IN COMPLIANCE™

THE COMPLIANCE INFORMATION RESOURCE FOR ELECTRICAL ENGINEERS

THE 2021 ANNUAL REFERENCE GUIDE

A Compliance Handbook for Electrical and Electronics Engineers

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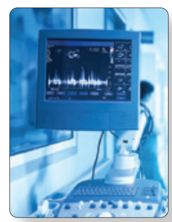

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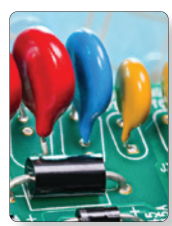

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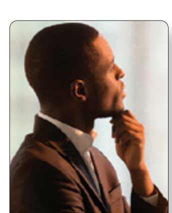

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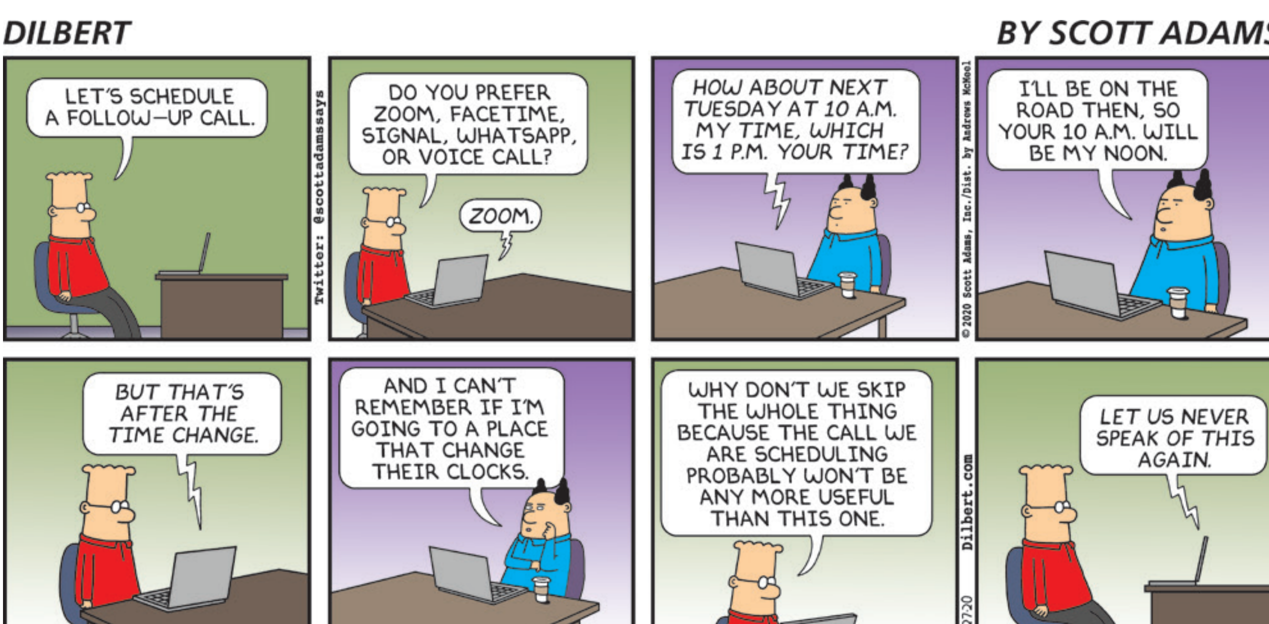

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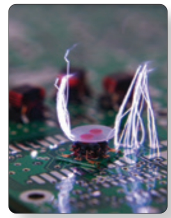

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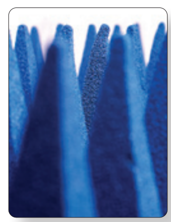

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A LETTER

From the Editor

Welcome to a new year and to the 2021 edition of *In Compliance Magazine's* Annual Reference Guide!

In so many ways, 2020 has been a year like none that any of us have ever experienced. From the earliest indications about the emergence of a potentially deadly virus in January and February, through the rapid, deadly spread of COVID-19 in major metro areas in the Spring and elsewhere in the country during the summer months, the lucky among us struggled to cope with the "new normal," balancing responsibilities at work and home and doing our best to chart a path forward in the face of continued uncertainty.

And the stress has been even greater for those working in the hardest hit sectors of our economy. Even now, too many people are waking up each day not knowing when or how they'll be able to make their rent or mortgage payments or put food on the table for their families.

Although we still have a long way to go, science and scientists have once again provided us with light at the end of the tunnel. The regulatory approval of innovative vaccines toward the end of the year, and the promise of additional vaccines in the pipeline, have given all of us hope that 2021 will be a year of healing and renewed economic certainty, and will provide us with the resilience to face new challenges along the way.

As we begin a new year, all of us here at *In Compliance Magazine* are eternally grateful to all our partners for their support in helping us and our publication survive and even thrive during 2020. Our readers continue to provide important guidance for our editorial coverage with their comments and suggestions. Our advertisers' financial support makes this adventure possible. And, lastly, our editorial contributors' commitment to sharing their knowledge and expertise in our pages makes *In Compliance Magazine* the trusted source for news and information in our field.

Our heartfelt thanks to all of you! And may only good things come your way in the year ahead!

Sincerely,

Bill von Achen

Features Editor

In Compliance Magazine

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Maximize Your RF Immunity

Now with the release of IEC-61000-4-3:2020 4th edition, multiple signals, or also commonly referred to as multi-tone, radiated immunity testing is an accepted test method. Using a multi-tone testing approach results in a significant decrease in test time due to the reduction in the number of dwell times required, as the EUT will be exposed to several test signals simultaneously.

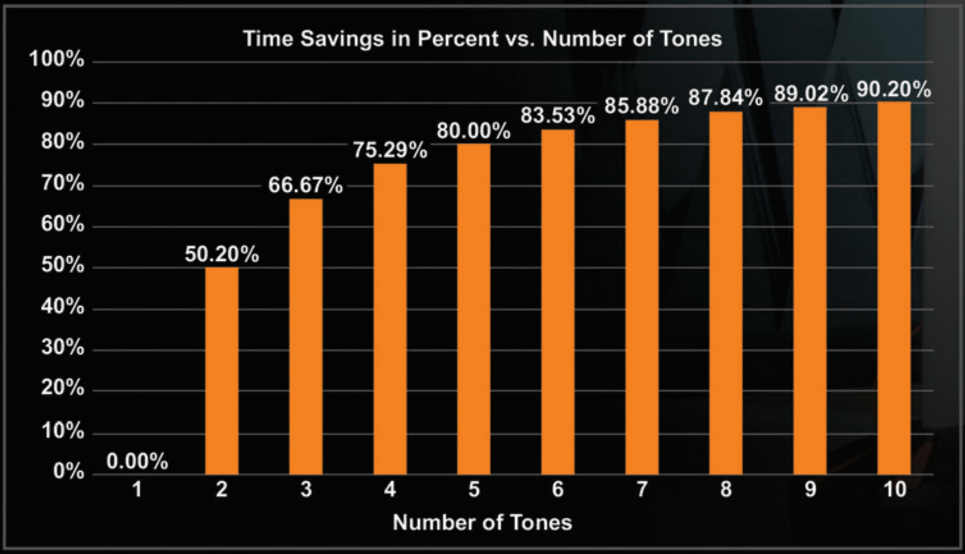
AR's MultiStar Multi-Tone Tester is perfect for performing multi-tone radiated immunity testing for commercial products and may also be used within the aviation, and automotive sectors. AR's Multi-Tone system's 10 kHz - 6 GHz frequency range, and 1 GHz instantaneous bandwidth, also allows for conducted immunity testing.

AR's proprietary software makes the most of its hardware use, offering users numerous test and calibration routines utilizing multi-tone methodology to meet these standards. The use of a PXI bus and vector signal transceiver not only allows for the generation of multiple signals, but an increase in system speed is gained through a much faster communication bus and signal processing. Additionally, the use of a PXI bus and AR's SC2000 system controller allows for seamless integration of all hardware and streamlined routing of all RF to and from the embedded vector signal transceiver and external RF amplifiers.

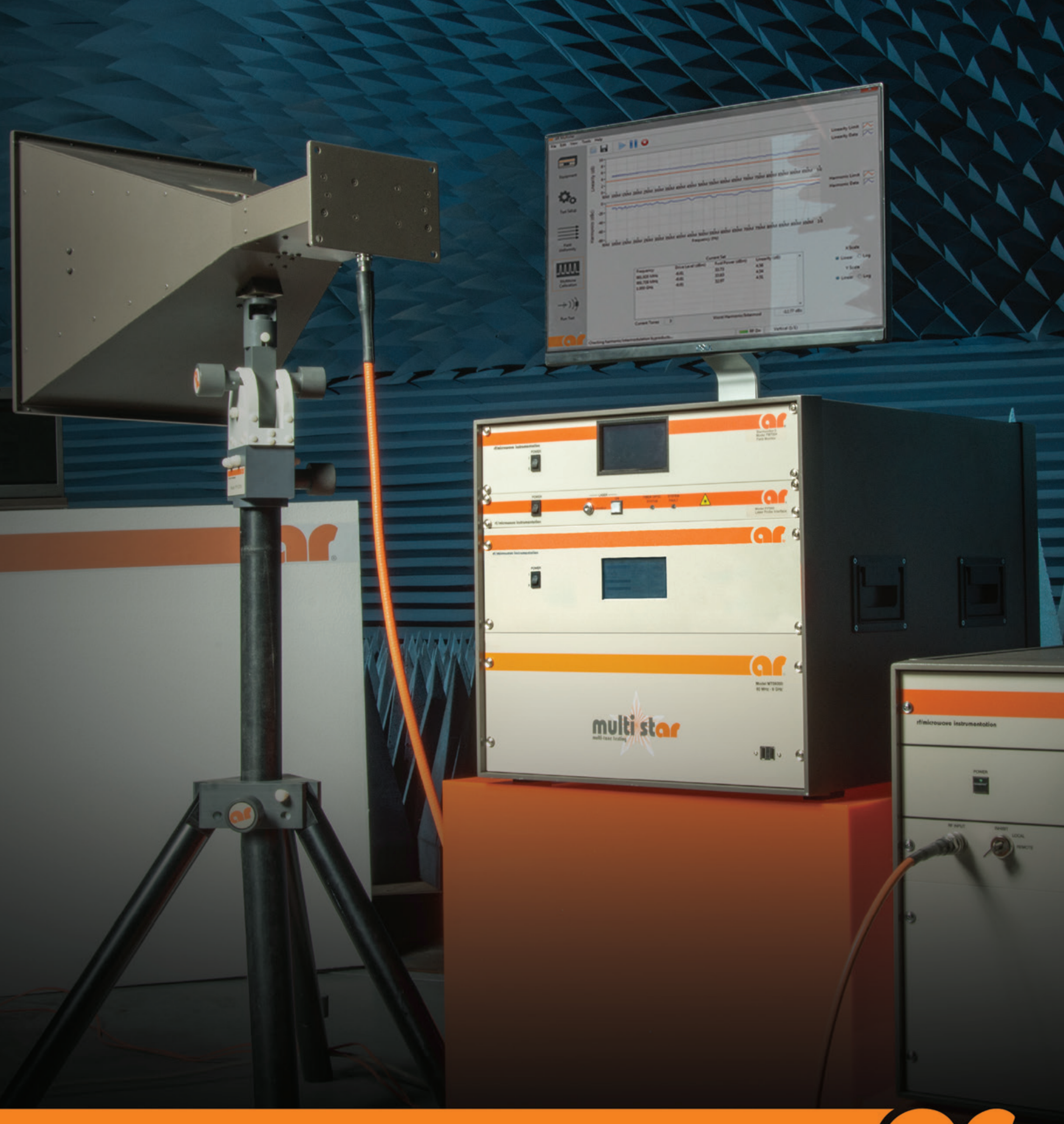
Each system may control up to four RF amplifiers, antennas, and directional couplers. In addition, up to four field probes can be monitored with the MT06002 M1 option. AR's Application Engineering department is here to help you size your amplifiers, antennas, and directional couplers based on your required field levels and testing needs.

Not only do Multi-tone systems significantly reduce test time, but in the event of an EUT failure, margin investigation (thresholding) and traditional single tone testing are easily performed through AR's software.

Visit us at www.arworld.us/MultiTone or call: 215-723-8181. For an applications engineer call: 800.933.8181.



Testing and Minimize Costs



A New Milestone in EMC Testing

TRY A MODAL EMI RECEIVER

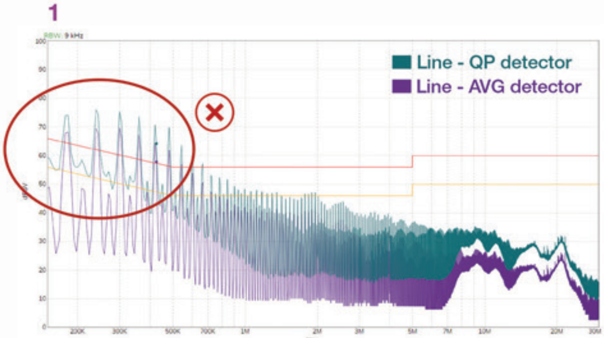
EMZER designs and develops breakthrough-enabling technology for electromagnetic interference measurements. Our instruments' advanced features help equipment manufacturers to effectively comply with the international EMC regulations, enhancing the overall quality and reliability of their products, reducing their development costs and time-to-market.

Our latest instrument, EMSCOPE, is a powerful and fast tool that performs full-band real-time EMI and modal measurements simultaneously using peak, quasi-peak, and average detectors. Obtaining instantaneous measurements of common and differential mode emissions allows R&D engineers to find the modal-dominant interference, and thus, to simply design the optimal power-line filter.

THE STRAIGHT PATH TO COMPLIANCE

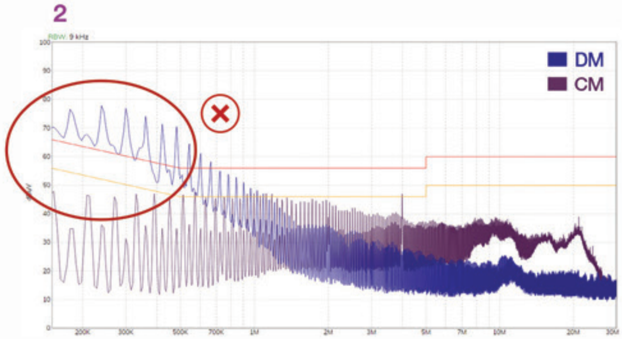
Using EMSCOPE Modal EMI receiver to reduce conducted emissions:

1



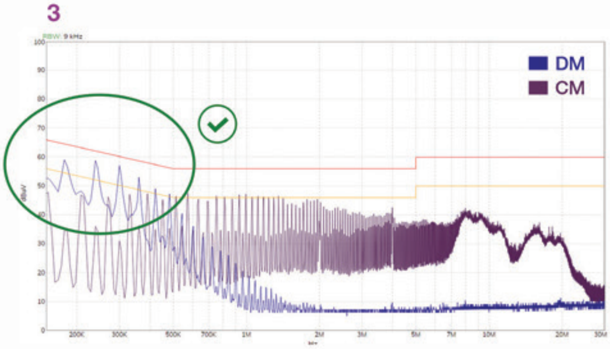
EMSCOPE is used to perform fully-compliant EMC testing. Example: the equipment under test fails the test; emissions are above the limits.

2



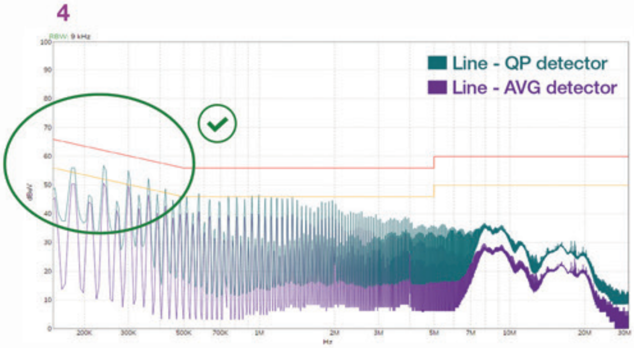
NEW APPROACH: the EMSCOPE modal receiver is used to decompose the noise in common mode (CM) and differential mode (DM); in this example DM is the cause of non-compliance. Once the predominant noise is detected, it is easy to improve your power line filter.

3



Following the results in step 2, simply adding the necessary filter components will reduce the noise (DM in this case). Using the real-time EMSCOPE receiver capabilities, engineers can easily design the minimum filter components required, hence reducing test time, product costs and also PCB space.

4



Last step: once the modal noise is filtered, the EMC conducted emissions test can be repeated to check compliance.

Visit us, follow us, watch us, and connect with us at:

FAST TRACK TO THE FUTURE OF EMC COMPLIANCE

The future is here! With the increasingly sophisticated technology in our homes and industry, as evident in modern personal electronics, mobile devices, medical equipment, and automobiles, the potential for electromagnetic interference is significant. In the case of automotive technology, where cars are now essentially computers on wheels with varying degrees of automated control and "infotainment" capabilities, testing of these emerging technologies to ensure safety and reliability has never been more important – or challenging. ETS-Lindgren, with decades of experience in compliance testing and measurement, boldly addresses the future of EMC performance – Beyond Measure.

As an international manufacturer of market-leading components and systems that measure, shield, and control electromagnetic and acoustic energy, ETS-Lindgren empowers some of the biggest industry names, and latest technological advances, to anticipate and meet global compliance standards. From chambers to test cells, absorbers, positioners, antennas, and software, ETS-Lindgren's EMC solutions are designed for repeatability, diversity, scale, and precision.

More importantly, through our ability to provide turnkey systems, create real-world test scenarios, troubleshoot potential failures, and maximize the chance of passing standards within the allotted time and budget, we help our customers bring life-changing products to market – faster.

To view our accreditations and case studies, visit our website at ets-lindgren.com.

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EXODUS ADVANCED COMMUNICATIONS
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The Company's Products

Exodus Advanced Communications, "Exodus" is a "Best-in-Class" SSPA manufacturer delivering products from 10kHz-51GHz. The company's extremely ruggedized product line consists of LDMOS, GaN (HEMT) and GaAs devices where the company manufactures significant quantities of their own devices. The company uses clean rooms for manufacturing and the latest advancements in technology designing and fabricating low, medium and high-power amplifiers with chip and wire technology. The company has a very wide range of stand-alone modules, integrated amplifier chassis configurations, and full turn-key systems as needed to satisfy customers specific applications.

About the Company

Exodus is a multinational RF communication equipment and engineering company serving commercial and government entities and their affiliates worldwide. Headquartered in Las Vegas, Nevada, the company utilizes its global network of sales and service partners to effectively support extensive wide ranges of customer applications and requirements.

Technical/Market Experience

Exodus is providing customers more than 100 Years of technical product, market and management experience with the broad knowledge of our management team.

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- HF, VHF, UHF, Power, Microwave, Millimeter
- Ultra-Broadband models
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Würth Elektronik eiSos: more than you expect

Würth Elektronik eiSos GmbH & Co. KG is a manufacturer of electronic and electromechanical components for the electronics industry. The company currently employs 7,250 people and is active in 50 countries. Production sites in Europe, Asia, and North America supply a growing number of customers worldwide. Würth Elektronik eiSos is part of the Würth Group, the world market leader for assembly and fastening technology.

The Würth Elektronik eiSos product range covers EMC components, inductors, transformers, RF components, varistors, capacitors, resistors, quartz crystals, oscillators, power modules, Wireless Power Transfer, LEDs, sensors, connectors, power supply elements, switches, push-buttons, connection technology, fuse holders, and solutions for wireless data transmission.

As one of the largest European manufacturers of passive components, Würth Elektronik eiSos sets itself apart from other component manufacturers in the following ways:

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- #askLorandt tutorials for electronic design support
- Reference designs of leading IC manufacturers
- EMC test lab racks and design kits with lifelong refill

Further Added Values

- Online platform REDEXPERT for simple component selection and performance simulation
- Toolbox: Search & Software Tools for engineers and developers
- Design seminars and webinars free of charge
- EMC Test lab search engine

In addition to that, Würth Elektronik eiSos supplies engineers with expertise: The “Trilogy of Magnetics,” “ABC of Capacitors,” “Trilogy of Connectors,” and “Simulation in LTsice IV” application manuals provide professionals and other interested parties with a compendium of practice-oriented expertise, which is unique of its kind.

Würth Elektronik: more than you expect!

WÜRTH ELEKTRONIK

EMC RESONANCE
PART II: DECOUPLING CAPACITORS

By Bogdan Adamczyk

In Part I [1] the concept of resonance was introduced and applied to the circuit models of the non-ideal passive components. In Part II the resonance phenomenon is explained using several common decoupling capacitor configurations. Simulation results are compared to the measurement results for different decoupling approaches.

1. DECOUPLING CAPACITOR AND AN RLC RESONANT STRUCTURE

In [1] it was shown that a capacitor itself is an *RLC* resonant structure, with the input impedance curve similar to the one shown in Figure 1.

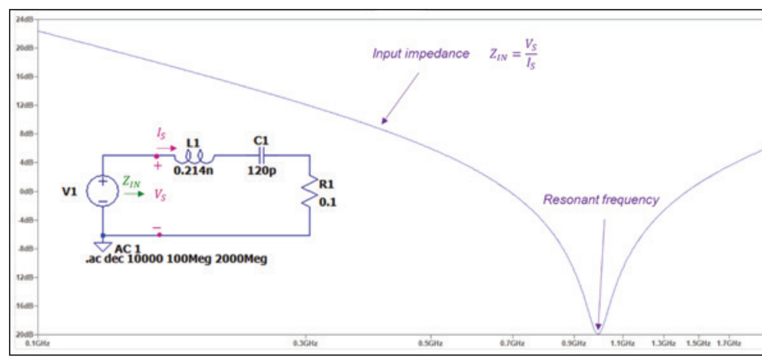

Figure 1: Input impedance curve of a *120 pF* capacitor with a parasitic inductance of *0.214 nH*

The plot shown in Figure 1 corresponds to a *120 pF* capacitor with an internal parasitic capacitance of *0.214 nH*. When a decoupling capacitor is placed on a PCB, an additional parasitic inductance coming from the PCB trace itself needs to be added to the circuit model.

