | | | | | | | | • | |
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| Brighton | Willow Run Test Labs, LLC<br>www.wrtest.com | (734) 252-9785 | | | • | | • | | • | | | | | | | | | | | | • | |
| Burton | Trialon Corporation<br>www.trialon.com | (810) 742-8500 | | | • | | • | | | | • | | | | • | | | | | | | |
| Detroit | National Technical Systems<br>www.nts.com | (313) 835-0044 | | • | • | | • | • | • | | • | | | | • | | | • | | | | |
| Detroit | TÜV Rheinland of North America, Inc.<br>www.tuv.com/en/middleeast/home.jsp | (734) 207-9852 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
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| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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| Sister Lakes | AHD EMC Lab<br>www.ahde.com | (269) 313-2433 | | | • | | • | • | • | | • | | | • | • | | | | | | • | |
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# USA continued

| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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# USA continued

| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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R&B Laboratory, a NVLAP accredited to ISO-17025 located outside Philadelphia, PA provides certified EMC testing and reports for Military, Avionics and Automotive applications. R&B is also capable of offering EMI solutions for non-compliance products. Our highly skilled technicians and engineers work closely with clients to fulfill their testing needs. The Laboratory facility includes 8 semi-anechoic shielded rooms and a reverberation chamber, each equipped with multiple power capabilities and automated data acquisition.

## CAPABILITIES

### EMC Testing and Engineering Support

- Military (MIL-STD-461, MIL-STD-704 and MIL-STD-1399)
- Aerospace (RTCA/DO-160, Boeing and Airbus)
- Automotive (SAE, ISO, Fiat Chrysler, Ford, and GM)
- CISPR / FDA
- Reverberation Chamber (HIRF)
- System Engineering Support
- Detail Design Support for EMC compliance
- Test Procedures / Control Plans
- Site Surveys
- NVLAP accreditation to ISO-17025

www.rblaboratory.com 610-825-1960 rvohra@rblaboratory.com

20 Clipper Road. West Conshohocken, PA 19428

# USA continued

| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hillsboro | Northwest EMC, Inc.<br>www.element.com | (503) 844-4066 | | • | • | | • | | • | | • | | | | • | | | | | • | • | |
| Portland | TÜV SÜD America, Inc.<br>www.tuv-sud-america.com/us-en | (503) 598-7580 | | • | • | • | • | • | • | | • | | | | | • | | | | | | |
| **PENNSYLVANIA** | | | | | | | | | | | | | | | | | | | | | | |
| Chambersburg | Cuming Lehman Chambers<br>http://cuminglehman.com | (717) 263-4101 | | | • | | | | | | • | | | • | | | | | | • | | |
| Glenside | Electro-Tech Systems, Inc.<br>www.electrotechsystems.com | (215) 887-2196 | • | | | | • | | | | | | | | | | | | | | • | |
| Harleysville | Retlif Testing Laboratories<br>www.retlif.com | (215) 256-4133 | | • | • | • | • | • | • | • | • | • | | • | • | • | • | • | | • | • | |
| Hatfield | Laboratory Testing Inc.<br>www.labtesting.com | (800) 219-9095 | | | | | | | | | | | | | • | | | | • | | | |
| New Castle | Keystone Compliance LLC<br>www.keystonecompliance.com | (724) 657-9940 | • | | • | • | • | • | • | | • | • | • | • | • | • | • | • | | • | • | |
| Pottstown | BEC Inc.<br>www.bec-ccl.com | (610) 970-6880 | | | • | | • | | • | | • | | | | • | | | | | | • | |
| State College | Videon Central, Inc.<br>www.videon-central.com | (814) 235-1111 | | | • | | • | • | • | | | | | | | | | | | • | | |
| West Conshohocken | R&B Laboratory<br>www.rblaboratory.com | (610) 825-1960 | | | • | • | • | | | | • | • | | • | | | • | • | | • | • | |
| **TENNESSEE** | | | | | | | | | | | | | | | | | | | | | | |
| Knoxville | Global Testing Labs LLC<br>www.globaltestinglabs.com | (865) 523-9972 | | | • | | | | • | | • | | | | • | | | | | | | |
| Knoxville | Southern Testing Services, Inc. | (865) 966-5330 | | | | | | | | | | | | • | | | | | | | | |
| Knoxville | AMS Corporation<br>www.ams-corp.com | (865) 691-1756 | | | • | | • | | | | • | | | • | | | | | | | | |
| **TEXAS** | | | | | | | | | | | | | | | | | | | | | | |
| Austin | Austin EMC<br>www.austinemc.com | (512) 926-2800 | | | • | | • | | | | • | | | | | | | | • | | | |
| Austin | BAE Systems IDS Test Services<br>www.baesystems.com | (512) 287-2500 | | | | | | | | | | | • | | | | | • | | | | |
| Austin | MET Laboratories, Inc.<br>www.metlabs.com | (855) 638-5337 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | | • | | • | • | |
| Austin | TÜV Rheinland of North America, Inc.<br>www.tuv.com | (512) 927-0070 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Cedar Park | TDK RF Solutions, Inc.<br>www.tdkrfsolutions.com | (512) 258-9478 | | | • | | • | • | • | • | • | | | | • | | | | | | | |
| Elmendorf | Intertek (Elmendorf)<br>www.intertek.com | (800) 967-5352 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Houston | DNV Certification | (281) 721-6600 | | | | | | • | | | | | | | | | | | | | | |
| Houston | ITW Richmond Technology | (510) 655-1263 | | | | | • | | | | | | | | | | | | | | | |
| Lewisville | Nemko USA<br>www.nemko.com | (972) 436-9600 | | • | • | | • | • | • | • | • | | | • | • | • | • | • | | • | • | |
| Plano | National Technical Systems<br>www.nts.com | (972) 424-8928 | • | • | • | • | • | • | • | • | • | • | | • | • | | | • | | • | • | |
| Plano | Northwest EMC, Inc.<br>www.element.com | (469) 304-5255 | | • | • | | • | | • | | • | | | | • | | | | | | | |
| Plano | Intertek (Plano)<br>www.intertek.com | (800) 967 5352 | | • | • | • | • | • | • | | • | | | | • | • | | | | | | |