To account for the inductance of a short PCB trace let's increase the parasitic inductance in the circuit of Figure 1 to 2.*4 nH* and study the resonance for different combinations of capacitor values, each with the parasitic inductance of 2.*4 nH*, and parasitic resistance of *0.1 Ω*.

We begin by comparing the input impedance of a single *1 nF* capacitor vs. the impedance of multiple capacitors of the same value.

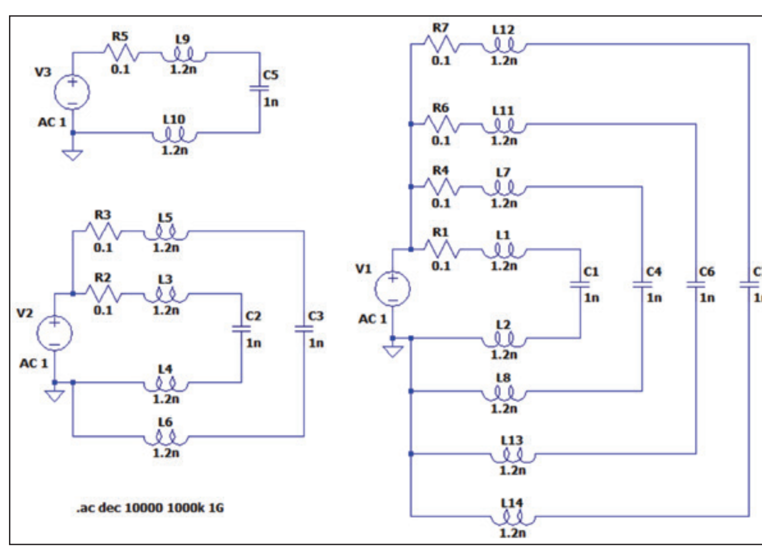

Figure 2: Single *1 nF* capacitor vs. multiple *1 nF* capacitors

Dr. Bogdan Adamczyk is professor and director of the EMC Center at Grand Valley State University (http://www.gvsu.edu/emccenter) where he regularly teaches EMC certificate courses for industry. He is an iNARTE certified EMC Master Design Engineer. Prof. Adamczyk is the author of the textbook "Foundations of Electromagnetic Compatibility with Practical Applications" (Wiley, 2017) and the upcoming textbook "Principles of Electromagnetic Compatibility with Laboratory Exercises" (Wiley 2022). He can be reached at adamczyb@gvsu.edu.

2. RESONANCE - SINGLE CAPACITOR VS. MULTIPLE CAPACITORS OF THE SAME VALUE

Consider a network consisting of a *1 nF* capacitor with a circuit parasitic inductance of *2.4 nH*, and a parasitic resistance of *0.1 Ω*. Let's look at the impedance curves of three different networks: single *1 nF* capacitor, two *1 nF* capacitors, and four *1 nF* capacitors, shown in Figure 2.

The impedance curves for these networks are shown in Figure 3.

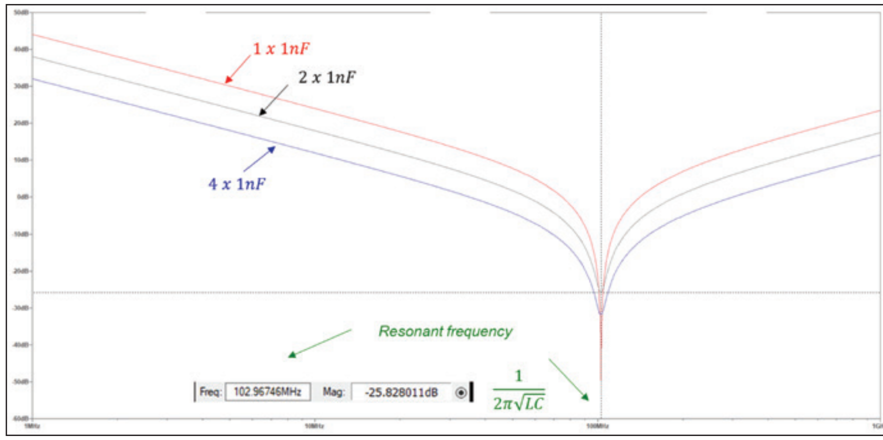

Figure 3: Impedance simulation results - capacitors of the same value

The resonant frequency of the series *RLC* circuit is given by [1]:

$$f_r = f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(2.4\times10^{-9})(1\times10^{-9})}} = 102.73\ MHz \quad (1)$$

and is consistent with the value shown in Figure 3. *L* and *C* in Eq. (1) are the total inductances and capacitances, respectively. These values do not change for different configurations of Figure 2 since, at resonance, the capacitor networks are connected in parallel. The total parallel capacitance, C_{par}, and the total parallel inductance, L_{par}, (assuming that the mutual inductances are negligible [2]) are given by

$$C_{par} = nC,\ L_{par} = \frac{L}{n} \quad (2a)$$

where *n* is the number of capacitors. And thus

$$C_{par} \times L_{par} = LC \quad (2b)$$

The impedance value at resonance does not stay constant and is equal to

$$Z(f_r) = R_{total} = \frac{R}{n} \quad (3)$$

In [3] we measured the impedance of four-layer PCBs populated with one *1 nF*, *two 1 nF* and four *1 nF* capacitors.

Figure 4 shows the impedance curves for the case of a single *1 nF* capacitor vs. two *1 nF* capacitors, while Figure 5. Compares two *1 nF* capacitors vs. four *1 nF* capacitors.

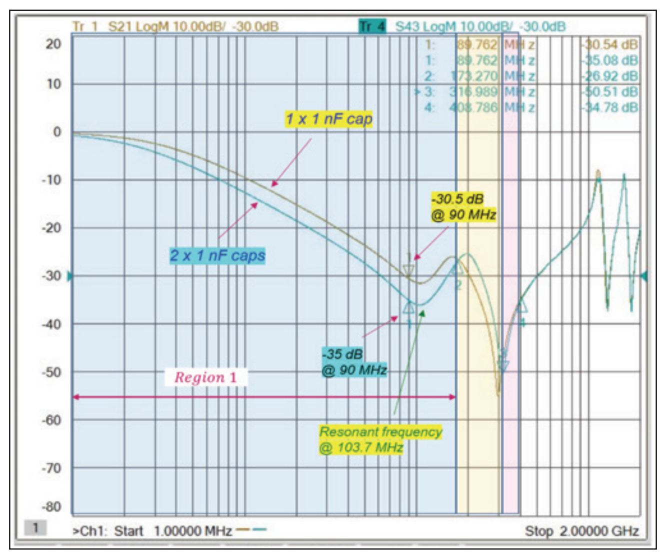

Figure 4: Impedance measurement - single *1 nF* vs. two *1 nF* capacitors

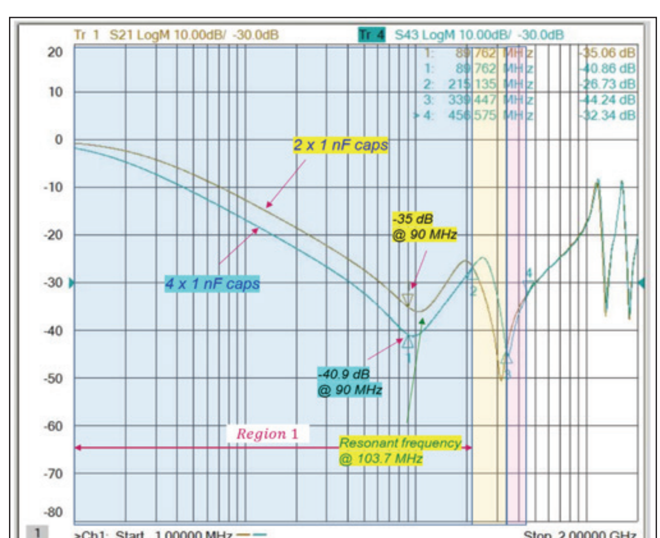

Figure 5: Impedance measurement - two *1 nF* vs. four *1 nF* capacitors

Note that, in Region 1, the measurement results, shown in Figures 4 and 5, are consistent with the simulation results of Figure 3.

3. RESONANCE - TWO CAPACITORS WITH VALUES DECADES APART

Next, consider a network with two capacitors, with their values either one or two decades apart, as shown in Figure 6.

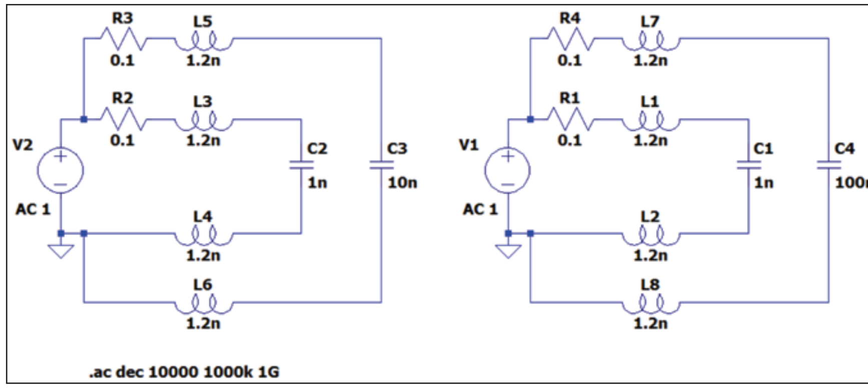

Figure 6: Two capacitors decades apart

The impedance curves for these networks are shown in Figure 7.

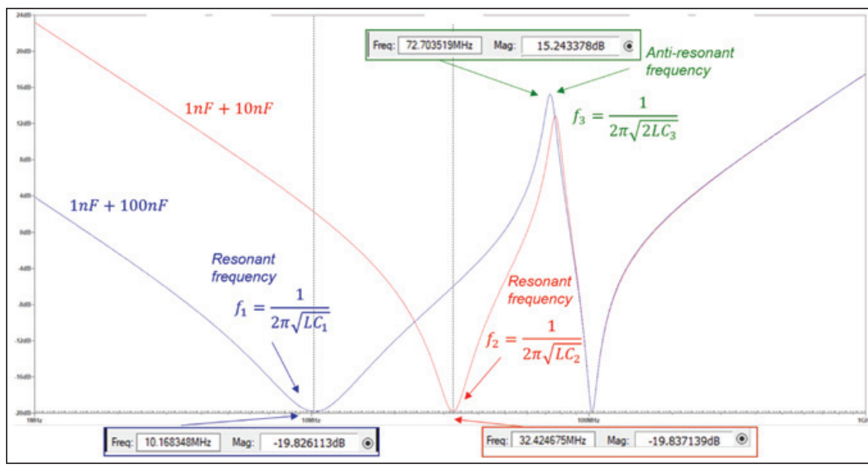

Figure 7: Impedance curves – two capacitors decades apart

Let $C_1 = 100\ nF$, $C_2 = 10\ nF$, $C_3 = 1\ nF$. Under the condition $C_1 << C_3$, the first resonant frequency is approximately [4],

$$f_1 = \frac{1}{2\pi\sqrt{LC_1}} = \frac{1}{2\pi\sqrt{(2.4\times10^{-9})(100\times10^{-9})}} = 10.27\ MHz \tag{4}$$

while under the condition $C_2 << C_3$, the second resonant frequency is approximately

$$f_2 = \frac{1}{2\pi\sqrt{LC_2}} = \frac{1}{2\pi\sqrt{(2.4\times10^{-9})(10\times10^{-9})}} = 32.48\ MHz \tag{5}$$

The anti-resonant frequency can be approximated from

$$f_3 = \frac{1}{2\pi\sqrt{2LC_3}} = \frac{1}{2\pi\sqrt{2(2.4\times10^{-9})(1\times10^{-9})}} = 72.64\ MHz \tag{6}$$

Note that these calculated resonant frequencies are consistent with the simulation results in Figure 7. Next, let's compare these results with the measured values, shown in Figure 8.

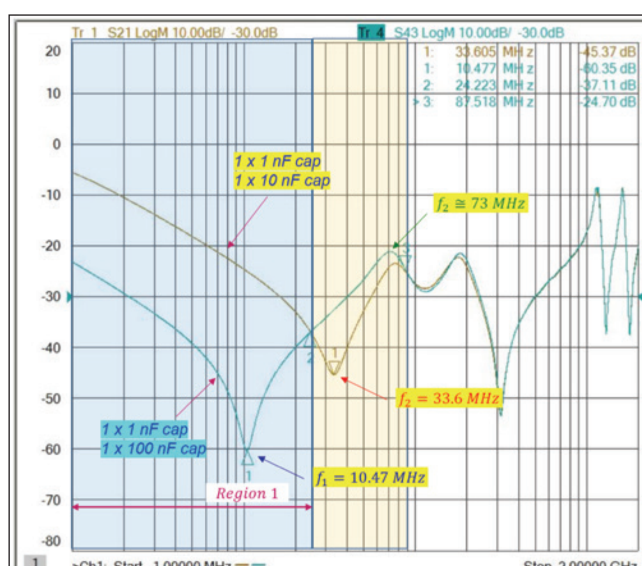

Figure 8: Impedance measurement – capacitors decade apart

Again, the measured resonant frequencies are consistent with the analytical and simulation results.

4. RESONANCE - THREE CAPACITORS WITH VALUES DECADES APART

Finally, let's consider a network with three capacitors decades apart and compare their impact against four capacitors of the same value, as shown in Figure 9.

The impedance curves for these networks are shown in Figure 10.

Note that now we have three resonant frequencies and two anti-resonant frequencies. Next, let's compare these results with the measured values, shown in Figure 11.

Note that the measured resonant frequencies are consistent with the calculated and simulated values. Also, the measured anti-resonant frequencies agree with the predicted simulated values.

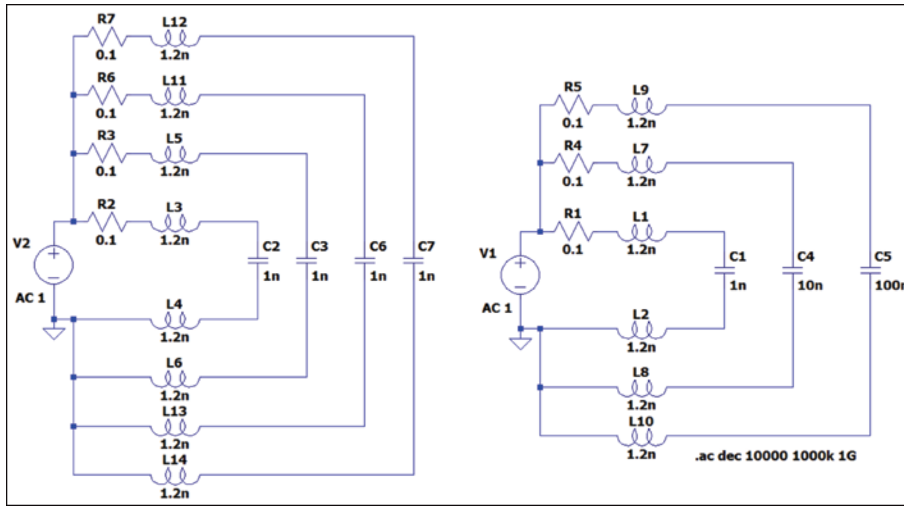

Figure 9: Three capacitors decades apart vs. four capacitors of the same values

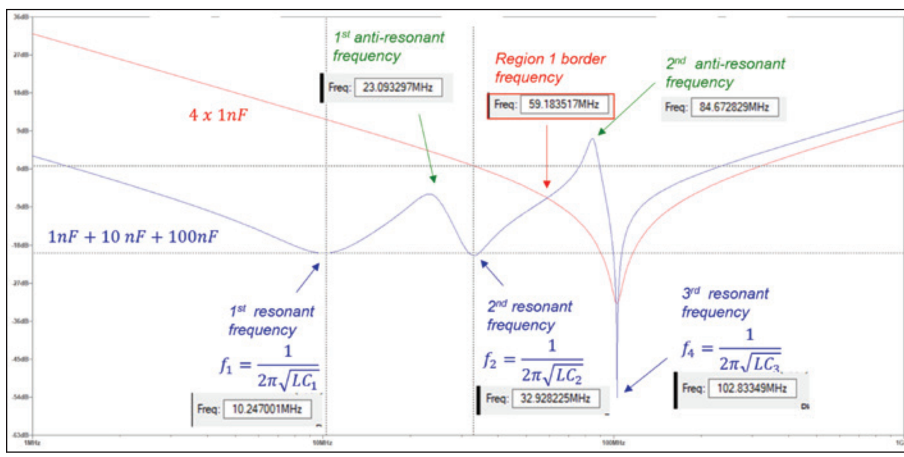

Figure 10: Impedance curves – three capacitors decades apart

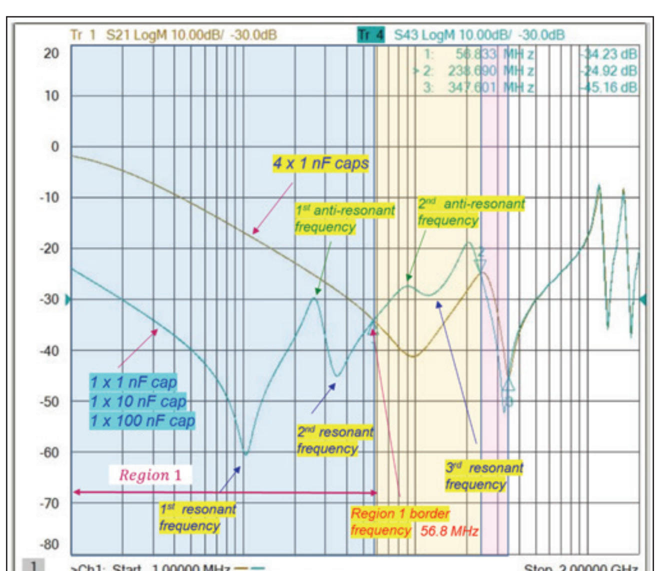

Figure 11: Impedance measurement – three capacitors decade apart

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EVOLUTION OF CHARGED DEVICE MODEL ESD TARGET REQUIREMENTS

By Charvaka Duvvury and Alan Righter for EOS/ESD Association, Inc.

HISTORICAL BACKGROUND

CDM is an important model for ESD qualification. The well-known CDM refers to the discharge of an IC package to a grounded surface, whether from automatic handlers in a production area or from when placing IC packages in empty sockets. However, it is strange that during the early years of ESD focus, CDM had not been either addressed as a big threat in a more urgent manner or even if considered, was always a step-sister for the HBM focus. It is not that there was not much recognition of the potentially serious issues for CDM threat.

It was in 1974 that Thomas Speakman that first mentioned, “CDM is as important as HBM” [1]. Also, credit should be given to Bossard et al. for first reporting about triboelectrically charged pins [2]. Then during the mid-1980s, workers from British Telecom performed the first experiments on the field-induced CDM threat [3]. This was quickly followed by the work of Siemens, where they demonstrated evidence of DRAM devices failing due to uncontrolled CDM in a production area. These events motivated the serious work on a CDM simulator [4] and Field-Induced CDM test methods. Thereafter, the focus on CDM rapidly increased, and IC protection methods to counter CDM started to develop. The factory control methods for CDM were also established where additional steps of controlling insulators, avoiding hard discharges, and controlling changed boards and devices are more than safe for 500 V CDM and even for 250 V CDM [5].

REALISTIC CDM TARGETS

The requirements for CDM target levels initially were set from customers, with no manufacturing or customer data to support them; levels of 750 and 1000V became commonplace and with some customers, mandatory. As applications for IC devices started advancing and the high-speed IO pins became part of the microprocessor technology, the 500 V CDM became increasingly difficult to achieve in design. As these challenges for 500 V CDM started increasing, which also incidentally affected the perennial 2 kV HBM requirement, the Industry Council performed exhaustive studies of shipped devices to the field at various passing levels of HBM or CDM and found no correlation to field returns with rates of <1 DPM [5,6]. As a result, 1 kV for HBM and 250 V CDM were deemed safe for all practical design considerations. Manufacturing ESD control methods for CDM target levels for manufacturing/assembly areas were detailed in [5].

HIGH-SPEED IO REQUIREMENTS AND CHALLENGES FOR CDM

Starting around the late 1990s, the concern for CDM target level started becoming an issue as the higher speed IO applications increasingly could not meet the expected CDM levels. The problem came from the introduction of microprocessors that were built in very advanced silicon technologies, with their IO applications demanding high data rates. At the same time, these processors were packaged in large BGA packages to accommodate the

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high density of designs with numerous high-speed IO pins on the IC package. The combined effects place severe restrictions on the achievable CDM targets. That is, advanced scaled technologies lead to lower breakdown voltages for the transistors, and at the same time, larger IC package sizes lead to higher CDM peak current for the same CDM stress voltage. These BGA package sizes have since increased from about 1000 pins as the largest device during early 2000 to now approaching nearly 6000 pins in 2020. At 500 V CDM, the capacitance from these packages can develop enough charge in a CDM charging event to result in peak CDM discharge currents from 6 Amps to nearly 14 Amps. On the other hand, the loading capacitance from the I/O pin ESD devices has to be reduced to achieve high data rates, necessary for high-speed serial (HSS) link designs. With the ensuing requirements of smaller diode sizes that are more resistive, combined with lower oxide breakdown voltages in 22 nm and beyond, the CDM passing voltage level rapidly tends to decrease for even higher data rate designs. Eventually, for data rates approaching 224 Gb/s, the loading capacitance is limited to < 50fF, forcing expected CDM designs to meet only 125V. This overall effect is shown below in Figure 1 along with corresponding to the technology nodes for these respective data rates.

THE CHANNING ROADMAP

As presented so far, the roadmap for CDM has constantly changed based on demands for adjustments to accommodate high-speed IO performance, compounded by restrictive process technology limitations and the use of larger IC package devices. This gradual reduction in practical target levels for CDM can be understood first from Figure 2 and then followed by Figure 3 on page 35. Starting from the first specified CDM targets of 1000 V during 1990, the targets reduced to 500 V as technology advanced to 90 nm nodes (the late 1990s), and eventually, this was recommended to be reduced to 250 V starting at 45 nm nodes. This last step took coordinated studies from the Industry Council to prove that with the basic manufacturing ESD controls this 250V level is safe and can allow high-speed designs [5]. During the year 2009, the Council also anticipated that these levels may need to be reduced to 125 V starting at 22 nm and lower technologies, as also indicated in Figure 2.

However, the reality of maintaining CDM sensitivity continued to be important even at 22 nm nodes, although the protections designs were beginning to face constrictions from lower breakdown voltages from the IO transistors. But this started changing around the year 2020 that ultra-high-speed interface designs at 5 nm and 7 nm FINFet technologies cannot meet 250 V CDM and that this has to be reduced to 125 V for these particular applications. This is indicated in Figure 3. To meet 112 Gb/Sec and higher, this lowering is mandatory, as indicated by the red arrow in Figure 3. But it must be mentioned that even at these advanced technology nodes, 250 V is still achievable for IOs known as General Purpose IO (or GPIO). That is, 125 V CDM is recommended only for ultra-high-speed interfaces. This is indicated in the update of [5], which is currently under preparation and will be released during 2021.

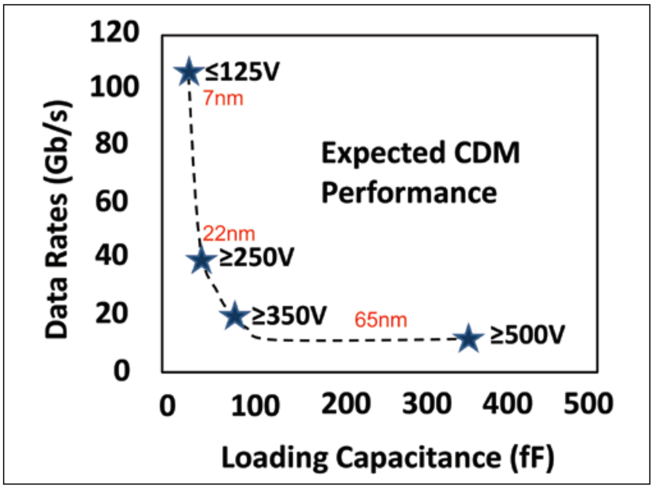

Figure 1: Achievable data rates versus loading capacitance from the ESD protection design as a function of advanced technology nodes in CMOS.

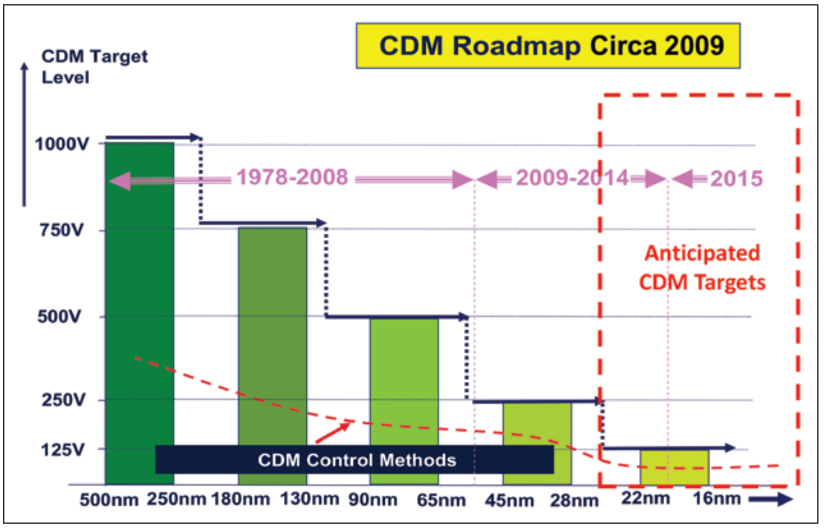

Figure 2: Projected CDM Roadmap during 2009.

With the above-forecasted CDM target level reductions, it becomes very important to implement both improved manufacturing ESD control and ESD measurement methods as well as implement more reliable and accurate CDM measurement methods. There has been an extensive effort to address the manufacturing ESD control methods and process ESD measurements to be commensurate with the expected lower CDM target levels. The details of these methods to more safely protect sensitive CDM devices will be addressed later in a separate article. The CDM test measurement issues are discussed in the next section.

CDM TEST IMPLICATIONS FOR ACCURATE STRESSING OF LARGE PACKAGE HIGH-FREQUENCY PINS

The reduced CDM passing levels of ICs below 250V (which are limited from the combination of large IC packages and high-frequency IC pins) must be measured accurately. ANSI/ESDA/JEDEC JS-002, published in 2015 by the EOS/ESD Association (ESDA) and updated in 2018 [7], is the most widely used field-induced CDM standard in the industry. It provides an extensive JEDEC CDM verification module waveform verification process combined with field-induced CDM tester hardware specification improvements, resulting in an improved accuracy test spanning over the CDM test range from 250 to 1000V. However, the inherent physical limitations of the air spark discharge, pogo pin alignment, and humidity result in increasing variation of peak current measurements at the lower charge voltages below 200V. In [8], Jack showed that the variation as a percentage of the mean increases significantly for pre-charge voltages below 200V (Figure 4).

In the field-induced CDM voltage range between 125 and 250V, this results in variations of more than +/- 50V, which greatly reduces the confidence of determining accurate CDM passing levels in the range between 125 and 250V. For example, single discharge testing between 200 and 250V often shows peak current waveform variability where one cannot tell the test voltage difference just from the waveform.

Fortunately, there are other CDM test methods in development that promise to deliver more reliable CDM test results. ANSI/ESDA/JEDEC SP5.3.3, Low Impedance Contact CDM [9] was published in 2018, which describes a contact-based method implementation of approximating the spark resistance of the field-induced method while eliminating the dependence on humidity. It has been shown to deliver repeatable, reproducible results in the 125V range and below (to 50V). Currently, the ESDA is conducting a worldwide multisite round-robin evaluation, a requirement

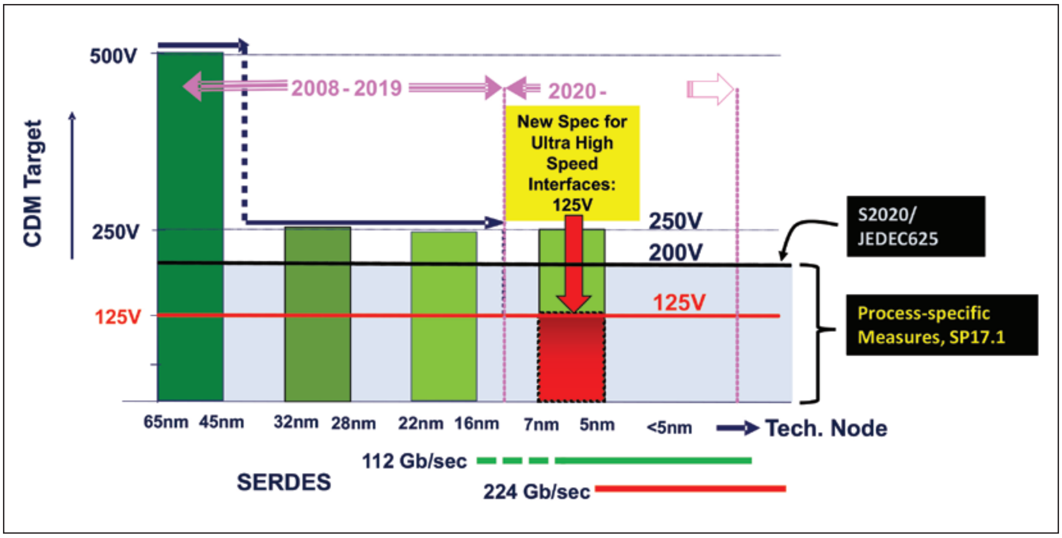

Figure 3: Realistic CDM Roadmap as a function of immediate and future technology nodes.

leading to a path to a standard test method document -> inclusion as a full CDM test standard in the next 1-2 years.

Capacitively-coupled TLP (CC-TLP) [10] is another complementary method of contact mode stressing, delivering charging followed by similar CDM-like discharging, which has also been shown to be repeatable and reproducible with no dependence on humidity. A CC-TLP standard practice document is currently in review by the ESDA with a later 2021 release.

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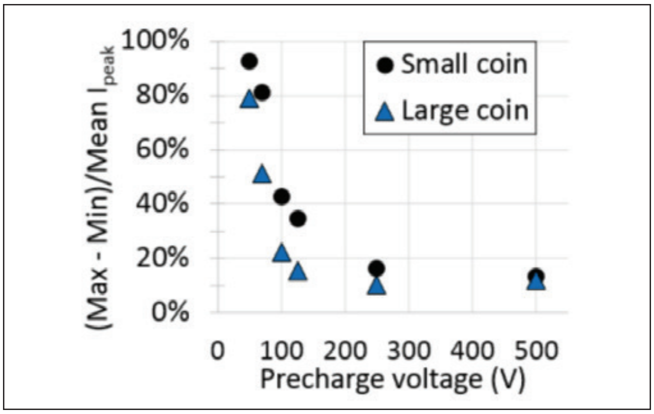


Figure 4 (Jack, et al. [Jack 2015]): Ipeak maximum-minimum (top) and the standard deviation (bottom) of 50 zaps to JS-002 calibration coins as a percentage of the mean; 26% relative humidity. Data was taken on an Orion2 FICDM system using an 8 GHz oscilloscope.

Banana Skins

322 Domestic switching transients interfere significantly with some DAB radio receivers

Browsing through *EMC & Compliance Journal* today I am reminded of a very obvious form of RFI generated at home. We are all aware of TVs and radios being affected by vacuum cleaners, food mixers, mobile phones, and the like (and some cars, but far fewer these days), but a more specific form of interference has exhibited itself ever since I was given a DAB radio for Xmas by my better half.

When switching low-energy bulbs on or off in the vicinity of the radio (but as far as 5m away) reception is, as often as not, completely halted for a second or so, a much more 'catastrophic' event than the usual crackle from conventional AM/FM radios. Such is the price of progress!

(Sent in by Dave Bethell, Principal Engineer, Anthony Best Dynamics Ltd, 12th January 2005.)

323 Self-inflicted EMC problems in the military

Banana Skin number 6 refers to EMC problems during Desert Shield and Desert Storm. EMC problems can be self-inflicted; I remember seeing a radio listener's report on a USENET forum that tactical inter-plane chatter was heard in the US on the US Navy UHF satellite outputs, apparently from aircraft in the initial attack waves of Desert Storm. This seems to have been due to frequency coordinators unknowingly assigning attack frequencies in the satellite uplink range.

(Sent in by Cortland Richmond, KA5S, May 21, 2005.)

324 Small brushless DC motor interferes with microwave comms link

We had a receiver noise problem with a 'C' Band SNG van when the dish was pointing near the horizon (over the air con unit). We were getting random loss of signal (broadcasters NOT happy!). Investigation (with a spectrum analyser probe near the motor body) revealed that the (DC brushless) fan for the air-con unit was radiating a strong comb spectrum from the 150KHz-ish of it's SMPSU up to over 6GHz and a reduced level was still detectable at 14GHz! It seems that the (CE marked!) motor of Italian manufacture (used extensively for vehicle radiator cooling as well as in air-con units) recently had it's die-cast motor end plate changed to a plastic moulding (plus perhaps newer faster switching transistors?). The un-shielded motor/electronics was therefore radiating quite strongly.

Our solution was to fit a metal disc/plate over the motor hub (a screen between the source and our 1.2M dish antenna). This effected about a 20dB improvement and enabled the system to work as intended (signal now above rather than below the interference!). I suspect that if any EMC testing was performed, the type of product would suggest that only conducted and power clamp measurements should be performed and NO radiated emissions (certainly not above 1GHz). After all a DC motor cannot cause many problems can it????

Unfortunately it seems even small low power internal air circulating fans of the brushless DC type produce quite heavy conducted and some radiated RF. Some of our products have had problems with fan EMC within a unit. We now, as a matter of course tightly twist the wires and sometimes add a common mode choke to the fan feed to avoid noise on the 5V, or 12V rails corrupting signals and data within our broadcast encoders etc.

(Sent in by Dave Keston, Approvals Engineer, Vislink Communications, 20th January 2005.)

325 TV antenna boosters the cause of interference from new radio service

The new emergency services radio system, called Airwave, has been blamed for interfering with television reception, but where problems occur the fault lies with the filters on domestic aerial amplifiers. Trade and Industry minister Steven Timms, in a Parliamentary written answer, said: "Ofcom is aware of instances of interference to domestic installations from Airwave radio base stations. In all the instances so far investigated the consumer's own masthead aerial amplifier, used to boost weak signals, has had a pass-band wide enough to boost the television signal and, inadvertently, the unwanted radiocommunications signal."

Airwave is being rolled out across the Great Britain for police and public safety communications, with completion due by 2005, when existing frequencies will be withdrawn. It is a digital system based on the ETSI-approved Tetra (Terrestrial Trunked Radio) standard. Mr Timms went on: "Testing has shown that the Tetra transmitters were operating correctly and within their designated licence parameters. In most cases a suitable filter fitted between the masthead amplifier and the TV aerial will resolve the interference, and affected residents have been advised to have such filters fitted. As a goodwill gesture Airwave has arranged for filters to be fitted to the affected television installations in certain circumstances."

("Aerial amplifiers cause Tetra TV interference", from 'EMC Industry News 2004-01-15' on the IEE's EMC Professional Network website, 18th January 2004, https://www.theiet.org.)

326 Mobile phones interfere with railway signalling and ticketing

In south Jutland, the Danish state railways, DSB, have forbidden mobile phones on all marshalling yards in the district. The reason is that GSM telephones have caused the signal system to switch from green to red, and have also caused interference in the ticketing system used.

(Sent in by John Whaley, 16th May 2005)

327 Wi-Fi hotspots interfere with military radars

Northwest Florida Daily News reported that Air Force officials say high speed and wireless internet connections are interfering with their tracking radar at Eglin Air Force Base, Fla. The radar is a vital tracking tool for high-tech weapons over the Gulf of Mexico. They notified Okaloosa County officials, who responded by warning that if the interference were intentional, violators would be fined and their equipment confiscated. The troubled frequency band is in the 5.6 GHz to 5.8 GHz range.

"There are evidently people who are firing up (wireless Internet) hot spots without (Federal Communications Commission) licensing," County Manager Chris Holley said. He said Air Force officials told him the interference is infrequent but that they hope to stop the trouble before it becomes widespread.

(Taken from the "From the Grapevine" *section of the Joint E3 Bulletin, Volume 11, Issue 2, April 2005, A Publication of the U.S.A. Department of Defense. The article was originally called* "High Speed Net, Wi-Fi Interfering with Military Radar" *and was sent in by Terry Dunford of the CAA, https://www.caa.co.uk. Terry would like to point out that in the UK, meteorological radars work on 5.6 GHz."*

328 Many WLAN products returned to stores due to interference

Interest in using smart antennas in Wireless LAN (WLAN) and mobile networks is gathering pace, according to Tim Berghuis of US-based InterDigital Communications. Mr. Berghuis, who was demonstrating the company's AIM (adaptive interference management) antenna at the recent 3 GHz Global System for Mobile (GSM) World Congress. He stated that, "On the WLAN side there's been lots of interest; and we're seeing quite a bit of interest on the mobility side - both GSM and Code-Division Multiple Access (CDMA) 2000."

Berghuis noted that the "bigger problem" lies with WLAN, which accounts for approximately 25 percent of the products returned to stores because customers cannot get them to work. Berghuis said, "People hook it up and it's not working and we think a good portion of this is attributable to interference."

(Taken from the 'From the Grapevine' section *of the 'Joint E3 Bulletin', Volume 11, Issue 2, April 2005, A Publication of the U.S.A. Department of Defense. The article was originally called "3GSM: Interest rises in Smart Antennas" and was sent in by Terry Dunford of the CAA.)*

329 Vatican radio operators prosecuted

In a follow-up to a long running story, sources throughout Europe are reporting that an Italian court has convicted a Roman Catholic priest and a cardinal of polluting the atmosphere with powerful electromagnetic waves. Cardinal Roberto Tucci and Father Pasquale Borgomeo were given 10-day suspended jail sentences and ordered to pay damages and court costs. Earlier two scientific studies had suggested that the cluster of powerful broadcast towers north of Rome could be responsible for the high cancer rates in the area.

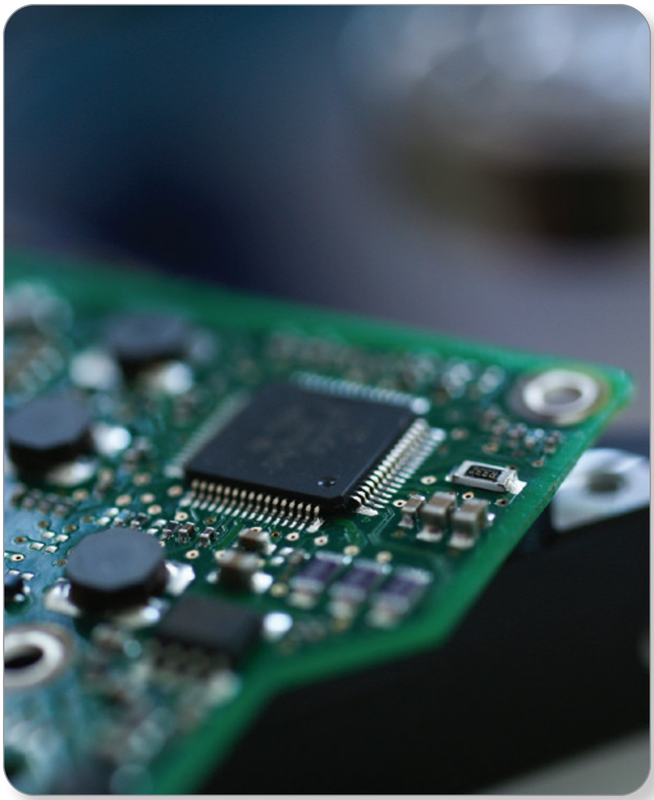
Earlier court actions were thrown out because of a now over-turned ruling that Italian courts had no jurisdiction over the Vatican, which is a separate sovereign state. Vatican Radio Program Director, the Reverend Frederico Lombardi, vowed to appeal.

(Taken from the 'EMC News' section of Interference Technology's on-line EMC newsletter, May 18, 2005. A similar story "Vatican Radio officials convicted" *appears in the BBC News at: http://news.bbc.co.uk/go/pr/fr/-/1/hi/world/europe/4531247.stm, published 2005/05/09 20:43:52 GMT.)*

The regular "Banana Skins" column was published in the EMC Journal, starting in January 1998. Alan E. Hutley, a prominent member of the electronics community, distinguished publisher of the EMC Journal, founder of the EMCIA EMC Industry Association and the EMCUK Exhibition & Conference, has graciously given his permission for In Compliance to republish this reader-favorite column. The Banana Skin columns were compiled by Keith Armstrong, of Cherry Clough Consultants Ltd, from items he found in various publications, and anecdotes and links sent in by the many fans of the column. All of the EMC Journal columns are available at: https://www.emcstandards.co.uk/emi-stories, indexed both by application and type of EM disturbance, and new ones have recently begun being added. Keith has also given his permission for these stories to be shared through In Compliance as a service to the worldwide EMC community. We are proud to carry on the tradition of sharing Banana Skins for the purpose of promoting education for EMI/EMC engineers.

Firmware: The Inexpensive Way to Address EMC Issues

BY CLAUDIO STAZZONE



In more than ten years working in labs as an EMC engineer, the majority of devices and systems I have tested include two important elements that interact with each other, thereby allowing the equipment under test to work. Electronic boards and firmware. It is difficult to imagine an electronic board without firmware running in a microcontroller. Even a simple wall charger for batteries has integrated firmware to switch the behavior of the charger from constant voltage to constant current, and to switch into trickle charging or to begin the discharge process.

Over the years, I've come to think of firmware as the soul of every electronics board since, without firmware, almost every PCB would be "dead." But because firmware is now so deeply embedded into the working mode of a device, what is the influence, if any, on a device's EMC performances? Could, in theory, at least, a device using different firmware versions behave differently during EMC measurements? We'll explore that question in this article.

FACT: EMC MEASUREMENTS ARE EXPENSIVE

We all know that EMC measurements can be expensive, especially if issues arise during the test process. Projects have to stay on budget, and layout modifications can be expensive in terms of both time and money. In fact, every new hardware release of a PCB is usually seen as something potentially problematic that should be avoided at all costs. Electronics engineers always want their boards to work right the first time, but sometimes that simply doesn't happen.

During my daily time in our testing laboratory, I often feel the pressure faced by the electronics designer, who is deeply involved in matters like costs and budgets. As a result, EMC measurements should be taken into account inside the budget analysis of a project. As an example, a full compliance EMC measurement evaluation of a medical device with a power cable, one I/O cable, and radiating emissions up to 6GHz could result in an expenditure of thousands of Euros, even if the equipment under test (EUT) meets every testing criteria.

Claudio Stazzone began his experience in 2008 as an EMC technician. In 2017, he was the Technical Responsible for the EMC lab of a big worldwide company. At present, he is Senior Project Handler in an EMC lab in Turin, Italy. He is a member of the IEEE Electromagnetic Compatibility Society. Claudio can be reached at claudiostazzone@gmail.com.