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| CITY/STATE | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Round Rock | Professional Testing (EMI), Inc.<br>www.ptitest.com | (512) 244-3371 | | | • | | • | | • | | • | • | | • | • | • | | | • | • | • | |
| San Antonio | Southwest Research Institute<br>www.swri.org | (210) 684-5111 | • | | • | • | • | • | • | • | • | • | • | • | • | • | | • | | • | • | |
| **UTAH** | | | | | | | | | | | | | | | | | | | | | | |
| Coalville | DNB Engineering, Inc.<br>www.dnbenginc.com | (435) 336-4433 | • | | • | | • | • | • | • | • | | | | | • | | | | | | |
| Draper | VPI Technology<br>vpilaboratories.com | (801) 495-2310 | | | • | | • | • | • | • | • | | | • | • | • | | | | | | |
| Ogden | Little Mountain Test Facility (LMTF) | (801) 315-2320 | | | • | • | • | | | | • | | • | • | | | | • | | • | • | |
| Salt Lake City | L3 Communication Systems–West<br>www2.l-3com.com | (801)594 2000 | | | • | | | • | • | | | | | • | | | | | | • | | |
| **VERMONT** | | | | | | | | | | | | | | | | | | | | | | |
| Essex Junction | Huber & Suhner<br>www.hubersuhner.com | (704) 790 7228 | | | | | | | | | | • | | | | | | | | | • | |
| Middlebury | Green Mountain Electromagnetics, Inc.<br>www.gmelectro.com | (802) 388-3390 | | | | | | • | • | • | | | • | • | | | | | | | | |
| **VIRGINIA** | | | | | | | | | | | | | | | | | | | | | | |
| Dulles | Orbital Sciences Corp.<br>orbitalatk.com | (703) 406-5000 | | | • | | | | | | • | | | • | | | | • | | | • | |
| Falls Church | Raytheon Prototype Services<br>www.raytheon.com | (703) 748-8670 | | | • | | | | | | • | | | • | | | | | | | | |
| Fredericksburg | E-LABS INC.<br>www.e-labsinc.com | (540) 834-0372 | | | • | | • | | | | • | | | • | • | | • | | | • | • | |
| Fredericksburg | Vitatech Engineering, LLC<br>http://vitatech.net | (540) 286-1984 | • | | • | | | | • | • | • | | • | • | | | | | | | • | |
| Herndon | Rhein Tech Laboratories, Inc.<br>www.rheintech.com | (703) 689-0368 | | | • | | • | • | • | | • | | | • | • | • | | | | • | • | |
| McLean | American TCB | (703) 847-4700 | | | • | • | | • | • | | • | • | | | • | | | | | | | |
| Reston | TEMPEST, Inc. (VA)<br>www.tempest-inc.com | (703) 836-7378 | | | • | | • | • | • | • | • | | • | • | | | | | | | • | • |
| Richmond | Technology International, Inc.<br>www.techintl.com | (804) 794-4144 | | • | • | | • | • | | | • | | | | | • | | | | | | • |
| **WASHINGTON** | | | | | | | | | | | | | | | | | | | | | | |
| Bothell | CKC Laboratories, Inc<br>www.ckc.com | (425) 402-1717 | | • | • | • | • | • | • | | • | • | • | • | • | | | • | | • | • | |
| Bothell | Northwest EMC, Inc.<br>www.element.com | (425) 984-6600 | | | • | | • | | • | | • | | | | • | • | | | | | | |
| **WISCONSIN** | | | | | | | | | | | | | | | | | | | | | | |
| Cedarburg | L.S. Research<br>www.lsr.com | (262) 375-4400 | | • | • | | • | | • | | • | | | | • | | | | | | | |
| Genoa City | D.L.S. Electronic Systems, Inc.<br>www.dlsemc.com | (262) 279-0210 | | • | • | | | | • | | | | | | • | | | | | | | |
| Middleton | Intertek<br>www.intertek.com | (800) 967-5352 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Neenah | International Compliance Laboratories<br>www.icl-us.com | (920) 720-5556 | | | • | | • | | • | | • | | | | • | | | | | | | |

# CANADA

| CITY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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| **ALBERTA** | | | | | | | | | | | | | | | | | | | | | | |
| Airdrie | Electronics Test Centre - Airdrie<br>www.etc-mpb.com | (403) 912-0037 | | | • | | • | • | • | | • | | | • | • | | | | | • | • | |
| Calgary | EMSCAN Corporation<br>www.emscan.com | (403) 291-0313 | | | • | | | | | | • | | | | | | | | | | • | |
| Medley | Aerospace Engrg. Test Establishment (DND)<br>www.rcaf-arc.forces.gc.ca/en/4-wing/index.page | (780) 840-8000 | | | • | | | | | | | | | | | | | | | • | | |
| **BRITISH COLUMBIA** | | | | | | | | | | | | | | | | | | | | | | |
| Abbotsford | Protocol EMC<br>www.protocol-emc.com | (604) 218-1762 | | | • | • | • | • | • | | • | • | | • | • | • | | | | | • | |
| Kelowna | Celltech Labs, Inc.<br>www.celltechlabs.com | (250) 765-7650 | | • | • | | • | • | • | • | • | | | | • | | | | | | • | • |
| Pitt Meadows | QAI Laboratories<br>www.qai.org | (877) 461-8378 | | | • | | • | • | • | | • | | | | | | | | | | | |
| Richmond | LabTest Certification, Inc.<br>www.labtestcert.com | (855) 346-0444 | | | • | • | • | • | • | • | • | | | • | • | • | | | | • | | |
| **ONTARIO** | | | | | | | | | | | | | | | | | | | | | | |
| Gormley | Global EMC Inc.<br>www.globalemclabs.com | (905) 883-8189 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • |
| Kanata | Electronics Test Centre<br>www.etc-mpb.com | (613) 599-6800 | • | | • | • | • | • | • | • | • | • | | • | • | • | • | • | | • | • | |
| Merrickville | EMC Consulting, Inc.<br>www.emcconsultinginc.com | (613) 269-4247 | | | • | • | • | • | • | | • | • | • | • | | | | | | | • | |
| Nepean | Multilek Inc.<br>www.multilek.ca | (613) 226-2365 | | | • | | • | | | | • | | | • | | | | | • | | | |
| Oakville | Ultratech Group of Labs<br>www.ultratech-labs.com | (905) 829-1570 | | • | | • | • | • | • | • | | • | | • | • | • | • | • | | • | • | |
| Ottawa | ASR Technologies<br>www.asrtechnologiesinc.com | (613) 737-2026 | | | | • | • | • | • | | | • | • | • | | | | | | | • | |
| Ottawa | David Florida Laboratory (CSA)<br>http://www.asc-csa.gc.ca/eng/dfl/ | (613) 998-2044 | | | • | | • | | | | • | | | • | | | | • | | • | • | |
| Ottawa | Nemko<br>www.nemko.com | (613) 737-9680 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| Ottawa | Power & Controls Engineering Ltd.<br>www.pcel.ca | (613) 829-0820 | | | • | | | | | | | | • | • | | | • | | | | • | • |
| Ottawa | Raymond EMC Enclosures Limited<br>http://raymondemc.ca | (800) EMC-1495 | | | | | | | | | | | | | | | | | | | • | |
| Scarborough | Vican Electronics<br>http://vican.ca | (416) 412-2111 | • | | • | | • | • | • | • | • | | | • | | | | | • | | • | • |
| Toronto | CSA International<br>http://www.csagroup.org/ | (866) 797-4272 | | • | • | | | • | • | | • | | | | • | • | | | | | | |
| Toronto | TÜV Rheinland of North America, Inc.<br>www.tuv.com | (416) 733-3677 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| **QUEBEC** | | | | | | | | | | | | | | | | | | | | | | |
| Laval | Les Enterprises EMC Monde Inc.<br>www.globalemclabs.com | (450) 687 4976 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| Montreal | Centre de Recherche Industrielle du Quebec<br>www.criq.qc.ca | (514) 383-1550 | | | • | | | • | • | | • | | | | | • | | | | | | |
| Quebec | Comlab, Inc.<br>www.comlab.com | (418) 682-3380 | | | | | • | • | • | | • | | | | | | | | | | | |
| Quebec | FISO Technologies<br>www.fiso.com | (418) 688-8065 | | | | • | | | | | • | | | • | | • | • | | | | • | |

# ASIA

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
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| **CHINA** | | | | | | | | | | | | | | | | | | | | | | |
| Beijing | SIEMIC Beijing (China) Laboratories<br>www.siemic.com.cn | +86 1068049809 | | • | • | • | • | • | • | • | • | • | | | • | • | | | | | | |
| Beijing | TÜV Rheinland (China) Ltd.<br>www.tuv.com | +86 1065666660 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Guangzhou | Intertek (Guangzhou)<br>www.intertek.com | +86 2082139688 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Guangzhou | TÜV Rheinland (GuangDong) Ltd.<br>www.tuv.com | +86 2028391888 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Hangzhou | Intertek Hangzhou<br>www.intertek.com | +86 571 2899 7800 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Hong Kong | TÜV Rheinland Hong Kong Ltd.<br>www.tuv.com | +85 221921000 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Liaoning | Intertek (Liaoning)<br>www.intertek.com | +86 4118282 7769 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Nanjing | SIEMIC (Nanjing) China Laboratories<br>www.siemic.com.cn | +86 2586730128 | | • | • | | • | | • | • | • | • | | | • | • | | | | | • | |
| Shandong | Intertek (Shandong)<br>www.intertek.com | +86 532 80993309 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Shanghai | CETECOM Shanghi<br>www.cetecom.com | +86 2168795890 | | • | • | | • | • | • | | • | | | | • | • | | | | | | |
| Shanghai | SIEMIC (Shanghai) China Laboratories | +86 2164812901 | | • | • | • | • | • | • | • | • | • | | | • | • | | | | | | |
| Shanghai | TÜV Rheinland (Shanghai) Co., Ltd.<br>www.tuv.com | +86 2161081188 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Shenzhen | Intertek (Shenzhen)<br>www.intertek.com | +86 75586016288 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Shenzhen | SIEMIC (Shenzhen) China Laboratories<br>www.siemic.com | +75 52601462 | | • | • | • | • | • | • | • | • | • | | | • | • | | | | | | |
| Sichuan | Intertek (Sichuan)<br>www.intertek.com | +86 28 6626 5802 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Suzhou | Intertek (Suzhou)<br>www.intertek.com | +86 51288168100 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Taipei | TÜV Rheinland Taiwan Ltd.<br>www.tuv.com | +88 6221727000 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Wenzhou | Intertek Wenzhou<br>www.intertek.com | +86 59 2516 2906 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Yuyao | Intertek Yuyao<br>www.intertek.com | +86 574 2267 6567 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **JAPAN** | | | | | | | | | | | | | | | | | | | | | | |
| Chiba | Kashima EMC Lab<br>www.ul.com | +81 478 88 6500 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |
| Fukuoka | Intertek (Fukuoka)<br>www.intertek.com | +81 (0) 50 3823 0447 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Ibaragi | Intertek (Ibaragi)<br>www.intertek.com | +81 479 40 1097 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Kanagawa | Intertek (Kanegawa)<br>www.intertek.com | +81 465 89 2316 | | • | • | | • | • | • | | • | | | | | | | | | | | |