ENCOUNTERING EMC MEASUREMENTS: SHOULD YOU TAKE A "HARDWARE" OR A "FIRMWARE" APPROACH?

We are now entering the EMC laboratory with the EUT in hand. What are the common issues an electronics engineer has to face during immunity and emission tests?

According to what I have written above, the great advantage of taking the "firmware approach" is the cost and speed of implementing the solution. So it might be useful here to provide examples of common solutions involving firmware changes. Of course, the list is far from being complete, but I think it represents a good starting point.

Here are four different solutions, two solutions each for emission measurements and immunity testing.

Emissions Solution #1: Clocks and Data Transfers

Let me start with a radical proposition regarding clocks and data transfers. When you are designing an electronics board, assuming that the design requirements allow you to do so, don't set its fastest speed as the default. In other words, the electronics and firmware engineer should estimate the actual speed required to transfer data as related to the requirements and characteristics of the system being designed. If speed is one of the essential requirements, then plan the design of the board and firmware to accommodate that. Otherwise, go slow!

Emissions Solution #2: Unconfigured Pins

Sometimes, leaving default configurations of the unused pins can be dangerous. Read the datasheet and application notes, since often these details are explained. Usually, it is a good idea to apply the information in the documentation of a microcontroller, especially when some PINs require particular treatment (such as speed configuration, idle configuration or not-used state with some kind of high impedance setting, etc.).

Immunity Solution #1: Watchdog

A watchdog is an electronic timer that is updated by the CPU/microcontroller at regular intervals. If the timer is not updated due to a microcontroller or CPU block, a timeout signal is generated by the watchdog. The presence of the timeout signal could be checked by the firmware (running on another microcontroller), and a reset signal could be issued to the CPU/microcontroller in order to reset the state of the device. This is very useful in order to successfully pass pulsed immunity testing, where the performance criterion is usually of B or C type.

In some cases, a full reset (with data retention) is permitted for tests like pulsed immunities.

Immunity Solution #2: De-bounce Code and Averaging

In cases in which the firmware has to read the state of a pressed button or a signal coming from a capacitive touch control (or any other sensitive interface), it is recommended to implement a de-bounce algorithm in the code in order to exclude spurious button presses. The de-bounce code can be a useful tool in excluding unwanted effects related to RF injection, which could lead to a microcontroller sensing the activation of a button when no button has been pressed.

Figure 1 shows an example of a de-bounce algorithm based on a timer and interrupt method. A firmware engineer can

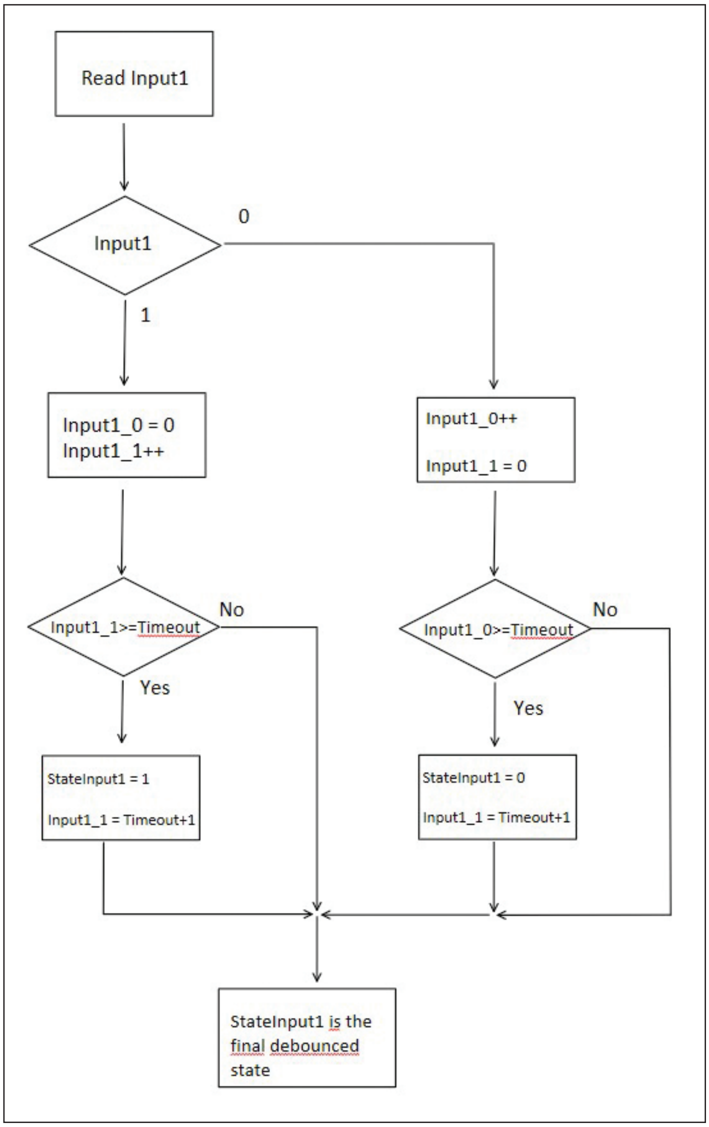


Figure 1: When Input1_0 or Input1_1 exceeds or is equal to Timeout, means that it was at 1 or 0 for at least the time of Timeout. Which means that the logical states 1 and 0 must remain the same for all the Timeout timer.

implement different techniques, depending on the final application and the object of the de-bounce (capacitive touch control, mechanical switch, and so on).

Another technique used to avoid spurious data is averaging. It is used mainly when slow phenomena have to be acquired by sampling a huge amount of data, for example, environmental parameters like temperatures, humidity, etc. In case the injection of a disturbance during immunity tests (both conducted and radiated) alter some data, the averaging keeps the trend stable by reducing unwanted variations.

CASE STUDIES

In this final part of the article, I would like to present three case studies I've collected in recent months. They are all about the impact of firmware on EMC measurements, and I'm hoping that you recognize yourself in some of these cases.

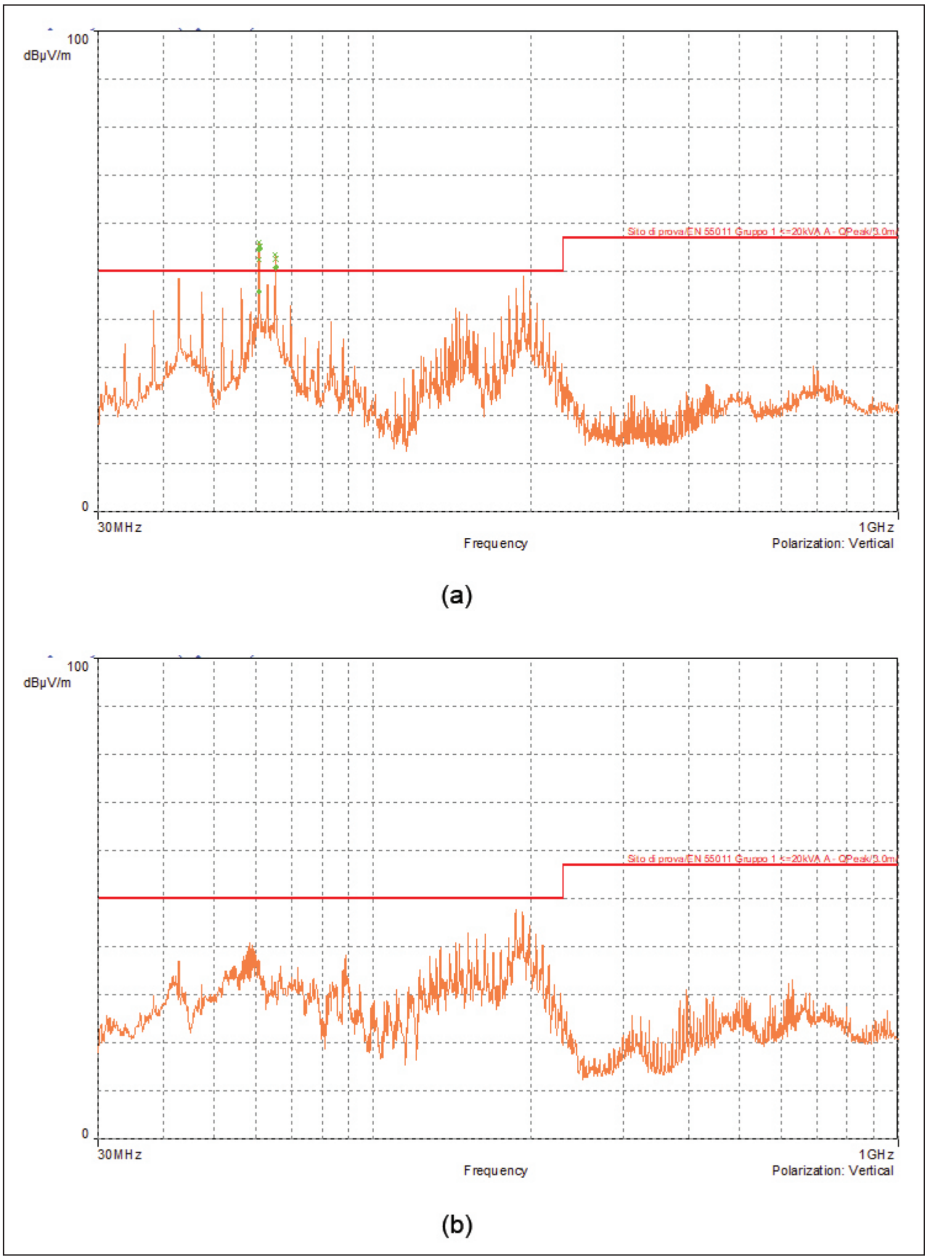
Case Study 1: Medical Device, Inexpensive Ending

This case study is very recent and relates to a medical device that measures biological electrical signals from body nerves (very small signals, hence, huge amplification required). The system has shielded cables and two microcontrollers inside. Radiated emissions were above the limits (see Figure 2a). The person present during the testing process was the developer of both the hardware and firmware of the device.

After some tests (e.g., disconnect cables, switch off one module after the other, etc.), we managed to spot the issue.
On one 3 meter length cable, two signals were present:
1) an SPI to read from an ADC; and 2) a serial communication for the link between the two microcontrollers (115200 baud). The datasheet for the microcontrollers noted that, in cases where the PINs are configured as outputs, a speed selection command was available. This command was not set but by default, the compiler set the speed at its maximum rate. By slowing down the two speeds maintaining the overall performance and stability of the system, the problem was solved without adding a single capacitor or ferrite bead to the board (see Figure 2b).

Case Study 2: Capacitive Keypad, Inexpensive Ending

Capacitive keypads are extremely sensitive. There are a lot of controllers available on the market, from plug-and-play models (usually cheap, less customization) to those



Figures 2a and 2b: Figure 2a shows the radiated emissions between 30 and 1000MHz before the firmware modification. Figure 2b shows the radiated emissions of the same board, but different firmware.

that are more flexible (usually expensive, but offering full customization). Over time, I have noticed that, in many cases, the key issue is traceable to this difference.

A customer brought in the laboratory a system (an access control system for home use) with a capacitive keypad. During testing, we discovered issues with conducted immunity levels, in which the system was taking unwanted commands when a disturbance was applied. Overcoming this issue was as simple as changing the configuration of the capacitive controller by modifying a few lines of code. This modification solved the problem.

Case Study 3: Capacitive Keypad, Expensive Ending

This case study has a very different ending from the previous ones but involved another touch control using capacitive technology embedded into an industrial lighting system. In this case, the controller belonged to the "plug-and-play" category, with no access to the code whatsoever. As a result, every behavior was fully automated by code inside the controller that communicated to the main microcontroller via a serial protocol. There was no way to change code, no way to change anything, in fact, ultimately requiring a change in the layout of the board to improve ground planes and ground connections. The challenge was further complicated by the lack of space inside the enclosure.

CONCLUSIONS, WITH SOME Q&AS

I'd like to end this article with answers to two questions about EMC measurements campaign and firmware modifications during the life of a product, as follows:

Q. Who are the most suitable people to assist during the measurements?

A. Electronics engineers and electronic designers with deep knowledge of the board under test, and software engineers who developed the firmware (in some cases, these two are the same person).

Q. If the firmware of a product is changed/updated, do EMC measurements need to be repeated?

A. It depends on the modifications implemented in the firmware. The firmware is very often connected to the results of EMC tests, both for immunity and emission. Taking that into account, it's unlikely that testing two samples of the same equipment loaded and running with different firmware will produce the same test results. Would you take the risk?

I confess that it was hard to find resources for this article, which is mainly based on my experience and daily laboratory life. However, here is a short list of resources where the reader can find some hints and further suggestions on firmware-related issues.

In addition, I would like to give the reader some thoughts about the reactions this article generated on social networks, with some suggestions and hints received from readers and commenters.

Two other ways of solving EMC issues during measurement campaigns using firmware-related techniques are spread spectrum and data scrambling. The first is very well known and often implemented, for example, in switch-mode power supplies (SMPSs), sometimes in a transparent way to the designer. The latter is related to the way of transmitting high data rate digital information. Its purpose is to smooth out the spectrum of the transmitted data from peaks and spikes by acting on the bit sequences in order to resemble the spectrum of white noise instead of the one produced by data transfer. For the curious reader, the last reference is about these two techniques.

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The IEC 60601 Amendment Updates Have Published: Changes and Impacts

Make Plans Now to Start Your Gap Assessment

BY LEONARD (LEO) EISNER

Over the many years of my career, I have noticed that standards keep changing at an ever-increasing rate. Most recently, I have been involved in four of the standards committees dedicated to IEC 60601-1, Medical electrical equipment, one of eight standards in the IEC Amendments Project. Part of our work is reflected in the recently released Ed. 3.2 of IEC 60601-1.

Medical device standards are being developed more and more rapidly and some existing standards are being updated in shorter time frames (i.e., the rules for IEC standards development has changed to allow for shorter development cycles), and national medical device regulations (including guidances) keep changing at a faster pace. As a result, it is becoming more difficult for medical device manufacturers as well as medical device consultants to keep up to date with the proliferation of changes. Ultimately, this impacts the manufacturer's quality systems and technical documentation, increases product development cycle times, and stretches out product time to market.

This article will focus on the IEC 60601 series of medical electrical standards, and specifically on the IEC Amendments Project, a project that was completed under Sub Committee 62A (SC62A). The article provides a summary of some of the changes from the previous version of the standards impacted by the Amendments. There are literally hundreds of changes in these standards, and it would be impossible to adequately provide details on all of these changes.

But we'll do our best in the pages that follow.

ABOUT THE IEC AMENDMENTS PROJECT

The Amendments Project under SC62A covers the general standard (IEC 60601-1) and most of the collateral standards (IEC 60601-1-XX, except for IEC 60601-1-3). (For background on the Amendments Project, refer to my previous article, "The Future of the IEC 60601 Series: An Update," published in the *In Compliance* 2020 Annual Reference Guide.) Six of the standards that fall under the Amendments Project were published in July 2020, and IEC 60601-1 was published in August. IEC 60601-1-2, the remaining standard of the Project was published in September. IEC 60601-1-3 is not part of the Amendments

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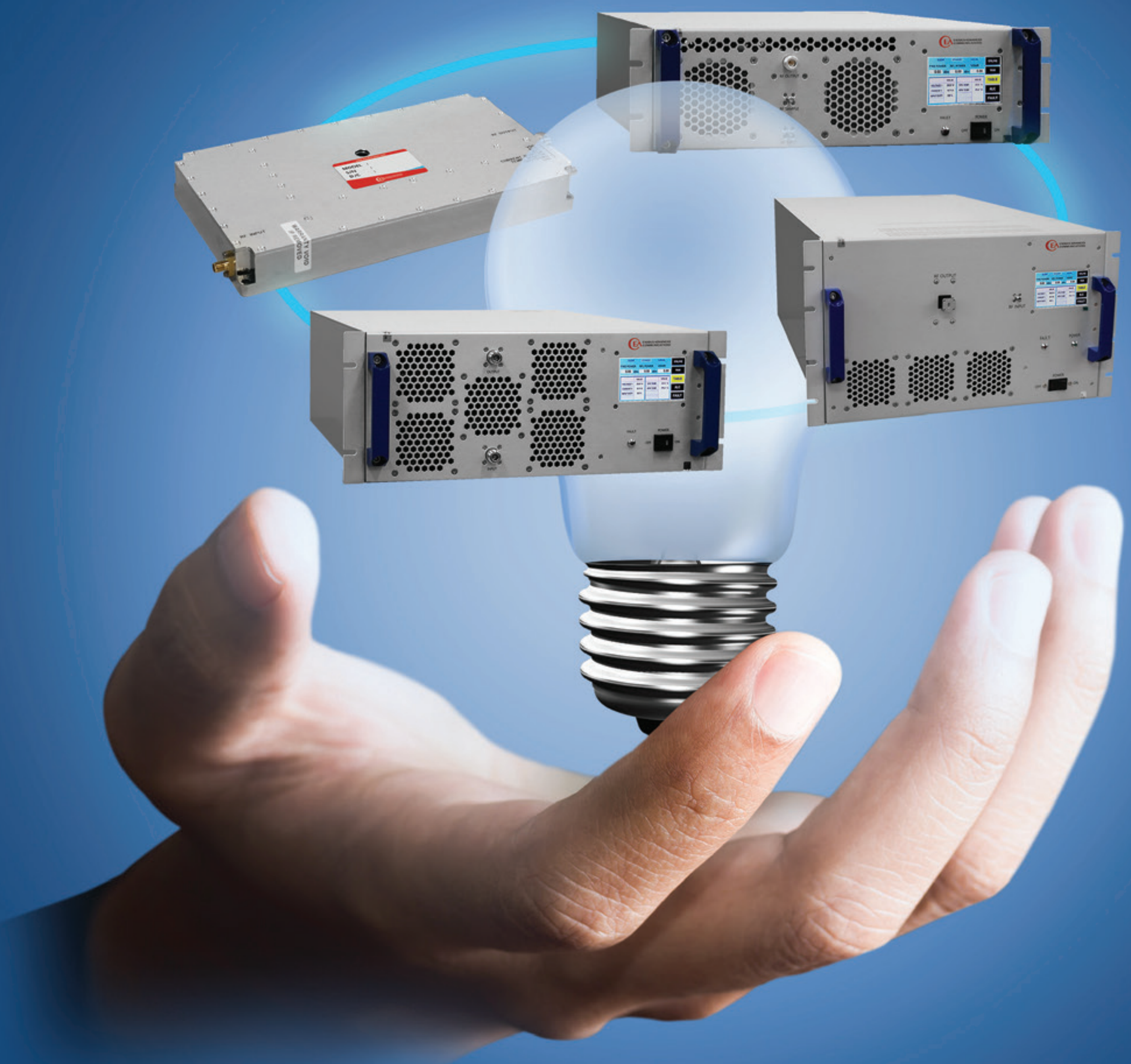

Project. It is expected that IEC 60601-1-3 will be published around September 2021 to align with the Amendments Updates. See Table 1 for publication dates.

It is important to understand that the particular standards of IEC 60601-2-XX / IEC/ISO 80601-2-XX have not yet been updated to align with the Amendments. If the particular standard applicable to your device has not yet been updated to align with edition 3.2 of the general standard, you can continue to use edition 3.1. However, the new versions of collateral standards (e.g., IEC60601-1-2 ed 4.1) may still apply because of new regulatory requirements (e.g. FDA CDRH).

Some particular standards in the series are likely to be updated fairly quickly, while others may take up to three or more years before they are published. This extended timeline may determine when manufacturers begin the process of transitioning from IEC 60601-1, Ed. 3.1, and the applicable collateral and particular standards to the pertinent Amendments.

The decision to transition may be impacted by additional factors such as:

- Transition dates of national certifiers such as UL, CSA, BSI;
- National regulators transition periods;
- New product being ready for market or legacy product lines;
- Regulatory approvals;
- Existing safety certifications;
- Business, regulatory, quality system strategy and impact.

Therefore, it is important for device manufacturers to initiate a full gap assessment as soon as possible to understand the consequence of the anticipated changes, as they are likely to impact design requirements, testing laboratory approvals, regulatory approvals, and more.

Each of the IEC standards of the Amendments Project were concurrently voted on by CENELEC for adoption

Standard	Current Version	Amended Version	Date Published/ Expected Publication	Types of changes Major/Minor/Editorial
IEC 60601-1	Edition 3.1	Edition 3.2 = 3rd ed. + A2 Medical electrical equipment	2020-08-20	Major
IEC 60601-1-2	Edition 4.0	Edition 4.1 = 4th ed. + A1 Electromagnetic disturbances – requirements & tests	2020-09-01	Major
IEC 6060601-1-3	Edition 2.1	Edition 2.2 = 2nd ed. + A2 Radiation protection in diagnostic X-ray equipment	Est'ed: 2021-09	Not Determined - In process still
IEC 60601-1-6	Edition 3.1	Edition 3.2 = 3rd ed. + A2 Usability	2020-07-22	Minor Editorial Changes: Terms & referenced standards. Transition to IEC 62366-1.
IEC 60601-1-8	Edition 2.1	Edition 2.2 = 2nd ed. + A2 Alarm Systems in MEE & MES	2020-07-23	Major
IEC 60601-1-9	Edition 1.1	Edition 1.2 = 1st ed. + A2 Environmentally conscious design	2020-07-22	Minor Editorial Changes: Referenced standards No Technical Changes
IEC 60601-1-10	Edition 1.1	Edition 1.2 = 1st ed. + A2 Physiologic closed-loop controllers	2020-07-22	Major
IEC 60601-1-11	Edition 2.0	Edition 2.1 = 2nd ed. + A1 Home healthcare environment	2020-07-22	Minor
IEC 60601-1-12	Edition 1.0	Edition 1.1 = 1st ed. + A1 Emergency medical services environment	2020-07-22	No Technical Changes

Table 1: Current status of IEC 60601 Amendments

and final approval as European standards (EN Norms). These EN Norms are not currently harmonized under either the EU's Medical Device Directive (MDD) or the EU's Medical Device Regulation (MDR). Therefore, it will be up to the national standardization bodies (NSBs) throughout EU Member States to issue their own versions of the European equivalent standards. These delays are likely to further complicate an already challenging process for obtaining device approval under the EU's MDR.