# ASIA continued

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kanegawa | Shonan EMC Lab<br>www.ul.com | +81 463 50 6400 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |
| Nagano | Intertek (Nagano)<br>www.intertek.com | +81 266 47 5311 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Osaka | Intertek (Osaka)<br>www.intertek.com | +81 (0) 6 6150 0580 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Osaka | TÜV Rheinland<br>www.tuv.com | +81 06 7656 6888 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Shin-Yokohama | CETECOM Japan<br>www.cetecom.com | +81 045 594 9990 | | • | • | | • | • | • | | • | | | | • | • | | | | | | |
| Tochigi | Intertek (Tochigi)<br>www.intertek.com | +81 289 86 7121 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |
| Tokyo | e-Ohtama, Ltd.<br>http://www.e-ohtama.jp/english/ | +81 044 980 2050 | | | • | | | | | | • | | | | | • | | | | | • | |
| Tokyo | Intertek (Tokyo)<br>www.intertek.com | +81 (0) 3 6435 3424 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Tokyo | TÜV SÜD<br>www.tuv-sud-america.com/us-en | + 81 3 6858 9100 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Yamagata | TÜV SÜD<br>www.tuv-sud-america.com/us-en | +81 238 28 2880 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Yokohama | TÜV Rheinland Japan Ltd.<br>www.tuv.com | +81 045 470 1850 | | • | • | | • | • | • | • | • | | | | | • | | | | | | |
| Yokowa | Yokowa EMC Lab<br>www.ul.com | +81 463 50 6400 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |
| **KOREA** | | | | | | | | | | | | | | | | | | | | | | |
| Anyang | CETECOM MOVON Ltd.<br>www.cetecom.com | +82 031 321 2988 | | • | • | | • | • | • | | • | | | | • | • | | | | | | |
| Gyeonggi-do | MET Laboratories, Inc.<br>www.metlabs.com | +82 31 697 8202 | | • | • | | | | | | | | | | | • | | | | | • | |
| **SOUTH KOREA** | | | | | | | | | | | | | | | | | | | | | | |
| Seoul | Intertek (Seoul)<br>www.intertek.com | +82 2 567 7474 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **TAIWAN** | | | | | | | | | | | | | | | | | | | | | | |
| New Taipei City | MET Laboratories, Inc.<br>www.metlabs.com | +886 2 8226 1579 | | • | • | | | | | | | | | | | • | | | | | • | |
| Taoyuan | SIEMIC Certification Servces<br>www.siemic.com | +886 3 212 1075 | | • | | | | • | | | | | | | | | | | | | | |
| Taichung City | Intertek (Taichung)<br>www.intertek.com | +886 4 23598819 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Taichung City | TÜV SÜD<br>www.tuv-sud-america.com/us-en | +886 4 2287 0566 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Taipei City | CETECOM Taiwan<br>www.cetecom.com | +886 9 722 02380 | | | | | | • | | | | | | | | • | | | | | | |
| Taipei City | Intertek (Taipei)<br>www.intertek.com | +886 2 66022729 | | • | • | | • | • | • | | • | | | | | | | | | | | |

# EUROPE

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BELGIUM** | | | | | | | | | | | | | | | | | | | | | | |
| Erpe-Mere | Blue Guide EMC Lab<br>www.bgemc.com | +32 (0) 53 60 16 01 | | | • | | • | • | • | | • | | | | | • | | | • | | • | |
| **DENMARK** | | | | | | | | | | | | | | | | | | | | | | |
| Copenhagen | Intertek (Copenhagen)<br>www.intertek.com | +45 2928 7030 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **FRANCE** | | | | | | | | | | | | | | | | | | | | | | |
| Antony | Intertek (Antony)<br>www.intertek.com | +33 1 46 74 15 10 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **GERMANY** | | | | | | | | | | | | | | | | | | | | | | |
| Bloomberg | Phoenix Testlab GmbH<br>www.phoenix-testlab.de | +49 5235 9500 0 | | | • | | | | | | • | | | | | | | | | | | |
| Dortmund | EMC Test NRW GmbH<br>www.emc-test.de | +49 231 974 2750 | | | • | | • | • | • | | • | | | | | | | | | | • | |
| Egling | MOOSER Consulting GmbH<br>www.mooser-consulting.de | +49 817 692250 | | | • | • | | | | | • | | • | • | | | | | | | • | • |
| Erlangen | Siemens AG<br>www.siemens.com | +49 9131 180 | | | • | | • | | | | • | | | | | | | | | | | |
| Essen | CETECOM GmbH (Germany)<br>www.cetecom.com | +49 205 495 190 | | • | • | | • | • | • | | • | | | | | • | | | | | • | |
| Karlsruhe | Siemens AG<br>www.siemens.com | +49 721 5950 | | | • | • | • | • | | | • | | | • | | • | | | | | | |
| Kaufbeuren | Intertek (Kaufbeuren)<br>www.intertek.com | +49 711 27311 152 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Leinfelden-Echterdingen | Intertek (Leinfelden-Echterdingen)<br>www.intertek.com | +49 711 27311 152 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Ludwigsburg | Mooser EMC Technik GmbH<br>www.mooser-consulting.de | +49 714 164 8260 | | | • | | • | • | | | • | | | • | | | | • | | | | |
| Moggast | EMCCons Dr. Rasek GmbH & Co<br>www.emcc.de | +49-9194-7262-0 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | | | | |
| Nürnberg | TÜV Rheinland<br>www.tuv.com | +49 911 655-5227 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Ratingen | 7Layers<br>www.7layers.com | +49 210 27490 | | | • | | • | • | • | | • | | | | | | | | | | • | |
| Wismar | CEcert GmbH<br>www.cecert.com | +49 (0)3841 - 303050 | | | • | | • | | | | • | | | | | | | | | | | |
| Saarbruecken | CETECOM ICT Services GmbH<br>www.cetecom.com | +49 681 598 8438 | | • | • | | • | • | • | | • | | | • | | • | • | • | | • | | |
| Siegen | EMC Testhaus Dr. Schreiber GmbH<br>www.emc-testhaus.de | +49 271 382702 | | | • | • | • | • | | | • | • | | • | | • | | | • | • | • | |
| Straubing | TÜV SÜD SENTON GmbH<br>www.tuev-sued.de | +49 942 155220 | | • | • | | • | • | • | | • | | | • | | | | | | • | | |
| Unterleinleiter | EMCCons Dr. Rasek GmbH & Co<br>www.emcc.de | +49-9194-7263-0 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| Verden | Block Elektronik GmbH<br>http://www.block.eu/en_US/home | +49 4231 6780 | | | • | | | | | | | | | | | | | | | | | |
| Wiesbaden | Intertek (Weisbaden)<br>www.intertek.com | +49 711 27311 152 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Würzburg | TÜV Rheinland LGA Bautechnik GmbH<br>www.tuv.com | +49 1806 252535 1500 | | • | • | | • | • | • | | • | | | | | | | | | | | |