THE SCOPE OF CHANGES

We had a variety of changes between all these documents. The majority of changes fall under one of the following issues:

- Some of these changes were intended to align the standards with regulatory requirements and with the updates to ISO 14971, IEC 62366-1 and IEC 62304 to facilitate the regulatory approval process:
    - IEC 60601-1, 60601-1-2, 60601-1-6 and 60601-1-10 refer to the most recent standard ISO 14971:2019 Medical devices - Application of risk management to medical devices standard.
    - IEC 60601-1-6, 60601-1-8, 60601-1-10, & 60601-1-11 refer to the most recent standard IEC 62366-1:2015 + A1:2020 for Medical devices - Part 1: Application of usability engineering to medical devices. Note that IEC 60601-1 refers bibliographically to IEC 62366-1:2015 as an informative reference, not as a normative standard.
    - IEC 60601-1 refers to the current IEC 62304:2006 + A1:2015. It was hoped that IEC 62304 2nd edition would have been published but that edition had issues in committee and has not yet been published. So the Amendments Project couldn't wait any longer to align with the anticipated IEC 62304 2nd edition requirements. We will have to live with this version for now.
- Updates to key standard references - Normative references that were updated in IEC 60601-1, Ed. 3.2 include the following standards (a number of which will be discussed later in this article):
    - IEC 60601-1-2:2014 + A1:2020, EM disturbances
    - IEC 60601-1-3:2008 + A1:2013, Diagnostic X-ray equipment

  - IEC 60601-1-6:2010 + A1:2013 +A2:2020, Usability
  - IEC 60601-1-8:2006 + A1:2012 + A2:2020, Alarm systems
  - IEC 60747-5-5:2007 or later, Optoelectronic devices - Photocouplers
  - IEC 60825-1:2014, Safety of laser products - Part 1: Equipment classification and requirements
  - IEC 60950-1:2005 + A1:2009 +A2:2013, Information technology equipment
  - IEC 62133-2, Lithium systems
  - IEC 62368-1:2018, Audio/video, information and communication technology equipment
  - ISO 7010:2019 Safety signs
  - ISO 15223-1:2016, Medical devices - Symbols to be used with medical device labels, labelling and information to be supplied
- New or updated terms in IEC 60601-1 and some of the other standards. Some of the terms come from the regulatory standards. IEC 60601-1 has two new definitions internal to the standard itself.
- IEC 60601-1 required a significant number of clarifications, as did several other standards. The primary reason for these clarifications stemmed from:
  - Safety gaps identified by WG14 decisions, many of which are published in IEC TR 60601-4-3:2018 (2nd Ed) Guidance and interpretation - Considerations of unaddressed safety aspects in the third edition of IEC 60601-1 and proposals for new requirements
  - Inconsistencies within a standard
  - Technical errors which generated new and updated test requirements

The following sections detail the changes of significance found in IEC 60601-1, Ed. 3.2.

Clause 8 & Annex A, Clause 8

IEC 62368-1:2018 is being used as an alternative solution for means of operator protection (MOOP) to IEC 60950-1, which was the only other option in IEC 60601-1, Ed. 3.0 and 3.1 for MOOP. (Note that one level of means of patient protection (MOPP) of IEC 60601-1 can't always be provided by the lower level of two levels of MOOPs detailed in either IEC 60950-1 or in IEC 62368-1.)

We found some drawbacks with IEC 62368-1:2018 when we did our analysis for an alternative option to IEC 60601-1. There are areas where voltages for 2 MOOP don't meet the requirements for 1 MOPP, so manufacturers should carefully read and evaluate the examples and extensive details included in Clause 8 of Annex A (Guidance & Rationale) to determine if they apply to a given device or component, such as switch mode power supplies.

In many cases, working voltages that are above 354Vdc/250Vrms become problematic for double insulation for 2 MOOP for air clearance for IEC 62368-1:2018 as it may not necessarily meet the needed 1 MOPP for air clearance. Similar to IEC 62368-1, IEC60950-1:05, A1:09, A2:13 working voltages that are above 707Vdc/500Vrms in many cases become problematic for double insulation for 2 MOOP for air clearance as it may not necessarily meet the needed 1 MOPP for air clearance. Adding in IEC 62368-1 was not originally part of IEC 60601-1, Ed. 3.2 but was inserted into the project given the anticipated shortage of IEC 60950-1 certified power supplies in the near future.

If you can't you use an IEC 62368-1 switch mode power supply, here are some other options:

1. Substitute an IEC 60601-1 and IEC 60601-1-2 compliant power supply. This is our recommendation to clients anticipating FDA review and since reviewers may have concerns about the use of a power supply intended for ITE applications.
2. Look at the isolation in your overall device/system and determine if you can add additional isolation that will get you the isolation needed. This may mean a redesign and additional testing, and could add cost and testing time.

Another piece of the puzzle is that EN 60950-1 (the CENELEC equivalent of IEC 60950-1) will be withdrawn as of 12/20/2020, and will no longer qualify as a harmonized standard under the EU's Low Voltage Directive (LVD). Therefore, EN 62368-1 is probably the best alternative as it remains a harmonized standard under the LVD, and it enables you to use an ITE type (non-medical) power supply for MOOP.

The changes also relate to other components that provide MOOP isolation on the mains side of power isolation of medical devices, as well as system requirements related to monitors, keyboards, computers, printers, etc. The updates to IEC 60601-1, Ed. 3.2 reflect these considerations.

Alarms and Indicators (Table 2)

The revised Table 2 of the standard represents a significant improvement over that found in the prior edition of the standard. This updated table was generated by the Joint Working Group on Alarms IECSC62A JWG2 (the Committee which also developed the alarm system standard IEC 60601-1-8). The revised table shows much more clearly and precisely what is expected for indicators (warnings & cautions) and alarms. The most significant change is the addition of more detailed specifications regarding alarms. This is especially important since it may encourage the inclusion of alarm systems that conform with the requirements of IEC 60601-1-8 in the design of medical devices (new and existing).

Detachable Power Cords (Clause 8.6.4)

Prior to the release of the updated edition of IEC 60601-1, testing laboratories were required to use a 3 meter power cord consistent with the requirements of Clause 8.11.3.3 and Table 17 in cases where a device manufacturer neither provided nor specified one. But testing laboratories don't typically stock power cords, so this requirement wasn't always tested consistent with the requirements. The updated edition of the standard now includes new requirements that specify that testing to be carried out "using a DETACHABLE POWER SUPPLY CORD as provided or specified (length and cross-sectional area) by the MANUFACTURER." This means that device manufacturers may either provide samples of all variations of power cords intended for use with their device or specify in their IFU the length and cross-sectional area of each power cord. Providing cord samples to the test lab for this requirement can add time to testing and increase the cost.

Conductive Coating (New Clause 8.9.1.16)

A new requirement was added to the standard, even though most test houses have applied this requirement for many years. The requirement involves confirmation that flaking or peeling of conductive coatings doesn't reduce spacings. If compliance can't be verified by an examination of construction and available data, the appropriate testing of the coating must be conducted. UL 746C has always served as the default standard for such testing, but the updated IEC 60601-1 now includes references to UL 746C as well as ISO 2409 and ISO 4624.

Table 2 – Colours and meanings of indicator lights and alarm indicator lights for ME EQUIPMENT

Name	On when	Indicator light [a]	Alarm indicator light	Accompanied by sound	Operator requirement
Warning [b]	HAZARDOUS SITUATION is to be avoided	Red, not flashing	–	– [c]	Avoidance of a HAZARDOUS SITUATION which could cause death or serious injury
Caution [b]	HAZARDOUS SITUATION is to be avoided	Yellow, not flashing	–	–	Avoidance of a HAZARDOUS SITUATION which could cause minor or moderate injury or equipment damage
Ready for use	ME EQUIPMENT is ready for use	Green	–	–	–
HIGH PRIORITY ALARM CONDITION	Interruption of current workflow is needed	–	Red, flashing [d]	Typically [d]	Immediate action to prevent injury
MEDIUM PRIORITY ALARM CONDITION	Re-planning of current workflow is needed	–	Yellow, flashing [d]	Typically [d]	Prompt action to prevent injury
LOW PRIORITY ALARM CONDITION	Planning of future workflow is needed	–	Yellow or cyan, not flashing [d]	Optional [d]	Awareness for future action
Other	Situations other than that of red, yellow or green	Any colour other than red, yellow, cyan or green	–	–	–

[a] These indicator lights are INFORMATION SIGNALS and IEC 60601-1-8 requires that they be perceived as different than visual ALARM SIGNALS.

[b] Such warnings and cautions are frequently accompanied by a SAFETY SIGN.

[c] Sound may be utilized, but IEC 60601-1-8 requires that it be perceived as different than auditory ALARM SIGNALS.

[d] As specified in IEC 60601-1-8.

Table 2: Color and meanings of indicator lights and alarm indicator lights for medical electric equipment (Table reproduced with permission of the IEC)

IEC 62133-2 for Secondary (Rechargeable) Lithium Batteries (Clause 15.4.3.4)

IEC 62133-2 has been added as an alternative to the older IEC 62133 standard. But if your testing lab/regulator (i.e., EU Notified Body) or customer expects you to meet the newer IEC 62133-2 standard, you'll need to retest in order to obtain a new test report and CB certificate. The implication is increased test costs, additional test samples, project delays and potential redesign of batteries/battery packs to meet the new requirements. The two standards (IEC 62133 vs IEC 62133-2) don't have identical tests between them.

IEC 60747-5-5:2007 or later for Optoelectronic devices, Photocouplers (Clause 8.5.1.2)

An added requirement in Clause 8.5.1.2 (MOPP) recognizes that opto-couplers found compliant with IEC 60747-5-5:2007 or later editions are considered acceptable, assuming that their dielectric voltage withstand are acceptable for the given application, and that the air clearance and creepage distances at the outside of the opto-coupler meet the requirements. Opto-couplers complying with IEC 60747-5-5:2007 or later are considered equivalent to the requirements of solid insulation (Clause 8.8.2) and insulating compounds (Clause 8.9.3).

Small Spacings (Clause 8.9.4 and Figure 23)

Not all testing laboratories are involved in the development of the interpretations (WG14). So they may be unaware of the change to the minimum X mm away vs. the 1 mm gap in some of the creepage and air-clearance limits illustrated in Figures 23-25 and 27-31 of the standard. These changes could have impact primarily on PCB layouts and their spacings. For example, Figure 1 (Figure 23 in the standard) shows X mm (underlined), while Ed. 3.1 uses 1 mm.

Figure 23 was the only one in the series of figures in the standard that had a 1 mm instead of X mm in the figure when the previous update was made. The X mm rules in Clause 8.9.4 had to be updated slightly to align properly but have been in the standard since Ed. 3.1.

ISO 14971:2019

As detailed in IEC 60601-1, essential performance requirements are directly connected to risk analysis.

So certification to IEC 60601-1 is based in part on demonstrating compliance with the requirements of ISO 14971, the standard addressing risk management issues. There are no significant changes to risk management within IEC 60601-1, Ed. 3.2, but many of the ISO 14971:2019 terms that are referenced in the standard have been updated. These updates may necessitate updating the content of your risk management files in advance of resubmitting devices for testing.

OTHER CHANGES IN STANDARDS IN THE AMENDMENT PROJECT

Changes of significance for IEC 60601-1-2, Ed. 4.1

Conducted emissions (CISPR 11) now test at minimum and maximum rated voltage versus the single voltage test previously used. Note that this change may affect RF emission levels.

New tests Table 11, Clause 8.11 immunity to proximity magnetic fields. Two of the three tests per Clause 8.11 (134.2 kHz @ 65A/m and 3.56Mhz @ 7.5A/m) are from the AIM 7351731 standard. The third test (30kHz @ 8A/m) is for the home healthcare environment (radiant cooktops).

The Guidance section on the application of risk management with regard to electromagnetic disturbances has been totally rewritten to clarify risk management references in the standard.

Changes of significance for IEC 60601-1-8, Ed. 2.2

Clause 6.3.3.1 references Annex G - new sound files. These are new, optional audio sound files for alarms in addition to the previously listed sound files. The Alarms committee is considering making Annex G mandatory in the next revision of 60601-1-8.

Clause 6.3.3.2 - The test set-up and configuration has been changed to correct references to figures and tables in ISO 3744. This means test source and locations (based on

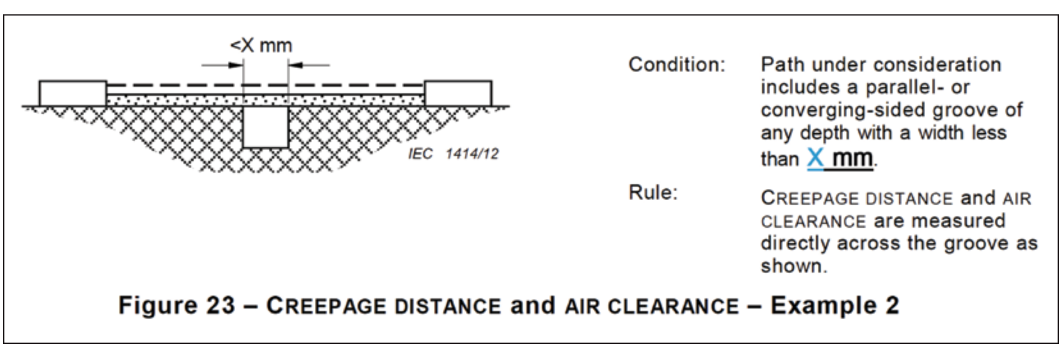

Figure 1: Creepage and air clearance examples (Figure 23 in the standard)

figures) will change. Therefore, the test results may vary from past results.

Added new distributed Alarm systems requirements in Clause 6.11.1.

WRAPPING UP

I'm continually being asked by manufacturers about the expected timeline for the adoption of these standards by national regulators. Each of the standards in the Amendments Project includes a recommendation for a three year transitional period from the date of each standard's publication. I checked with the Standards and Conformity Assessment program of the U.S. Food and Drug Administration's CDRH, and they confirmed that internal discussions are already underway regarding the recognition and transition period for these standards. They are anticipating adopting the three-year transition period recommended in the standards in the Fall of 2020.

What is not clear is how long it will take the FDA to "recognize" the particular standards (IEC 60601-2-XX & IEC/ISO 80601-2-XX) once they are aligned with the Amendments Project. I recommend that device manufacturers take a "state of the art" approach and apply the latest version of each standard when designing their devices, recognizing at the same time that this approach has limitations in cases where regulatory authorities have requirements that reference earlier editions of a given standard (i.e., MDD Harmonized Standards) and insist on using these outdated standards.

The goal of the Amendments Project was to make the more immediately needed changes to the IEC 60601-1 series of standards in advance of efforts to develop a 4th Edition of the standard, expected to begin by about 2025. We believe that the work of the Amendments Project will help clarify many important issues around the current use of IEC 60601-1 and its collateral standards, and make it easier to use the standard in the near term. At the same time, the changes are likely to result in some additional work, as device manufacturers will need to conduct a gap assessment and review their documents and systems to determine what needs to be updated before they resubmit to their test laboratories and regulators to meet these revised requirements.

How and Why Varistor Failure Occurs Including the Effect of Multipulse Surges

The Story of the Varistor and the Often-Unappreciated Ways It Can Fail

BY ALBERT R. MARTIN

The year was 2011, and an experiment was being done in China to record the effects of a triggered lightning flash on an overhead transmission line. The line was instrumented to record the induced currents, and the instruments were protected with a metal oxide varistor (MOV).[1] The lightning flash recorded consisted of multiple return strokes, none of which exceeded the Imax rating of the MOV. But, much to the surprise of the experimenters, the MOV was damaged.

How could this happen? And more importantly, why might Imax not be a good basis for selecting an MOV for lightning protection, and are there alternatives? To help answer these questions, we'll discuss in this article what an MOV is and how the way it is made influences its behavior when surged, how failures occur, and how multipulse surges differ from single surges in their effect on MOV properties.

VARISTOR BASICS

In order to understand failure, it's useful to discuss how varistors are made. In this regard, there are three things of note.

1. A varistor is often called an MOV (Metal Oxide Varistor)

First, varistors are a ceramic material composed primarily of zinc oxide (ZnO). At ambient conditions, ZnO crystallizes into a hexagonal wurtzite structure, as shown in Figure 1, where the large balls represent Zn and the small balls represent oxygen (O). This is a complicated structure that, if it crystallized perfectly, would be an insulator. But because the crystallization process isn't perfect, the resulting oxygen vacancies or zinc interstitials cause this structure to become a wide-gap semiconductor having a relatively low resistivity of 1 – 100 Ω-cm at room temperature.

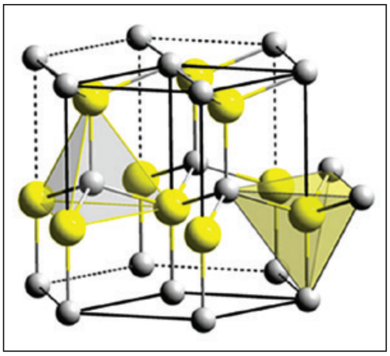

Figure 1: Wurtzite structure. The large balls represent Zn and the smaller balls represent oxygen.

Second, a varistor is not one uniform wurtzite crystal, but many which coalesce into grains. To make ZnO into

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a varistor, a small amount of Bi_2O_3 is added. The Bi_2O_3 goes into the grain boundaries, as shown in Figure 2. In addition to Bi_2O_3, MnO may be added to enhance the nonlinear properties; Sb2O3 to control the ZnO grain growth; and a small amount of Al_2O_3 to increase the ZnO grain conductivity.

The Bi_2O_3 between two ZnO grains results in the formation of back-back Schottky diodes. So essentially, a varistor is a series-parallel arrangement of n-type material separated by back-back Schottky diodes having a voltage drop of about 2V-3V per grain boundary Junction (independent of grain size). According to He [1], this structure can be characterized electrically by Equation (1).

$$I = A_1 exp\left(-\frac{E-mV^{0.5}}{kT}\right) + A_2\left(\frac{V}{V_{th}}\right)^{\alpha} \quad (1)$$

Where V is the applied voltage and I is the current through the varistor. Here, E, A_1, A_2, V_{th} and m are constants related to the electrical characteristics of varistor[2], and α is the usual nonlinear coefficient of the varistor. Equation (1) is useful for explaining the shape of the varistor V-I curve.

The first term in Equation (1) is seldom included in the V-I description of a varistor. It is the Schottky emission current in the low current region of the varistor. The second term is the usual nonlinear current in the high current region.

The constants in Equation (1) are controlled by varying the composition of the varistor material and sintering time of the manufacturing process. The threshold voltage V_{th} also depends on composition and sintering conditions. These control the number of grain boundaries between the two electrodes. Since V_{th} is proportional to the number of grain boundaries, more grain boundaries result in a higher V_{th}.

Third, this variation in the varistor fabrication process and the accompanying statistical fluctuations in properties that generally occur in polycrystalline materials cause the resulting varistors to have inhomogeneous electrical properties. That suggests that:

1. The constants in a varistor model like Equation (1) are likely to be different for every varistor; and
2. Not all varistors of the same dimensions have the same properties – an important consideration when choosing a MOV for protection.

VARISTOR FAILURE

Varistors need to absorb the energy deposited by temporary overvoltage, switching surges, or lightning impulses.

2. E is the excitation energy of varistor, K Boltzmann's constant, A_1, A_2, and m are constants related to the electrical characteristics of varistor, V_{th} is the threshold voltage.

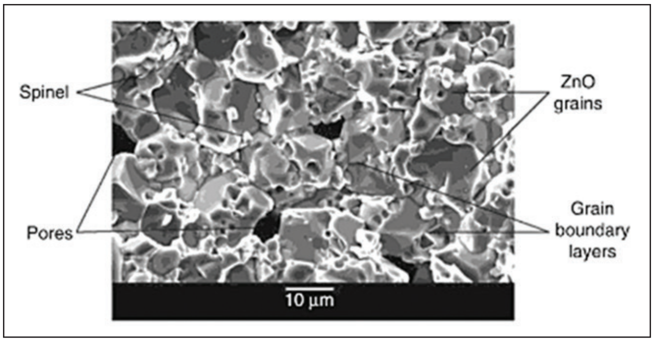

Figure 2: Typical micrograph of varistor structure

Experiments show that differences in grain sizes and grain boundary characteristics cause nonuniform microstructure. Nonuniform microstructure results in the variability of varistor current handling capabilities and related energy absorption capability. That, in turn, has a direct relation to failure modes, which include electrical puncture, physical cracking and thermal runaway.

The energy absorption capability can be divided into thermal energy absorption capability and impulse energy absorption capability. Impulse energy absorption capability depends on how the impulse is applied:

- Single impulse stress
- Multiple impulse stress (without sufficient cooling between the impulses)
- Repeated impulse stress (with sufficient cooling between the stresses)

Thermal energy absorption capability, on the other hand, is mainly affected by the heat dissipation capability of the overall arrester design, in addition to the electrical properties of the varistors.

Let's first consider varistor failure caused by heating. At lower currents, the heating localizes in strings of tiny hot spots, which occur at the grain boundaries where the potential is dropped across Schottky-type barriers (see Figure 3). The heat transfer, in this case, is too fast to permit temperature differences that could cause failure.