# EUROPE continued

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Würzburg | TÜV Rheinland LGA Products GmbH<br>www.tuv.com | +49 911 655 5227 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **HUNGARY** | | | | | | | | | | | | | | | | | | | | | | |
| Budapest | TÜV Rheinland InterCert Kft.<br>www.tuv.com | +36 146 11100 | | • | • | • | • | • | • | | • | | | | | • | • | | | | • | |
| **IRELAND** | | | | | | | | | | | | | | | | | | | | | | |
| Dunshaughlin | Compliance Engineering Ireland Ltd<br>www.cei.ie | +353 1 8017000 | | • | • | • | • | • | • | | • | • | | • | | • | • | | | • | • | |
| **ITALY** | | | | | | | | | | | | | | | | | | | | | | |
| Campoformido | Intertek (Campeformido)<br>www.intertek.com | +39 0432 653411 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **THE NETHERLANDS** | | | | | | | | | | | | | | | | | | | | | | |
| Breda | EMCMCC<br>www.emcmcc.nl | +31 653 81 1267 | | | • | • | • | | | | • | | | • | | • | | • | | | | |
| Dordrecht | Holland Shielding Systems BV<br>www.hollandshielding.com | +31(0)78-2049000 | | | | • | • | | | | | • | | • | | | | | | • | | • |
| Eindhoven | Philips Innovation Services<br>www.innovationservices.philips.com | +31 402 748060 | | • | • | | • | | • | | • | | | | | • | | | | | | |
| Woerden | DARE!! Measurements<br>www.dare.nl | +31 348 430 979 | | • | • | | • | • | • | | • | | | • | | • | | • | • | | • | |
| **POLAND** | | | | | | | | | | | | | | | | | | | | | | |
| Poznan | ILiM - Laboratory of Electronic Devices<br>www.ilim.poznan.pl/LA | +48 61 852 63 76 | | • | • | | • | • | | | • | | | | | • | | | | | | |
| **SERBIA** | | | | | | | | | | | | | | | | | | | | | | |
| Beograd | Idvorsky Laboratories<br>www.idvorsky.com | 011 67 76 329 | | | • | | • | | | | • | | | | | | | | | | | |
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| Barcelona | GCEM-UPC<br>www.upc.edu/web/gcem | +34 93 401 1021 | | | • | | • | • | • | | • | | | | | | | | | | | |
| Pamplona | TÜV Rheinland Ibérica Inspection, Certification & Testing, S.A.<br>www.tuv.com | +34 948 309 081 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Sevilla | TÜV Rheinland Ibérica Inspection, Certification & Testing, S.A.<br>www.tuv.com | +34 954 210 748 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Valencia | TÜV Rheinland Ibérica, S.A.<br>www.tuv.com | +34 963 787 702 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Zaragoza | TÜV Rheinland Ibérica Inspection, Certification & Testing, S.A.<br>www.tuv.com | +34 976 430 777 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| **SWEDEN** | | | | | | | | | | | | | | | | | | | | | | |
| Kista | Intertek (Kista)<br>www.intertek.com | +44 (0) 116 296 1620 | | • | • | • | • | • | • | | • | | | | | • | | | | | | |
| **SWITZERLAND** | | | | | | | | | | | | | | | | | | | | | | |

# EUROPE continued

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Berikon | Euro EMC Service (EES)<br>www.euro-emc-service.de | +41 566 33 7381 | | | • | | | • | | | • | | | | | | | | | | | |
| Geneva | SGS International Certification Ser.<br>www.sgsgroup.us.com | +41 22 794 83 74 | | | • | • | • | • | • | | • | • | | | | • | | | | | | |
| **UNITED KINGDOM** | | | | | | | | | | | | | | | | | | | | | | |
| Aberdeen | SGS<br>www.sgsgroup.us.com | +44 (0) 1224 793 600 | | | • | • | • | • | • | | • | • | | | | • | | | | | | |
| Basingstoke | RFI Global Services Ltd. (UL)<br>www.ul.com | +44 1256 312000 | • | • | • | | • | • | • | • | • | | | | • | • | | | | | • | |
| Blackwood | Kiwa Blackwood Compliance Lab<br>www.kiwa.co.uk | +44 (0) 1495 229219 | | | • | | • | | | | • | | | | | • | | | | | | |
| Bideford | ETC Ltd.<br>www.etcal.co.uk | +44 (0) 1237 423388 | | | | | | | | | | | | • | | • | | | | | | |
| Brentwood | RN Electronics<br>www.rnelectronics.com | +44 (0) 1277 352219 | | • | • | | • | | • | | • | | | • | • | • | | | | • | • | |
| Buckinghamshire | Intertek (Buckinghamshire)<br>www.intertek.com | +44 1908 857777 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |
| Burgess Hill | METECC<br>www.metecc.eu | +44 (0) 7725 079956 | | | • | | • | | • | | • | • | | • | | • | | | | | • | |
| Cambridge | dB Technology Cambridge Ltd.<br>www.dbtechnology.co.uk | +44 (0)1954 251974 | | | • | | • | • | • | | • | | | | | | | | | | | |
| Cheshire | Intertek (Cheshire)<br>www.intertek.com | +44 1244 882590 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Dorset | TRAC Global<br>www.tracglobal.com | +44 (0) 1202 811700 | | | | | | | | | | | | • | | • | | | | | | |
| Eastleigh | Hursley EMC Services<br>http://www.emctesting.co.uk | +44 (0) 2380 271111 | | | | | | | • | | | | | • | | | | | | • | | |
| Fareham | TÜV Product Service/BABT<br>www.tuvps.co.uk | +44 (0) 1489 558100 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Guildford | Underwriters Laboratories<br>www.ul.com | +44 1483.302.130 | • | • | • | | • | • | • | • | • | | | | • | • | | | | | • | |
| Leicestershire | Cre8 Associates Ltd<br>www.cre8-associates.com | +44 (0) 1162 479787 | | | | | | | | | | | | • | | | | | | | | |
| Malvern | Element<br>www.element.com | + 44 (0) 1684 571700 | | | | | | • | | | | | | | | | | | | | | |
| Malvern | TRaC Global (EMC Projects Ltd)<br>www.tracglobal.com | +44 (0) 1684 571700 | | | | | | | | | | | | • | | | | | | | | |
| Northamptonshire | 3C Test Limited<br>www.3ctest.co.uk | +44 (0) 1327 857500 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Renfrew | EMC Centre<br>www.emc-centre.com | +44 141 886 7300 | | | | | | | • | | | | | | | | | | | | • | |
| Sheffield | Frequensys Limited<br>www.frequensys.co.uk | +44 (0) 114 2353507 | | | | | • | | | | • | | | | | | | | • | | • | |
| Solihull | TRW Conekt<br>www.conekt.co.uk | +44 (0) 121 6274242 | | | • | | | | | | • | • | | • | | | | | | • | | |
| Stebbing | Electromagnetic Testing Services Ltd<br>www.etsemc.co.uk | +44 (0) 1371 856061 | | | | | | | • | | | | | • | | | | | | • | | |
| St. Helens | MVG EMC<br>www.mvg-emc.com | +44 (0) 1942 296190 | | | • | | • | • | • | | • | | • | | | • | | | | • | | |
| Stropshire | Cranage EMC & Safety<br>www.cranage.co.uk | +44 (0) 1630 658 568 | | | | | | | | | | | | | | • | | | | | | |

# EUROPE continued

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| Surrey | TÜV SÜD<br>www.tuv-sud-america.com/us-en | +44 (0)1932 251200 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Towcester | 3C Test Ltd<br>www.3ctest.co.uk | +44 (0) 1327 857500 | | • | • | | • | • | • | | • | | | | | • | | | | | | |
| Wimborne | AQL EMC Limited<br>www.aqlemc.co.uk | +44 (0) 1202 861175 | | | | • | | | | | | | | | | | | | | | | |
| Wimborne | Element<br>www.element.com | +44 1202 811700 | Contact lab for testing capabilities. | | | | | | | | | | | | | | | | | | | |

# OCEANIA

| CITY/COUNTRY | COMPANY NAME / WEBSITE | PHONE # | BELLCORE/TELCORDIA | CB/CAB/TCB CB/CAB/TCB | EMISSIONS | EMP/LIGHTNING EFFECTS | ESD | EURO CERTIFICATIONS | FCC PART 15 & 18 | FCC PART 68 | IMMUNITY | LIGHTNING STRIKE | MIL-STD 188/125 | MIL-STD 461 | NVLAP/A2LA APPROVED | PRODUCT SAFETY | RADHAZ TESTING | RS103 > 200 V/METER | REPAIR/CALIBRATION | RTCA DO-160 | SHIELDING EFFECTIVENESS | TEMPEST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AUSTRALIA** | | | | | | | | | | | | | | | | | | | | | | |
| Heidelberg West | TÜV Rheinland Australia Pty Ltd<br>www.tuv.com | +61 3 9458 3988 | | • | • | | • | • | • | | • | | | | | | | | | | | |
| Knoxfield | Compliance Engineering Pty Ltd<br>www.compeng.com.au | + 61 (3) 9763 3079 | | | • | | • | • | | | • | | | • | • | | • | • | • | • | • | |
| Melbourne | EMC Technologies Pty Ltd<br>www.emctech.com.au | +61 (3) 9365 1000 | | • | • | • | • | • | • | | • | • | • | • | • | • | • | • | • | • | • | • |
| Sydney | EMC Technologies Pty Ltd<br>www.emctech.com.au | +61 (3) 9365 1000 | | • | • | • | • | • | • | | • | • | • | • | • | • | • | | • | • | • | |
| Sydney | Austest Laboratories<br>www.austest.com.au | + 612 9624 2777 | | | • | | | | • | | • | | | • | | | | | | | | |
| Victoria | EMC Technologies<br>www.emctech.com.au | +61 (3) 9365 1000 | | | | | | | | | | | | • | | | | | • | | • | |
| **NEW ZEALAND** | | | | | | | | | | | | | | | | | | | | | | |
| Auckland | EMC Technologies<br>www.emctech.com.au | + 64 93600 862 | | | | | | | • | | | | | | | | | | | | • | |
| Christchurch | Braco Compliance Ltd<br>www.bracocompliance.com | +64 (2) 1208 4303 | | | • | | | | | | | | | | | | | | | | | |

# ADDITIONAL TEST LABS

FOR TEST CAPABILITIES, CONTACT LAB

| CITY/COUNTRY | COMPANY | PHONE# | WEB URL |
|---|---|---|---|
| **AUSTRIA** | | | |
| Seibersdorf | Seibersdorf Laboratories | +43 (0) 50550 2805 | www.ait.ac.at |
| **CHINA** | | | |
| Beijing | SGS-CSTC | +86 (0) 10 6845 6699 | www.sgs.com |
| Shanghai | SGS-CSTC | +86 (0) 21 6140 2666 | www.sgs.com |
| Shenzhen | MET Laboratories Inc. | +86 755 82911867 | www.metlabs.com |
| Tianjin | SGS-CSTC | +86 (0) 22 6528 8000 | www.sgs.com |
| **DENMARK** | | | |
| Horsholm | Delta EMC Services | +45 72 19 45 00 | www.madebydelta.com |
| **GERMANY** | | | |
| Essen | CETECOM GmbH (Germany) | +49 20 54 95 19 0 | www.cetecom.com |
| Hagen | HF-SHIELDING Joachim Broede GmbH | +49 54 05-99 99 04 | www.hf-shielding.de |
| Iserlohn | H+H High Voltage Technology GmbH | +49 2371 18530 | www.hundh-mk.com |
| Munich | National Technical Systems (NTS) | +49 89 787475 160 | www.nts.com |
| Neckartenzlingen | Hirschmann Car Communication GmbH | +49 7127 14 1437 | www.hirschmann-car.com |
| Siegen | EMC Testhaus Schreiber GmbH | +49 271 382702 | www.emc-testhaus.de |
| Straubing | EMV Testhaus GmbH | +49 9421 568680 | www.emv-testhaus.com |
| **ISRAEL** | | | |
| Lod | Israel Testing Laboratories | 972 8 9797799 | www.itl.co.il |
| **JAPAN** | | | |
| Watari | Cosmos Corporation | +81 596 63 0707 | www.cosmoscorp.com |
| Chiba | EMC Kashima Corporation | +81 478 82 0963 | www.emc-kashima.co.jp |
| Ise | Underwriters Laboratories Japan Inc. | +81 596 2 6717 | www.ul.com |
| Yokohama | Kikusui Electronics Corp. | +81 45 593 7570 | www.kikusui.co.jp |
| **NORWAY** | | | |
| Oslo | Nemko, Inc. | +47 229 60330 | www.nemko.com |