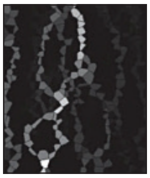

Figure 3: Typical micrograph of grain boundary hot spots

Now consider higher currents. In small varistors (e.g., <25 mm) where the number of ZnO grains between the electrodes might be only about 40, a variation of 3 - 4 grains can cause the current flow in a given path to be an order of magnitude different from surrounding paths. The paths with low breakdown voltages carry most of the current and become hotter, with consequences noted in the study of Sargent *et al* [4]. In that study, analysis of the failed MOV samples showed cracking and a formation of new amorphous material near the conduction channel. Examination of this amorphous material suggested that local hot spots (actually hot channels) were formed when the energy resulting from a current pulse applied to the MOV was absorbed faster than it could be dissipated. The amorphous material in these hot spots likely resulted from a plasma formed during the current pulse. The hot spots rapidly cooled afterward due to heat conduction to the surrounding ZnO grains.

Under different current conditions, failure modes include electrical puncture (see Figure 4), physical cracking (see Figure 5), and thermal runaway. Cracking happens because varistors are basically a ceramic material, and hitting them with a sharp high-amplitude surge is like hitting a dinner plate with a hammer.

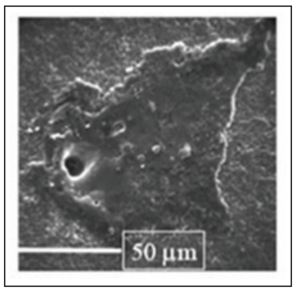

Figure 4: Typical micrograph of a puncture

Puncture destruction occurs in small varistors when the current is relatively low and of long duration (for example, see Figure 6). The net effect is that the varistor heats up. The analysis of a puncture in these varistors strongly indicates that a filament forms with temperatures high enough to melt the Bi_2O_3 (817° C). When this

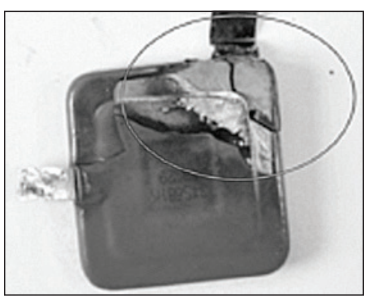

Figure 5: Typical crack formation

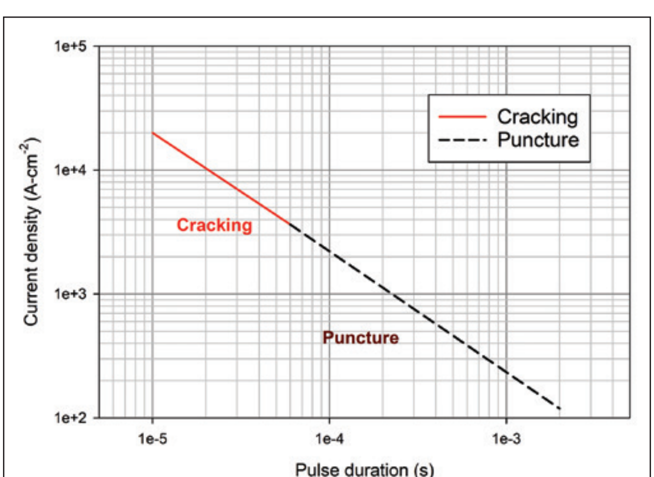

Figure 6: Example of current density and pulse duration combinations that cause failure in varistors. This plot is for a specific varistor. For any other varistor, the scales could be different from those shown.

happens, the back-to-back Schottky diodes are destroyed, resulting in reduced filament resistance [1]. Reduced filament resistance permits higher current density, sometimes causing a high enough temperature to melt the ZnO (2000° C).

If the current is continued long enough, the energy deposited in the varistor may raise its temperature to the point of thermal runaway due to the material's negative temperature coefficient of resistivity [1].

Most high impulse currents with short duration can cause a cracking failure (see Figure 5), which typically occurs at the edge of the varistor, since the temperature increases more at the edge of the chip (the white area in Figure 7). The reason is that grain growth during sintering is often more rapid in the outer part of the block than in the center of the block, resulting in fewer and larger grains between the electrodes, and hence a lower breakdown voltage.

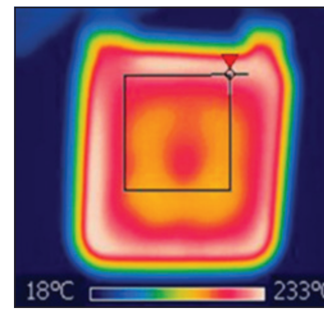

Figure 7: Typical thermal scan of a varistor pulsed under high current

Figure 6 illustrates the conditions under which cracking and puncture can occur. For a given varistor, the red solid line shows cases under which cracking might occur, and the black dashed line cases under which puncture might occur.

FAILURES DUE TO MULTIPULSE LIGHTNING

Why are we talking about multipulse lightning? Well, lightning observations and artificially triggered lightning data summarized in [6] show that nearly 70% of cloud-to-ground lightning strokes involve from two and up to 26 strikes. These strikes have a geometric mean interstroke interval of about 60 ms. They can also have a long continuing current with an interstroke interval as large as several hundreds of milliseconds. A typical multipulse sequence is illustrated in Figure 8.

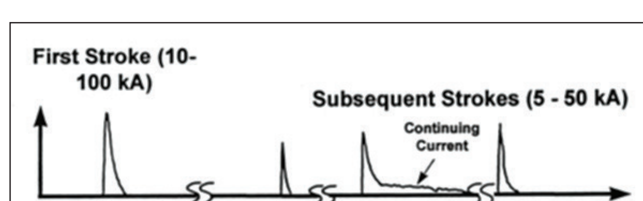

Figure 8: Example of a multipulse lightning flash

Multipulse lightning of the type just described is important because it is capable of producing the temperature rises that lead to the kind of failures just discussed, whereas a single surge might not. For example, in the study by Sargent et al [4], half a set of 18 mm MOV samples were subjected to a multipulse burst of 8/20 surges at rated current. These samples showed signs of damage, whereas the other half of the samples tested with a single 8/20 surge at rated current repeated at intervals of 60 seconds or more showed no damage. In another multipulse burst test, Rousseau et al [7] subjected a MOV to 60 20 kA 8/20 surges spaced 60 seconds apart, with no failure. But when the same type of MOV was subjected to as few as five 20 kA 8/20 surges spaced 50 ms apart, failure occurred. In these cases, varistor failure was likely caused by heat accumulation due to the relatively long thermal time constant of varistors (Figure 9), illustrated for a single surge using thermal modeling as shown in Figure 10 (for details, see [8]).

As noted previously, in the study of Sargent *et al*, analysis of the failed 18 mm MOV samples subjected to a multipulse burst test showed the formation near the conduction channel of a new amorphous material, which was thought to require a local temperature around 1000° C. Thermal modeling suggested that this temperature rise would occur if the pulse power was concentrated in about 2% of the MOV volume. This is an important observation because a calculation of the energy absorbed in the multipulse burst test showed that the temperature rise of the MOV would only have been 231° C if the temperature distribution were uniform, much less than the temperature thought to have caused the damage.

The results of Sargent *et al* suggest that the criterion for failure of an MOV is a localized temperature rise to 1000° C (or the vicinity thereof). So for an MOV under consideration, we need to determine if a localized area might reach 1000° C. Figure 11 shows the additional temperature rise that happens when the surge used to create Figure 10 is applied to the same MOV a second time after 30 ms. The additional temperature rise is due to the relatively long thermal time constant of the MOV, which prevents the MOV from dissipating much heat energy (and hence cooling) before the second surge arrives. The temperature rise is now in the red area above 1000° C, where failure is expected. So this is an example of how a varistor can be destroyed by multipulse surges.

In another look at the effects of multipulse lightning, a study by Zhang *et al* [5] explored the progression of failure in varistors under multiple lightning strokes, using a series of five-pulse groups of 8/20 lightning surges having pulse intervals of 50 ms and pulse amplitudes set at the

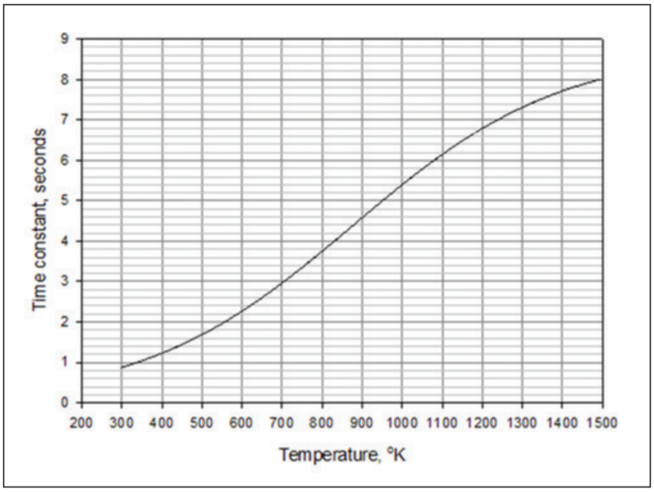

Figure 9: Thermal time constant of a varistor

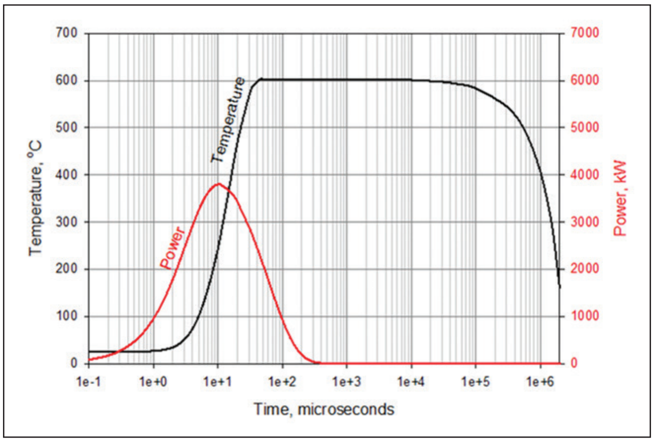

Figure 10: Example of temperature rise in a 25 mm MOV subjected to one 10/63 6 kA surge

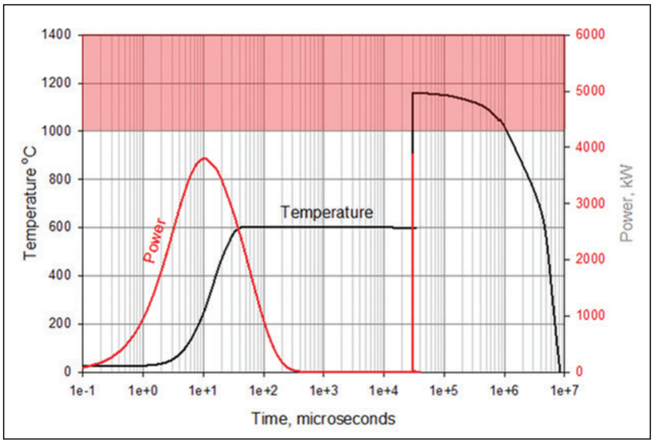

Figure 11: Example of temperature rise for a 25 mm MOV subjected to two 10/63 6 kA surges

20 kA nominal discharge current. The time between the application of one group of impulse currents to a varistor and that of the next group of impulse currents was 30 minutes, allowing a return to the original conditions.

Varistors were judged as having failed when a change greater than ±10% of the original varistor voltage U_{1mA}; the leakage current I_{ie} exceeded 20 µA; or direct damage occurred (typically by edge cracking). The average level change of the U_{1mA} and I_{ie} for the series of impulse groups is shown in Figure 12.

Figure 12 shows that in the absence of continuing current a single multipulse burst didn't deliver enough energy to the MOV to cause failure. Repeated application of the multipulse burst did eventually lead to failure.

So it is possible that a *single* non-destructive multipulse burst conditions the MOV for failure from future multipulse bursts, as suggested by the continually increasing leakage current. This conditioning could be viewed as a kind of accelerated wear-out process.

Microstructural examination of the failed varistors indicated that after the multiple lightning strokes, the grain size decreased and the proportion of Bi in the grain boundary layer increased significantly. These effects were the cumulative result of multiple lightning currents, and were

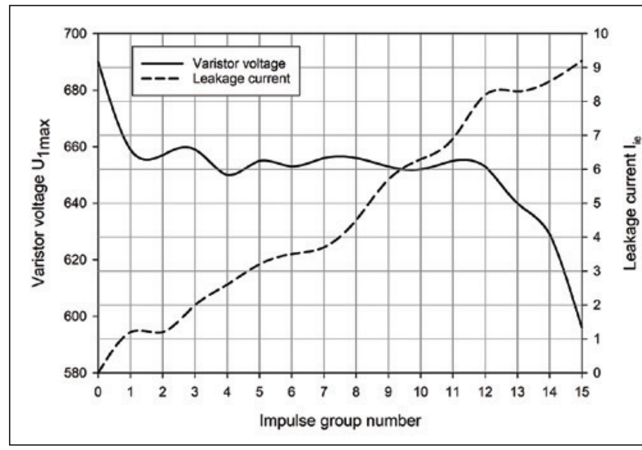

Figure 12: Varistor voltage U_{1mA} and leakage current I_{ie} variation of the varistors under multiple lightning impulse current (source: Zhang et al [5])

caused by thermal damage and grain boundary structure damage due to temperature gradient thermal stress. This damage eventually led to failure of the MOV. Note that a single surge test would miss this wear-out mechanism.

COMMENTS

It appears that repeated surging of an MOV alters its microstructure, and understanding how that happens is important to understanding how MOVs fail. Which raises some questions. In particular, is the microstructure degradation cumulative as suggested by the current plot in the previous figure? Or are the effects of degradation obscured until it reaches a critical point as suggested by the voltage plot in the previous figure? The answer is likely to depend on the magnitude and spacing of the surges, and there may be a threshold of surge magnitude and surge spacing below which no significant degradation occurs. More research is needed to answer the questions.

High amplitude short-duration single pulse tests (e.g., 6 kV, 3kA 8/20) are typically used to evaluate varistor failure. This type of test may cause a failure mode different from that in a varistor subjected to multipulse lightning at lower amplitude (e.g., cracking vs. wear-out). Single-pulse tests could also miss heat accumulation failures that multipulse lightning can cause, especially multipulse lightning that includes continuing current.

Case in Point

Back to the failure described at the beginning, a triggered lightning flash having multiple return strokes was recorded during a lightning Experiment. This flash damaged the SPD even though the Imax rating of the SPD (determined by a single surge test) was much higher than the recorded lighting peak current [9]. Why?

As pointed out in [10], what caused failure was the continuing current part of the multipulse sequence, and continuing current is not comprehended in the Imax rating. The continuing current deposited enough energy in the MOV to fail it.

Another Consideration

Since we generally live in a multipulse lightning flash environment, the typical derating plot (created with single surges), as shown in Figure 13, would need to be altered if it is to be used for an MOV that has been installed to protect against multipulse lightning. In particular, the lines in Figure 13 resulting from the (repeated) application of single surges would likely need to be lowered to take into account the microstructural degradation effect suggested by the studies of Zhang *et al* [5].

A multipulse derating plot could be created by repeating Zhang's multipulse group test in the same way as used to create the derating Figure Figure 13, but now using multipulse groups instead of single surges. So, for example, for the one-hit line, a group of surges with a relatively narrow waveshape would be applied at a current that would cause failure on the second application. The process would then be repeated using groups of surges with wider waveshapes. The result would be something like the top line in Figure 13.

Similarly, the amplitude of the current would be decreased such that a for the two-hit line, a second group of surges would cause failure on the third application, and the process repeated using groups of surges with wider waveshapes. This process would be continued until enough lines had been generated to adequately characterize the product.

Final note

For more information about varistors, see IEEE PC62.33 ™ Standard for Test Methods and Performance Values for Metal-Oxide Varistor Surge Protective Components [11].

SUMMARY

The varistor fabrication process and the statistical fluctuations in properties that generally occur in polycrystalline materials cause varistors to have inhomogeneous electrical properties. The result is that a few conducting paths with low breakdown voltages to carry most of the current and become hotter. If the temperature of these paths reaches the vicinity of 1000° C, melting occurs and the MOV is destroyed. In the case of

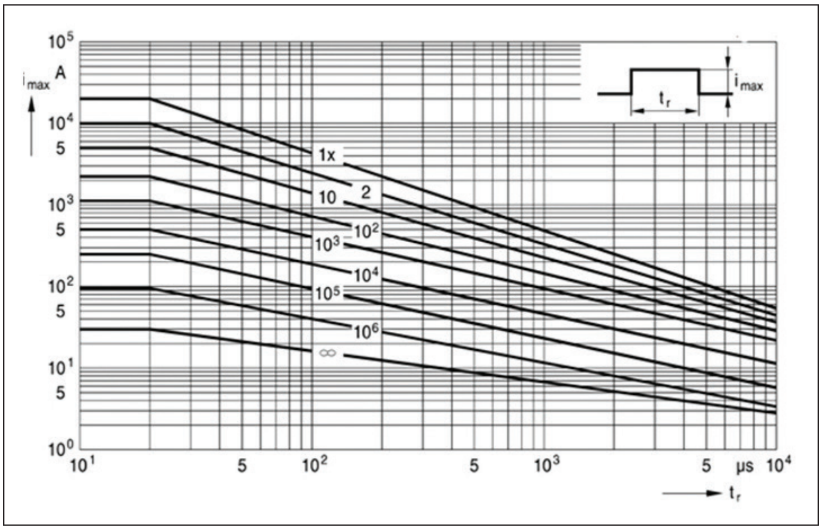

Figure 13: Typical derating curves for an MOV

18 mm MOVs, this temperature rise would occur if the inhomogeneities in the MOV cause the pulse power to be concentrated in about 2% of the MOV volume (the 2% may differ in other sizes of MOVs). This temperature rise could be the cause of puncture failure, noted for the case of long-duration lower amplitude surges.

In the case of short-duration high amplitude surges, MOV failure may occur by cracking before melting happens. Single short-duration high amplitude surges might occur on power lines, so MOV ratings established this way can be appropriate for power-line applications

For protection against lightning, ratings established by multipulse testing may be more important. This is because a multipulse lightning surge is often the driver for the temperature rise since it causes energy to accumulate in the MOV due to its long thermal time constant. This is why multipulse testing is important since a single surge test might miss failures that multipulse lightning can cause, notably wear-out, and especially multipulse lightning that includes continuing current. And most lightning is of the multipulse type. The microstructure degradation effect of repeated multipulse surges may need to be considered when constructing derating curves.

Understanding the mechanism of how surging an MOV alters its microstructure is important to understanding how MOVs fail. It is a topic that needs further research.

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Safety Considerations for Lithium and Lithium-Ion Batteries

Compliance with Applicable Standards Supports the Safety of These Essential Technologies

BY RICH BYCZEK

Lithium and lithium-ion batteries are an integral part of everyday life. They are small, lightweight and, due to a high energy density, offer a long life. Across industries, from medical to consumer electronics, industrial applications to transportation, the small, lightweight energy sources pack quite a punch, making them a popular choice for manufacturers everywhere.

Most lithium batteries used today are safe when designed, manufactured and used properly. However, if they have design defects, are comprised of low-quality materials, are assembled incorrectly, are used or recharged improperly, or become damaged, they can pose a risk. Additionally, because of their high energy density, lithium batteries are susceptible to overheating and can become a fire hazard. For these reasons, there are several safety standards that manufacturers need to apply when developing and using devices incorporating lithium batteries.

UN 38.3

Since lithium batteries can present a fire hazard during transport, they are classified as a dangerous good. To be transported, they must meet provisions laid out in UN 38.3, within the "UN Manual of Tests and Criteria." Section 38.3 applies to batteries transported on their own or within a device. It applies to all points in the battery's transportation process, including from sub-suppliers to end-product manufacturer, from manufacturer to distributor, from in or out of the product; in the field, or during product return or within non-original packaging. It is important for the manufacturer to be familiar with these requirements as the use of these batteries becomes more prevalent.

UN 38.3 has been adopted by regulators and competent authorities around the world, making it a requirement for global market access. The protocol includes identifying/classifying lithium batteries, testing/qualification requirements, design guidance/conditions, and packaging/shipping obligations.

Classification

There are four classifications based on battery type (lithium or lithium-ion) and how they are shipped (alone or in a device):

- *UN 3090 for lithium batteries and UN 3480 for lithium-ion batteries:* Apply to cells shipped alone, batteries shipped alone, consignment of cells and batteries, modules or other incomplete battery sub-assemblies, power banks,

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powerpacks, and batteries shipped in a separate package from the device they power (even if the device and batteries are on the same consignment or shipment).

- *UN 3091 for lithium batteries within a device and UN 3481 for lithium-ion batteries within a device:* Apply to devices with batteries installed; devices packed with a battery in the same package, but not installed in the product; up to two spare batteries shipped in the same package as the device (i.e., one installed, two spares).

Testing and Qualification

UN 38.3 requires several tests to ensure the relative safety of the batteries during transport. These tests vary based on the battery and components, as well as the characteristic they are intended to assess:

- Tests T1-T5, conducted on the same samples for all battery types in sequence:
  - Altitude simulation (Test T1)
  - Thermal properties (Test T2)
  - Vibration (Test T3)
  - Shock (Test T4)
  - External short circuit (Test T5)
- Test T6, conducted on the primary and secondary cells, evaluates impact and crush
- Test T7, conducted on secondary batteries, assessing overcharge
- Test T8, conducted on the primary and secondary cells, assessing forced discharge

Published in November 2019, the 7th Edition of the Manual includes several key changes regarding testing:

- *Integrated batteries:* Updated to allow testing of batteries within equipment.
- *Disassembly:* Allows for additional test criteria. We recommend any cases that may be considered "borderline" disassembly to be treated as test failures.
- *Rechargeable batteries considerations:* Changes to the cycling requirements reducing to 25 charge/discharge cycles prior to test, from 50 previously. Also updates testing tables to reflect these changes.
- *Test summary:* Now clearly defines "battery test summary," as well as the requirement that the test summary "shall be made available." Additionally, it notes the requirement for the name and title of the signatory as an indication of validity.