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- **Preliminary Full Paper Manuscript:** November 1, 2016 - January 16, 2017
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- **Final Paper Due:** May 3, 2017

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**To schedule, contact:**
Bob Scully - **bob.scully@ieee.org**
Sam Connor - **sconnor@ieee.org**

### Call for Abstract Reviewed Papers

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**Final Paper Due:** May 3, 2017

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**Proposals Accepted:** November 1, 2016 - December 20, 2016
**Notification of Acceptance:** January 8, 2017
**Preliminary Papers Due:** March 6, 2017
**Final Papers Due:** May 3, 2017

### Call for Workshops & Tutorials

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**Proposals Accepted:** November 1, 2016 - January 16, 2017
**Notification of Acceptance:** February 21, 2017
**Final Presentations Due:** May 3, 2017

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To schedule, contact:
Mark Maynard – **mmaynard@ieee.org**

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# Design & Test References

## USING DECIBELS

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- Power Gain = $P_{out}/P_{in}$
- Power Gain(dB) = $10\log(P_{out} / P_{in})$
- Voltage Gain(dB) = $20\log(V_{out}/V_{in})$
- Current Gain(dB) = $20\log(I_{out}/I_{in})$

We commonly work with…

- dBm (referenced to 1 mW)
- dBµV (referenced to 1 µV)
- dBµA (referenced to 1 µA)

### POWER RATIOS

3 dB = double (or half) the power
10 dB = 10X (or /10) the power

### VOLTAGE/CURRENT RATIOS

6 dB = double (or half) the voltage/current
20 dB - 10X (or /10) the voltage/current

## dBM, dBµV, dBµA (CONVERSION)

Log ↔ Linear Voltage

| | |
|---|---|
| Volts to dBV | $dBV = 20\log(V)$ |
| Volts to dBµV | $dB\mu V = 20\log(V) + 120$ |
| dBV to Volts | $V = 10^{(dBV/20)}$ |
| dBµV to Volts | $V = 10^{((dB\mu V-120)/20)}$ |
| dBV to dBµV | $dB\mu V = dBV + 120$ |
| dBµV to dBV | $dBV = dB\mu V - 120$ |

*Note: For current relationships, substitute A for V*

## LOG IDENTITIES:

If Y=log(X), then $X=10^Y$
Log 1 = 0
Log of numbers > 1 are positive
Log of numbers <1 are negative
The log (A*B) = log A + log B
The log (A/B) = log A – log B
The log of $A^n$ = n*log A

## dBm TO dBµV (ASSUMING A 50-Ohm SYSTEM)

| dBm | dBµV |
|---|---|
| 20 | 127 |
| 10 | 117 |
| 0 | 107 |
| -10 | 97 |
| -20 | 87 |
| -30 | 77 |
| -40 | 67 |
| -50 | 57 |
| -60 | 47 |
| -70 | 37 |
| -80 | 27 |
| -90 | 17 |
| -100 | 7 |

A common formula for converting spectrum analyzer amplitudes (dBm) to the limits as shown in the emissions standards (dBµV): To convert: dBm to dBµV, use: dBµV = dBm + 107

## POWER RATIOS (dB)

| UNIT | POWER | VOLTAGE OR CURRENT |
|---|---|---|
| 0.1 | -10 dB | -20 dB |
| 0.2 | -7.0 dB | -14.0 dB |
| 0.3 | -5.2 dB | -10.5 dB |
| 0.5 | -3.0 dB | -6.0 dB |
| 1 | 0 dB | 0 dB |
| 2 | 3.0 dB | 6.0 dB |
| 3 | 4.8 dB | 9.5 dB |
| 5 | 7.0 dB | 14.0 dB |
| 7 | 8.5 dB | 16.9 dB |
| 8 | 9.0 dB | 18.1 dB |
| 9 | 9.5 dB | 19.1 dB |
| 10 | 10 dB | 20 dB |
| 20 | 13.0 dB | 26.0 dB |
| 30 | 14.8 dB | 29.5 dB |
| 50 | 17.0 dB | 34.0 dB |
| 100 | 20 dB | 40 dB |
| 1,000 | 30 dB | 60 dB |
| 1,000,000 | 60 dB | 120 dB |

Double the value and it adds 3 dB to power, 6 dB to voltage and current. Halving the value subtracts 3 dB from power, 6 dB from voltage and current.

Multiplying 10X the value and it adds 10 dB to power, 20 dB to voltage and current. Dividing by 10X the value subtracts 10 dB from power, 20 dB from voltage and current.

## COMMONLY USED EQUATIONS

Ohms Law (formula wheel)

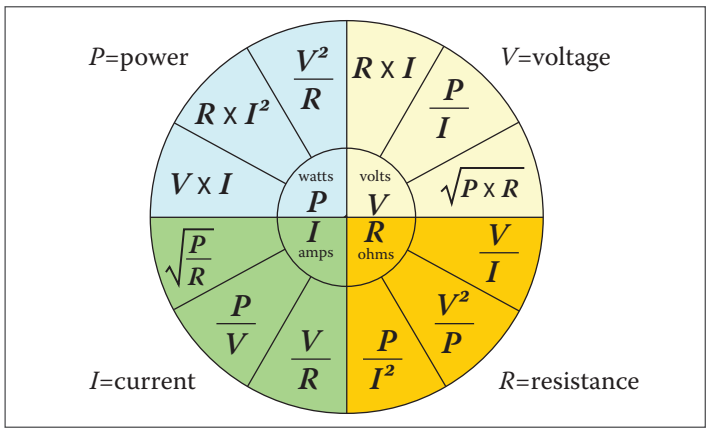


*Figure 1 – Ohms Law "formula wheel" for calculating resistance (R), voltage (V), current (I) or power (P), given at least two of the other values*

## VSWR AND RETURN LOSS

VSWR given forward/reverse power

$$VSWR = \frac{1 + \sqrt{\frac{P_{rev}}{P_{fwd}}}}{1 - \sqrt{\frac{P_{rev}}{P_{fwd}}}}$$