Other than clarifying the contents of the test summary, the 7th Edition of the Manual contains no additional changes to the test conditions, criteria or sample requirements as stipulated in the 6th Edition.

It is important to remember to get or create a test report summary, based on successful completion of UN 38.3 testing. These summaries must be made available from the shipper upon request. Obtain the test reports from cell vendors and subcontractors to complete the test summary for shipments, and maintain the supporting information.

Design Guidance and Conditions

UN regulations also include several sections related to design, which include adherence to the testing and qualification requirements, as well as incorporating a safety venting device or design elements to preclude a violent rupture. Design guidance also includes an effective means of preventing external short circuits, parallel connected cells/cell-strings equipped with a way to prevent dangerous reverse current flow, and the use of a quality management system during manufacturing.

Packaging and Shipping

Recent transport regulation updates include new labels to illustrate the risk of fire associated with the batteries in the package more simply and effectively. Passenger aircraft restrictions have also been updated to prohibit transport of lithium-ion cells/batteries as cargo on passenger planes, requiring that these items be labeled for cargo aircraft only. Lithium-ion batteries shipped alone must be set at or below 30% state of charge (SOC) for cargo air shipment. To meet this requirement, the method used should be documented, as well as how the shipment was verified. Competent authority approvals may be sought and granted for certain medical device batteries that must be shipped at greater than 30% SOC. This will allow for air shipment of such batteries at higher charge levels.

IEC 62133

IEC 62133 is one of the most important lithium-ion battery standards for global markets. It specifies requirements and tests for the safe operations of portable sealed secondary cells and batteries made from them. There are currently two versions of the standard in effect, IEC 62133 2nd Edition and IEC 62133-2 1st Edition. The names look quite similar, but the versions are different. And the requirements for a battery will vary depending on the market you wish to enter.

It is important to understand the difference between the two standards and how you can determine which is best to use. Some (but not all) of the changes in IEC 62133-2 1st Edition include:

- Separate nickel (IEC 62133-1) and lithium (IEC 62133-2) chemistries
- Inclusion of coin cells, if internal AC impedance is <3.0 Ohm
- Inclusion of single fault conditions
- Changes to cell level requirements
  - External short circuit now performed at +55° C ambient
  - Thermal abuse hold times have been changed
  - The crush test 10 percent deformation condition has been removed
  - End conditions changed for forced discharge, so they are not only time-based.
- Adjustments to battery level requirements
  - External short circuit should be performed with single fault condition
  - Different overcharge charge conditions than before
  - Vibration and mechanical shock tests have been added back to standard
- Incorporation of vibration and mechanical shock testing, based on UN 38.3, with UN 38.3 tests moved to reference Annex E.

The European Union (EU) adopted 62133-2 1st edition in March 2020. Now, all new portable lithium-ion batteries marketed or sold in the EU must comply with these new requirements. Existing batteries and systems generally only need to be recertified if there is a design change or an update to the end-product standard, as batteries are generally considered as components rather than stand-alone end products. Additionally, the U.S. and Canada have adopted ANSI/UL 62133-2 and CSA C22.2 No. 62133-2:20. Transition timelines for enforcement of these versions may vary between testing organizations.

Other countries and markets may adopt the new standard with different timelines. Ultimately, the intended market and end-product will determine which standard to use. When in doubt, partner and consult with experts who can help determine the best path forward.

UL 1642 AND UL 2054

UL 1642, "Standard for Lithium Batteries," is a U.S. standard to ensure the safety of lithium batteries. It covers both rechargeable and non-rechargeable batteries used as a power source in products. In practice, this standard is typically used for certification of component cells, while the resultant batteries are certified according to more application-specific standards.

There are several testing requirements under the standard. For both user- and technician-replaceable batteries, requirements include electrical, mechanical and environmental tests. Specifically, they include assessments for short-circuiting, heating, temperature cycling, forced-discharge, impact, humidity, shock, vibration, drop tests, abnormal changing and altitude simulation. There are also considerations for fire-exposure, flaming particles, projectiles and explosion for user-replaced situations.

UL 2054, "Standard for Safety of Household and Commercial Batteries," is a performance and safety standard for household and commercial batteries, covering portable rechargeable and non-rechargeable batteries in products. Specifically, the batteries covered in this standard consist of either a single electrochemical cell or two or more connected cells that create electrical energy through a chemical reaction, like lithium and lithium-ion batteries.

UL 2054 is specific to the battery. The safety of the product is covered by its applicable standard. The standard is intended to reduce the risk of fire or explosion when batteries are used in a product and when batteries are removed to be transported, stored or discarded. It includes testing requirements for performance, electrical considerations, temperature, mechanical assessments, battery enclosure and pack evaluations, and environmental tests.

Both UL 1642 and UL 2054 have marking requirements related to warnings about risk of fire, explosion and burns, and require the inclusion of instructions not to recharge, disassemble, crush or heat above certain points or to incinerate. The warning statements should also include instructions on disposal and instructions to call physicians or poison control if ingested. Products should also be marked regarding the use of lithium batteries and their risk, and instructions should include guidance on replacing and disposing of batteries.

CONCLUSION

With a growing prevalence in multiple industries, lithium batteries play an important role in the design and manufacture of products that fit consumer demands. The very properties that make them desirable—potency, portability, size—present risks and hazards that any manufacturer must address. It is important to familiarize yourself with the applicable standards, their requirements and needs. Knowledgeable teams and partners can make a huge difference in product success, global market access, building brands and ensuring safety.

EMC and Safety for Installations: Part 1

Developments in Ground Bonding Networks

BY KEITH ARMSTRONG

Editor's Note: In this article, the words "ground," "grounded" or "grounding" are used interchangeably with "earth," "earthed," or "earthing."

EMC[1] FOR SYSTEMS AND INSTALLATIONS

As the quantity and variety of electronic equipment used in systems and installations continues to grow, EMC is becoming an increasingly important issue. Almost all my work on systems and installations since 1990 has been involved with items of equipment interfering with the correct operation of other items on the same site.

In 1990, variable speed motor drives using insulated gate bipolar transistors (IGBTs) and power field-effect transistors (PowerFETs) for high-speed power switching were very new, as were private mobile radio systems, and they both caused many problems with legacy electronic equipment. Since then, EMC standards and regulations in most countries have considerably improved the emissions and immunity of equipment, but at the same time, variable speed motor drives have constantly improved – by switching faster. Faster switching makes them more efficient, smaller and less costly, with the result that they are being used much more widely. Unfortunately, switching faster causes increased noise emissions at higher frequencies, increasing the possibilities for interfering with other equipment (see Figure 1 on page 66).

The systems and installations concerned are not just land-based, because all new marine and submarine vessels now use electric motor drive technologies exclusively. They still have huge marine diesel engines, but they drive huge electricity generators rather than being directly connected to propellers. Electric automobiles are already proven in use and a growing industry, of course, and all-electric aircraft are on the drawing board.

Another big technological leap in switching power converters is happening right now: replacing IGBTs and PowerFETs with high electron mobility transitors (HEMTs), usually based on Gallium Nitride, GaN, and with silicon carbide (SiC) PowerFETs, which can switch efficiently at ten times (or more) higher rates, reducing size and cost even more.

This is all good news for improving power efficiency, saving on energy bills while also helping to save the planet

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by reducing emissions of CO_2. But it comes with the big EMC penalty of higher levels of noise emissions at higher frequencies, as Figure 1 illustrates.

Many higher-power switching converters such as variable-speed motor drives are supplied with installation instructions concerning EMC, which are usually quite good. However, my experience (and the experience of others in the EMC world) is that salespeople compete on price by ignoring the EMC installation requirements of new motor drive systems to help win contracts with customers who do not realize the EMI risks.

No one wants to invest in the construction of a new industrial plant, scientific research facility, offshore oil/gas platform, railway system, entertainment complex, data center, military vessel, cruise ship, or whatever, only to find that it cannot function properly due to self-generated EMI! The financial losses can be quite awesome, but even they can be exceeded by the cost of modifying the plant, platform, vessel, etc., to get it to function as intended.

As with all other EMC/EMI issues, it is much more cost-effective and financially less risky to design good EMC in from the beginning of any modern construction project.

Tim Williams and I co-wrote a book on EMC for Systems and Installations in 2000 [1]. It describes buildings and sites, but its material is easily extended to cover vehicles of all/any types, land, marine, subsea, air (fixed wing or rotorcraft), space, etc.

Among many other issues, this book covers the design and construction of the various kinds of (so-called) “earthing/grounding” systems/networks used in large systems and installations, including:

- Bonding networks (BNs)
- Isolated bonding networks (IBNs)
- Common bonding networks (CBNs)
- Meshed bonding networks (MESH-BNs)
- Meshed isolated bonding networks (MESH-IBNs)
- Meshed common bonding networks (MESH-CBNs)

This two-part article provides some background on these “grounding networks” that is not given in the book. It shows how and why, over the last few decades, they have had to develop from their original single-point-grounding schemes for safety, to meshed structures for cost-effectively managing EMC to minimize the costs of lost production and downtime due to EMI, including lightning.

THE PROTECTIVE EQUIPOTENTIAL BONDING SYSTEM

Metal and other conductive structures in buildings and vehicles, including all wiring and cables, can suffer from fault currents caused by insulation failures in their power supply equipment and distribution networks, and from surge transient currents caused by lightning.

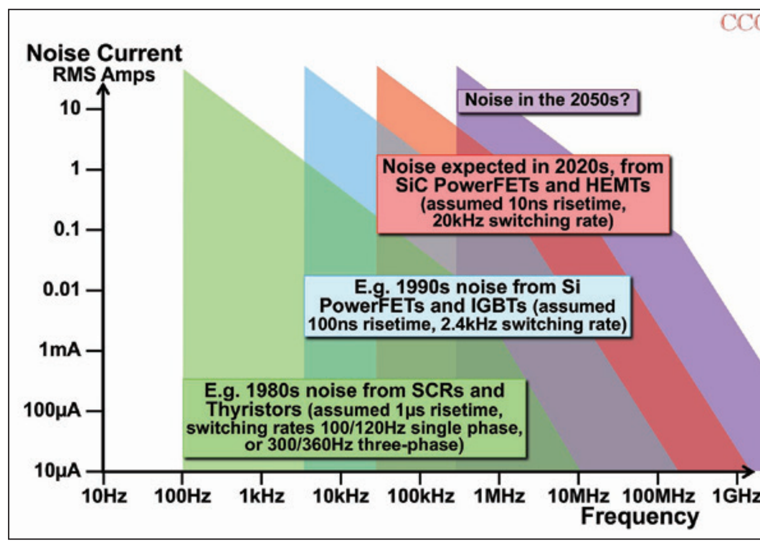

Figure 1: Illustrative example of noise spectra created by variable-speed motor drives and similar switching power converter equipment with power ratings around 100kW, having different technologies of power switching devices

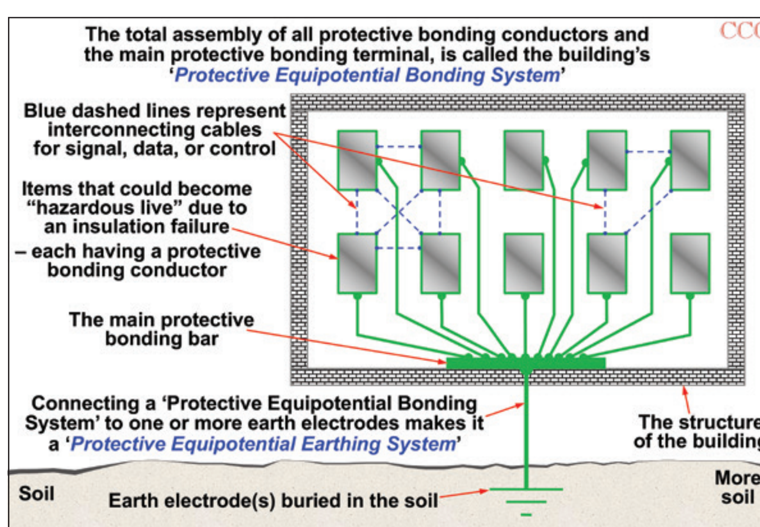

Figure 2: A sketch of a very basic protective equipotential bonding system

As fault or surge transient currents flow through the impedances of these metal structures and other conductors, they create heat and potential differences that could cause burns and electric shock hazards to people.

In flammable or explosive atmospheres, high temperatures could cause fires or explosions, as can the arcs or sparks that can be created when potential differences appear across gaps.

In IEC safety standards terminology, a protective equipotential bonding system is the total conductive structure created by interconnecting all of the "touchable" metal parts that could cause electric shocks to people due to insulation failures or the indirect effects of lightning[2] (see Figure 2).

"Touchable" means metal/conductive parts that are within the simultaneous reach of any parts of a person's body. This includes, for example, equipment cabinets or other conductive structures on either side of a walkway that are close enough to be touched by the fingertips of a person's left and right hands at the same time.

"Equipotential" is usually considered to mean – for dry environments – that the maximum continuous potential difference is no more than 25VAC rms at the 50Hz or 60Hz mains power frequency, or no more than 60VDC. Higher maximum values may be permitted for short-term potential differences and/or lightning-induced surge transients.

It is important to understand that the above values are general, and the actual values considered safe enough can vary from one standard to another, and from one country to another, and are usually specified at much lower values where environments can be wet or humid or skin could be sweaty, because human skin resistance is lower in such situations.[3]

It is often forgotten that "touchable" also includes the shells of mating connectors, and shielded cables that extend for many metres effectively extend a person's reach by the length of the cable! A good friend of mine fell from a very tall ladder when he disconnected an audio cable from a ceiling-mounted amplifier in a theatre and – because one hand was on the amplifier and the other on the disconnected cable's metal connector – got a severe electric shock. The fall broke his leg, and at that he was very lucky.

The maximum potential differences permitted for "equipotentiality" are achieved by ensuring sufficiently low impedances throughout a protective equipotential bonding system. The series impedance (Z) of a long conductor (well below its first quarter-wavelength resonance) is:

$$Z = \sqrt{[R^2 + (2\pi f L)^2]}$$

Where: R = series resistance in Ohms
L = series inductance in Henries
f = frequency in Hertz

For 50Hz and 60Hz, the impedance of most practical conductive structures is dominated by the R term in the above equation. However, most of the energy in lightning surge transients lies in the region of the spectrum up to 1MHz, and above a few kHz most conductor's Zs are dominated by the $2\pi f L$ term. So, the series impedances of ordinary conductors (e.g. those used for bonding items of equipment in protective equipotential bonding systems) become predominantly inductive above a few kHz, which is important for lightning protection (and for EMC, see later).

Mains power supplies are always protected by overcurrent protection devices, such as fuses. In the event of an insulation failure to the protective equipotential bonding system the resulting fault currents are so much higher than the normal mains currents that the overcurrent protection operates to remove the power from the conductor with the faulty insulation, generally within 1 second.

Metal structures and conductors in correctly designed, constructed and maintained protective equipotential bonding systems have low-enough resistances not to cause electric shocks. This almost always means that all their constituent parts have sufficient conductor mass and cross-sectional-area (CSA) to ensure that, in the time it takes the overcurrent protection to operate and stop current flowing from the faulty part or conductor, none of their parts will become heated up by enough to burn people's skin. Usually, the worst-case rise in temperature might just feel to the hand like a slight increase above ambient temperature.[4]

Indirect lightning surge transient currents could be as high as 10s of kA, but their durations are so short, at a few microseconds, that their heating effect in properly constructed protective equipotential bonding systems is also negligible. However, this is not necessarily the case for Lightning Protection Systems (LPSs).

Where flammable or potentially explosive atmospheres may be present some or all of the time, there are additional requirements for "equipotential bonding" to reduce the maximum potential differences between different metal parts. This is not to reduce electric shock risks, but to reduce the risk of sparking causing fire and explosion hazards. These are not covered here, but they are very well specified in the relevant standards.

For buildings on land, it is usual to connect this interconnected bonding structure to ground electrodes (conductors buried in the soil under and/or around the building) thereby creating a "grounded protective equipotential bonding system."[5]

It is important to understand that grounding (i.e., connecting to ground electrodes) is not always necessary, or desirable to protect against electric shock hazards. For example, even vehicles with on-board 230V AC mains distributions don't need grounding (in the strict sense of the word) to be safe. And trying to provide them with direct connections to ground electrodes would not be very successful!

In fact, the only reason for connecting a protective equipotential bonding system to the soil under and/or around a building is so that if people are stepping into or out of a building at the same moment as a nearby lightning strike to ground, or to the building, the surge transient voltage that is created between the building and its surroundings (e.g., sidewalks, roads, steps, stairs, gantries, etc.) is not so high as to cause them injury due to electric shock.[6]

In all non-medical equipment that complies with IEC safety standards for 230VAC rms mains supplies, the mains leads and the mains power converters are both insulated and galvanically isolated to withstand overvoltages caused by lightning surge transients up to at least 3kV rms, 4.24kV peak, repeated for many years. (Medical equipment safety standards generally require higher withstand voltages.)

A long, long time ago, electrical and electronic equipment was just a box on the end of a mains lead. For such equipment, the protective equipotential bonding system, grounded or not according to whether it was fixed or mobile, was sufficient.

However, signal/data cables connecting different items of equipment within an installation can be long, which exposes them to much larger potential differences. When such cables started to be used more often to interconnect items of equipment that were further apart, the cost, size and weight of insulating and isolating them to the same levels as used for mains cables was considered to be too high. So, bonding networks (BNs) were developed.

Unreliability of electronics due to the effects of lightning (within 5km or so!) is, for example, the reason why Ethernet transmitters and receivers always use data-isolating transformers – so that people could easily install Ethernets in legacy buildings which had protective equipotential bonding structures like those shown in Figure 2 (long wires from each piece of metal all the way back to a main bonding or grounding bar). These types of legacy installations suffered from high impedances above a few kHz, making them unable to control the lightning surge transient voltages that could occur between two items of equipment connected by a signal/data cable.[7]

BONDING NETWORKS (BNS)

This is IEC-speak for a part of a protective equipotential bonding system that uses additional cross-bonding of its conductors and other metalwork to reduce its overall impedance, so that the amplitudes of the high voltage surge transients that can arise between items of equipment that are located far apart, caused by lightning, are low enough to permit the use of affordable insulation/isolation on signal and data cables (typically, half of the peak voltage required for the insulation of mains supplies, and without the mains supply's requirement for galvanic isolation.)

To achieve a low enough inductive impedance up to 1MHz requires the lengths of the bonding conductors to be less than a metre. This can't be achieved by relying on the protective conductors in the equipment's mains leads, because the main bonding (or grounding) bars these conductors eventually connect to are often ten or more metres away, even in a small building like a domestic house. In an office block or industrial plant, the distances can be several tens of metres.

We sometimes see the impedance of conductors at the frequencies associated with lightning events referred to as the "surge impedance." This is a time-domain concept based on the surge test waveforms created by "combination wave generators" such as those specified by IEC 61000-4-5. Surge impedances are not relevant for EMC at frequencies above a few MHz.

Cross-bonding conductors and other metalwork has a strong effect on reducing the inductive impedances in a BN. To get the best protection for the lowest costs, the cross-bonding conductors should follow the routes (ideally, be strapped to) the signal/data conductors themselves, as shown in Figure 3.

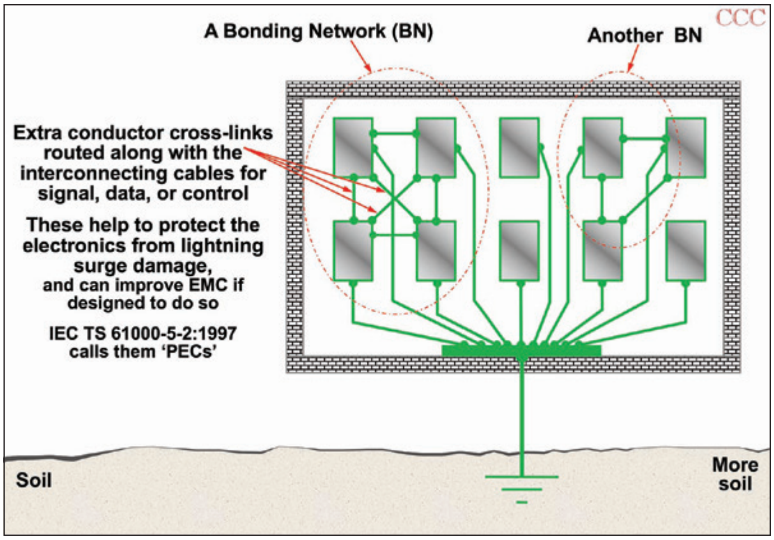

Figure 3: A sketch of two Bonding Networks (BNs)

IEC 61000-5-2 [3] calls cross-bonding conductors that follow the routes of the signal/data cables "protective earthing conductors" (PECs), and describes how existing structural metalwork, often called "natural metalwork," may be used to reduce the costs of implementing them. For example, in industrial and commercial applications, cables are usually supported by metal cable trays and conduits, which can be converted to very effective PECs merely by electrically bonding them together and to the chassis/frames of the different items of equipment whose cables they carry.[8]

Usually, a BN comprises a single room in a building where there are signal/data cables that need protecting because of the electronic equipment contained in that room. Where there are two or more individual BNs they are interconnected, at least by individual connections to the main bonding bar, as shown in Figure 3. (If the main bonding bar is used to connect the BNs directly to ground electrodes buried in the soil under and/or around the building, it is called a "main grounding bar.")

A question that always arises is whether the cross-bonding conductors have to be rated to carry the full fault currents that can arise due to insulation failures in the 50 or 60Hz mains power supplies and distribution networks. The answer is that, in cases in which a protective equipotential bonding system complies with modern safety requirements (and is maintained so as to ensure continual compliance) so that during such faults, it does not overheat sufficiently to suffer damage including to any insulation, then cross-bonding will not have to be rated to carry mains fault currents. Even cable shields electrically bonded at both ends (the only way to make them shield properly at RF, see [1], [3]) should not be damaged by a mains fault in a correctly-bonded protective safety system.