VSWR given reflection coefficient

$$VSWR = \frac{1 + r}{1 - r}$$

Reflection coefficient, ρ, given $Z_1$, $Z_2$ Ohms

$$r = \left| \frac{Z_1 - Z_2}{Z_1 + Z_2} \right|$$

Reflection coefficient, ρ, given fwd/rev power

$$r = \sqrt{\frac{P_{rev}}{P_{fwd}}}$$

Return Loss, given forward/reverse power

$$RL\ (dB) = 10 \log \left( \frac{P_{fwd}}{P_{rev}} \right)$$

Return Loss, given VSWR

$$RL\ (dB) = -20 \log \left( \frac{VSWR - 1}{VSWR + 1} \right)$$

Return Loss, given reflection coefficient

$$RL\ (dB) = -20 \log (\rho)$$

Mismatch Loss given forward/reverse power

$$ML\ (dB) = 10 \log \left( \frac{P_{fwd}}{P_{fwd} - P_{rev}} \right)$$

Mismatch Loss, given reflection coefficient

$$ML\ (dB) = -10 \log (1 - \rho^2)$$

## ANTENNA (FAR FIELD) RELATIONSHIPS

Gain, dBi to numeric

$$Gain_{numeric} = 10^{(dbi/10)}$$

Gain, numeric to dBi

$$dBi = 10 \log (Gain_{numeric})$$

Gain, dBi to Antenna Factor

$$AF = 20 \log (MHz) - dBi - 29.79$$

Antenna Factor to gain in dBi

$$dBi = 20 \log (MHz) - AF - 29.79$$

Field Strength given watts, numeric gain, distance in meters

$$V/m = \frac{\sqrt{30 * watts * Gain_{numeric}}}{meters}$$

Field Strength given watts, dBi gain, distance in meters

$$V/m = \frac{\sqrt{30 * watts * 10^{(dBi/10)}}}{meters}$$

Transmit power required, given desired V/m, antenna numeric gain, distance in meters

$$watts = \frac{(V/m * meters)^2}{30 * Gain_{numeric}}$$

Transmit power required, given desired V/m, antenna dBi gain, distance in meters

$$watts = \frac{(V/m * meters)^2}{30 * 10^{(dBi/10)}}$$

## EMC ORGANIZATIONS

- Automotive EMC – www.autoemc.net
- ESD Association – www.esd.org
- IEEE EMC Society – www.ewh.ieee.org/soc/emcs/
- iNARTE (International Association for Radio, Telecommunications and Electromagnetics) – http://www.narte.org

## EMC STANDARDS ORGANIZATIONS

- American National Standards Institute – www.ansi.org
- ANSI Accredited C63 – www.c63.org
- Asia Pacific Laboratory Accreditation Cooperation (APLAC) – www.aplac.org
- Canadian Standards Association (CSA) – www.csa.ca
- CISPR – http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1298,25
- Electromagnetic Compatibility Industry Association (UK) – http://www.emcia.org
- Federal Communications Commission (FCC) – www.fcc.gov
- IBIS (Input/Output Buffer Specification) – (www.eigroup.org) http://www.eigroup.org/ibis/default.html
- IEC – http://www.iec.ch/index.htm
- IEEE EMC Society Standards Development Committee (SDCOM) – http://standards.ieee.org/develop/project/electromagnetic_compatibility.html
- IEEE Standards Association – www.standards.ieee.org
- ISO (International Organization for Standards) – http://www.iso.org/iso/home.html
- SAE EMC Standards Committee – www.sae.org
- Society of Automotive Engineers (SAE) – http://www.sae.org/servlets/works/committeeHome.do?comtID=TEVEES17
- VCCI (Japan, Voluntary Control Council for Interference) – http://www.vcci.jp/vcci_e/

# 2016 EMC Supplier Quick Guide

**FOR 2016, WE HAVE CHANGED** the location of our full supplier directory from this print edition to our online directory at **buyersguide.interferencetechnology.com**-where information on products and contacts is now updated daily. In this section, we provide a quick guide to some of the top suppliers in each EMC category - test equipment, components, materials, services, and more. To find a product that meets your needs for applications, frequencies, standards requirements, etc., please search these individual supplier websites for the latest information and availability. If you have trouble finding a particular product or solution, email **geoff@item.media** for further supplier contacts.

## AMPLIFIERS

**AR RF / Microwave Instrumentation**
www.arworld.us
215-723-8181

**Advanced Test Equipment Rentals**
www.atecorp.com
800-404-2832

**HV Technologies**
www.hvtechnologies.com
703-365-2330

**R&K**
www.rk-microwave.com
+81-545-31-2600

**Rhode & Schwarz**
www.rohde-schwarz.com
Germany: +49 (0) 89 4129 12345
United States: 410-910-7800

## AMPLIFIERS (continued)

**Ophir**
http://www.ophirrf.com/index.php
310-306-5556

## ANTENNAS

**A.H. Systems, Inc.**
www.ahsystems.com
818-998-0233

**Advanced Test Equipment Rentals**
www.atecorp.com
800-404-2832

**AR-RF / Microwave Instrumentation**
www.arworld.us
215-723-8181

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United States: 410-910-7800

## CABLES & CONNECTORS

**Schurter**
www.schurter.com
707-636-3000

## CONSULTANTS

**Cherry Clough Consultants, Ltd.**
**Don Heirman Consultants**
**Henry Ott Consultants**
**Interference Technology**
**Leader Tech, Inc.**
**Montrose Compliance Services**
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www.astrodyneTDI.com
508-964-6300

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800-404-2832

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www.hvtechnologies.com
703-365-2330

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www.schurter.com
707-636-3000

## MEDIA

***Interference Technology***
www.interferencetechnology.com
484-688-0300

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**Parker Hannifin**
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**Spira**
http://www.spira-emi.com/
818-764-8222

**MVG**
www.mvg-world.com

## SOFTWARE

**CST of America, Inc.**
www.cst.com
508-665-4400

## SOFTWARE (continued)

**AR-RF / Microwave Instrumentation**
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## SEALANTS & ADHESIVES

**Master Bond**
www.masterbond.com
+1.201.343-8983

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**AMETEK Compliance Test Solutions**
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## TEST SYSTEMS (continued)

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**HV Technologies**
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703-365-2330

**Narda**
www.narda-sts.it
+39 0182 58641

**Rohde & Schwarz**
www.rohde-schwarz.com
Germany: +49 (0) 89 4129 12345
United States: 410-910-7800

## TESTING LABS

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**R&B Laboratory**
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