However, many legacy protective equipotential bonding systems might not meet modern safety requirements without extensive and costly modifications, and some owners or users of older buildings are known to use a "there is no evidence of a problem" approach to avoid such costs.

When asked to work for such an owner or user, I strongly recommend turning down the work unless you are allowed (and paid!) to do a "proper job" safety-wise. Never underestimate the ability of legal counsel to pin the blame for a costly or lethal fire or electrocution on anyone other than their client, even going against common sense that "everyone knows."[9]

Over time, systems have grown larger, variable speed drives have become larger and more common, and systems-of systems are now being created, meaning that signal/data cables have to span two or more BNs (e.g., computer networks, lighting control systems, air-conditioning systems, etc.). These BNs therefore have to be cross-bonded together to create larger BNs, ultimately cross-bonding the whole building and creating a common bonding network, or CBN.

But CBNs can be costly to retrofit to legacy buildings or vehicles, so the BN concept was developed to create the IBN – isolated bonding network. We'll discuss that in Part 2 of this article.

ENDNOTES

1. EMC = Electromagnetic Compatibility, the engineering discipline of ensuring that: a) electromagnetic emissions are low enough for radio/telecommunications and other electronic equipment to function as intended without suffering from unacceptable electromagnetic interference (EMI); and that, b) the electromagnetic immunity of equipment is sufficient for it to function as intended in the electromagnetic environment expected to be present where it is used. ***Note:*** EMC standards and legislation are not concerned with any safety issues, despite the fact that EMI can be a cause of functional safety risks.

For a number of articles on this topic, visit https://www.emcstandards.co.uk/emiemc-risk-management.

2. Protection from the direct effects of lightning to buildings themselves and the people and equipment within them, is provided by a Lightning Protection System (LPS), e.g. as specified in the four parts of IEC 62305. An LPS is a different structure from a Protective Equipotential Bonding System, although the two structures are usually connected together at one or more points. LPSs generally are designed to withstand surge transient currents of the order of 100kA – 200kA and are not covered any further in this article, but see Chapter 9 in [1] for information on Part 4 of IEC 62305, which deals with protecting electronic equipment rather than people and is relevant for the design of Protective Equipotential Bonding Systems.
3. 25VAC rms and 60VDC are both far higher than what would be understood as "equipotential" by electronic engineers, showing one of the dangers of misusing safety terminology in other applications. To help avoid costly confusion in projects, I always recommend only using the word "equipotential" for issues relating to personnel safety from electric shock, and never for anything to do with electrical or electronic circuits, or EMC.
4. However, there are some power supply systems for which this might not be true, and for which the temperature rise in the protective equipotential bonding system might need to be controlled to prevent burns, such as in installations that use large superconducting magnets. Large grid-storage batteries are another modern concern.
5. Regular readers of my blogs [2], or people who have attended my training courses are used to me banging on about the very costly confusion caused by the misuse of the words ground, grounded, grounding, etc. Strictly speaking, they should only ever be used for conductors that connect directly to the body of the planet by being buried in the soil. But people use them indiscriminately, e.g., they talk about "grounding" an electrical circuit in a cellphone; or about "safety grounding systems" in cars and aircraft, when none of these examples has anything to do with the soil, or any need to be grounded (in the strict sense) for either correct circuit operation or safety. I'm not the only one who complains about the misuse of terminology associated with "ground." Check out "The Ground Myth" by Dr. Bruce Archambeault of IBM, at http://web.mst.edu/~jfan/slides/Archambeault2.pdf, especially slide 37 for a good laugh.
6. This reminds us to be careful when stepping into or out of vehicles during thunderstorms! The best method is to jump in, or out, with both feet at once, keeping both hands and arms tight in against our sides. However, I should mention that an alternative method – simply trusting to luck that lightning won't strike the vehicle or near to it while getting in or out – is preferred by most people. Can't think why!
7. Telephone landlines are a special case because they do pick up lethal kV surge transients from lightning due to their very long lengths exposed outside of buildings. Telephone systems providers learned very early on to provide suitable protection, at the point where their landline entered/exited a building, because killing off your customers and/or setting fire to their houses is not good business sense.
8. I really wish they hadn't called them protective earthing conductors, because their protective function works just as well whether they eventually connect to earth electrodes or not. They should really have been called "protective bonding conductors" (PBCs), or "supplementary bonding conductors" (SBCs). IEC 61000-5-2 [3] is a truly excellent document in every way – a total game-changer in the 1990s (that most system integrators and installers still don't seem to know about) – except that it uses the words "earthed" and "earthing" when it really means "bonded" and "bonding." See my little rant earlier about the costly confusions still being caused by this age-old mistake.
9. It seems that even Ohm's Law can be a matter for juries (who are almost always non-technical people) to decide upon! Read https://www.emcstandards.co.uk/the-law-versus-reality.

REFERENCES

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   The practical material in the book is also available in a series of articles in 2000, free from: https://www.emcstandards.co.uk/emc-for-systems-and-installations-series; two free guidebooks posted at: https://www.emcstandards.co.uk/good-emc-engineering-practices-in-the-design-an1 and https://www.emcstandards.co.uk/good-emc-engineering-practices-for-fixed-instal2, and the up-to-date training course available from: https://www.emcstandards.co.uk/emc-for-systems-installations2.
2. Keith's blog: https://www.emcstandards.co.uk/blog.
3. IEC 61000-5-2:1997, "Electromagnetic Compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling," from the BSI and IEC web shops.

EMC and Safety for Installations: Part 2

Developments in Ground Bonding Networks

BY KEITH ARMSTRONG

Editor's Note: In this article, the words "ground," "grounded" or "grounding" are used interchangeably with "earth," "earthed," or "earthing."

The first part of this article introduced the first protective equipotential bonding/grounding systems, which only had requirements for human safety. It showed how – as electronics became more commonplace and more interconnected and variable-speed motor drives increased in power – these early structures developed into bonding networks (BNs) to protect electronics from damage due to insulation failures and lightning surges. Site-wide BNs are costly to create, so in those early days it was common to only provide BNs for the parts of a site where electronic equipment was installed. This led to the development of the isolated bonding network (IBN), which is where this Part 2 picks up.

ISOLATED BONDING NETWORKS (IBNS)

An IBN is a BN that is isolated from the rest of the protective equipotential bonding system, except for at one single point of connection (SPC) (see Figure 1 on page 74).

The idea of the IBN is that when fault or lightning currents occur in the rest of the building (or vehicle), their isolation prevents those currents from flowing through the nice low impedance created within the IBN, helping to protect the equipment it contains.

The usual guidance is that – with all of its mains power supplies isolated at the IBN's distribution cabinet(s) and any uninterruptible power supplies (UPSs) switched off, and then its SPC temporarily disconnected – an IBN should be able to withstand a voltage of at least 10kVDC with respect to the rest of the building's protective equipotential bonding system for at least one minute, without any current flowing in "sneak paths," including via corona discharges, arcs or sparks, once the IBN's stray capacitances have been charged up.

(It should go without saying that if an IBN is constructed where there could possibly be a potentially flammable or explosive atmosphere, its isolation should never be tested with high voltages as described above! Also, always remember to reconnect SPCs after successful voltage withstand tests, and do not reconnect the mains power

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supplies to any equipment within an IBN until after its SPC has been properly reconnected.)

Never rely on simply switching off the items of equipment within an IBN individually before testing its isolation as briefly described above. This is because all items of electronic equipment are fitted with EMI/RFI filters that "leak" milliamps of stray currents into the protective grounding conductor in their mains leads, and it does not take many such items for these leakage currents to build up to lethal levels. The EMI filters in high-power variable speed drives (VSDs) and other switching power converters can individually leak hundreds of mA, even Amps, into their protective ground.

These filters are usually fitted before the mains on/off switch, so they remain powered up and leaking current when the equipment has apparently been switched off using its own controls. This is why, before testing the voltage isolation of an IBN, all of its mains power supplies (there may be more than one) must be isolated at the IBN's power distribution cabinet(s), and any uninterruptible power supplies (UPSs) within the IBN switched off.[1]

In the old days, each commercial or industrial building had a dedicated electrical manager, a skilled electrical engineer who ensured that no one compromised its protective equipotential bonding system or did anything else that might cause fires, shocks, unreliability, etc., and also supervised any/all upgrades and modifications. These knowledgeable professionals maintained the electrical drawings and knew them like the backs of their hands.

But these days it is much more common not to employ an electrical manager. Instead, suitably skilled subcontractors are hired when upgrades and modifications are done, or for annual inspections. Of course, they may not be familiar with a particular building's electrical installation, or its history. And, if my experience is any guide, the building's owners or operators may not have ensured that its electrical drawings have been kept up-to-date, and may not even know where they are, or which subcontractor had them last!

In such situations, it is possible for very-carefully-designed IBNs to be seriously compromised by changes and modifications made by people who are unaware of their importance (or even existence). I have seen it happen even in major national infrastructure plants. All it takes to compromise an IBN is for a person to string an Ethernet cable from their office outside an IBN to a computer inside an IBN. The consequences for equipment damage, and even for significant fire and shock hazards, especially during a thunderstorm, can be very severe indeed.

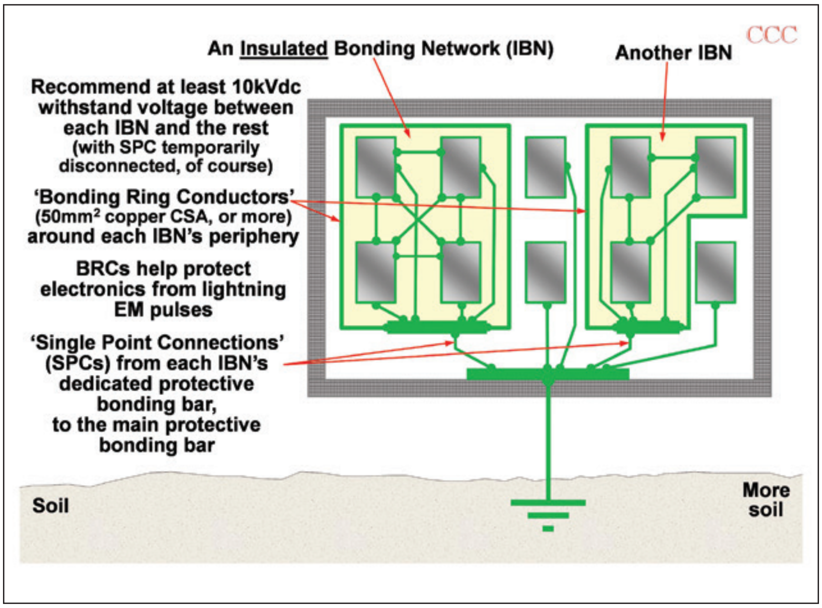


Figure 1: A sketch of two Isolated Bonding Networks (IBNs)

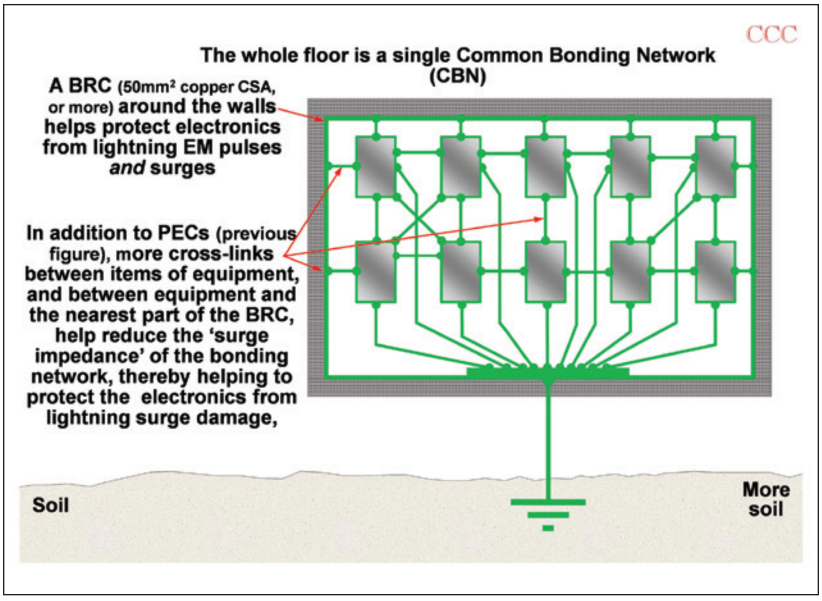


Figure 2: A sketch of a Common Bonding Network (CBN)

So, it is good general safety and reliability guidance to use CBNs, and not to use IBNs unless the building or site has 24/7/365 supervision by permanently-employed competent electrical engineers or technicians who understand where all the IBNs are and how (and why) to keep them isolated. These engineers or technicians should also approve any changes to any wiring (even Ethernet cables) and supervise all maintenance.

COMMON BONDING NETWORKS (CBNS)

A CBN is a single BN that is "common" to an entire building (see Figure 2).

The big advantage of a CBN is that signal/data cables may be run around anywhere in the building – ideally strapped to bonding conductors/metalwork along their entire lengths to use them as PECs – without having to make any alterations to its protective equipotential bonding system. This makes adding new equipment in the future easy to do and relatively inexpensive.

The previous discussion has only concerned human safety as regards electric shock hazards, and the protection of electronics from damage by surge transients caused (indirectly) by lightning. However, all conductive items behave like "accidental antennas".[2] This fact means that for good EMC, all conductors and any pieces of metal – that are not functional conductive parts in any electrical/electronic circuits, of course – should be interconnected so as to be integral parts of any BNs, IBNs or CBNs – whether these conductors or pieces of metal have anything to do with electrical safety or not.

MESHED BNS, IBNS AND CBNS

Computer electronics initially used circuits operating from 5VDC power rails, and with such low-voltage signals/data the "equipotential" voltages considered acceptable between "touchable" points during faults and thunderstorms in protective equipotential bonding systems were much too high. But the cost of fitting suitably rated insulation/isolation to every data cable regardless of how short it was would have been totally ridiculous.

So, when computer rooms and digital telephone exchanges (called Central Offices in the U.S.) started to be built in the 1970s, they invented much cheaper solutions: MESH-BNs, -IBNs and -CBNs. The word MESH in the acronym refers to the fact that multiple cross-bonds are needed to reduce the inductances in the protective equipotential bonding systems by enough to reduce the exposure of digital electronics to lightning surge damage, and (in the 1990s, when the European Union's EMC Directive loomed) to help achieve EMC for systems and installations.

Generally, these structures take the physical form of regular "grids" or "meshes" of bonding conductors – hence their name (see Figures 3 and 4).

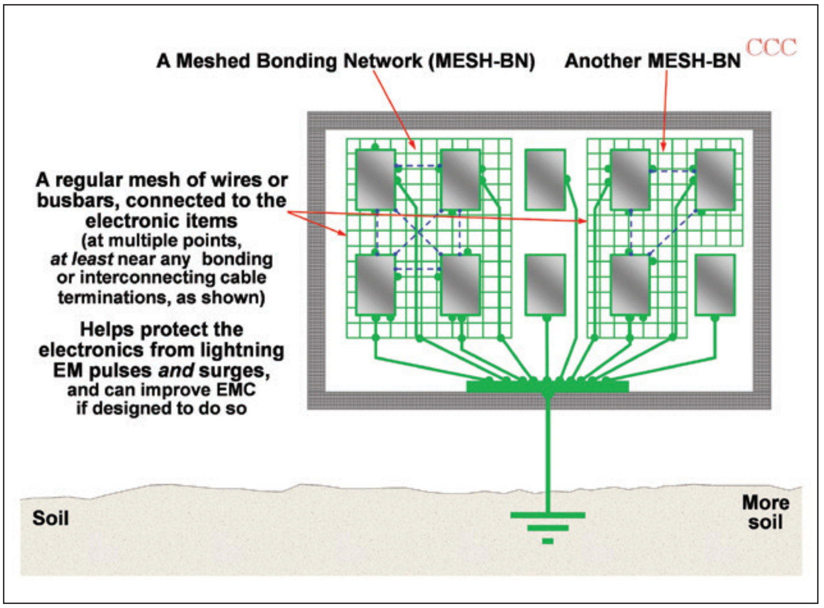


Figure 3: A sketch of a two MESH-BNs

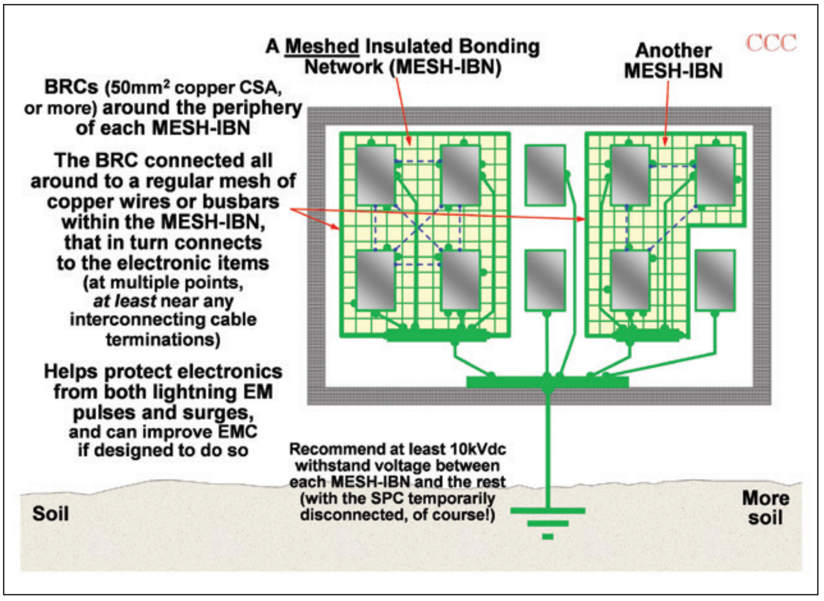


Figure 4: A sketch of two MESH-IBNs

Initially, these meshed conductive structures were called SRPPs (for system reference potential planes), BMs (for bonding mats) or a wide variety of jargon or proprietary terms that can be found in computer and telecom system installation guidance documents from the 1970s, 80s, and 90s.[3]

Figure 5 shows the sort of SRPP design that was often used. The conductors used for the mesh were usually 6mm diameter copper, soldered at their joints, but some preferred to use wide copper "lightning tape" because of its lower inductance and ease of jointing using the clamps used for that purpose when constructing LPSs. Some computer/telco system installers used "natural metalwork" instead of installing a copper mesh, either by using the metal framework that supported the computer false-floor tiles as the mesh, or interconnecting the metal backs of the computer floor tiles. Figure 6 shows a modern proprietary development of the latter approach.

As time went on, these computer systems grew to occupy more than one room, so the rooms' individual MESH-BNs or MESH-IBNs had to be mesh-bonded together to reduce the "surge impedance" of the new combined BNs or IBNs being created.

Remember that when the $Z = \sqrt{[R^2 + (2 L)^2]}$ expression was introduced in Part 1 of this article, I mentioned that this was only relevant for conductors well-below their first quarter-wave resonance. We now need to correlate this with mesh dimensions.

Most lightning energy is contained in the spectrum below 1MHz, but it is still considered to have significant amount of energy up to 10MHz. The wavelength in air of 10MHz is 30 metres, making its first quarter-wavelength resonance 7.5m. So, a mesh size of 5m or less on a side (in air) is considered effective against all lightning frequencies, and the smaller the mesh size the lower its inductance between any two points and the lower the surge transient voltages that can arise due to induced lightning currents.

For good EMC, we may want our meshes to be smaller, either to control higher frequencies than 10MHz due to speedier computer data, or to provide lower impedances below 10MHz due to high-power VSDs. For example, 30MHz was a common goal in early computer systems and required mesh dimensions of around 600mm on a side,

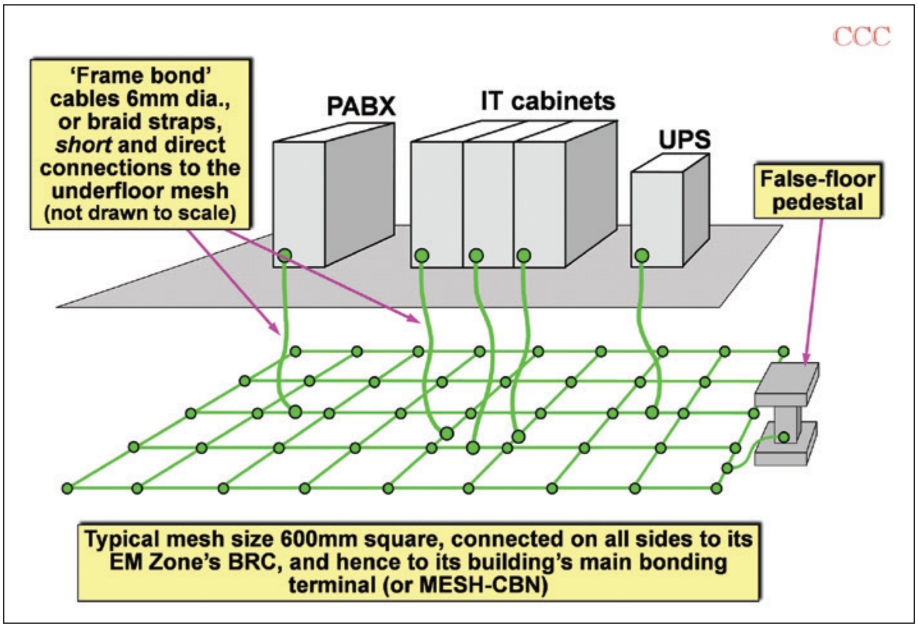


Figure 5: Example of constructing an SRPP, from the 1990s

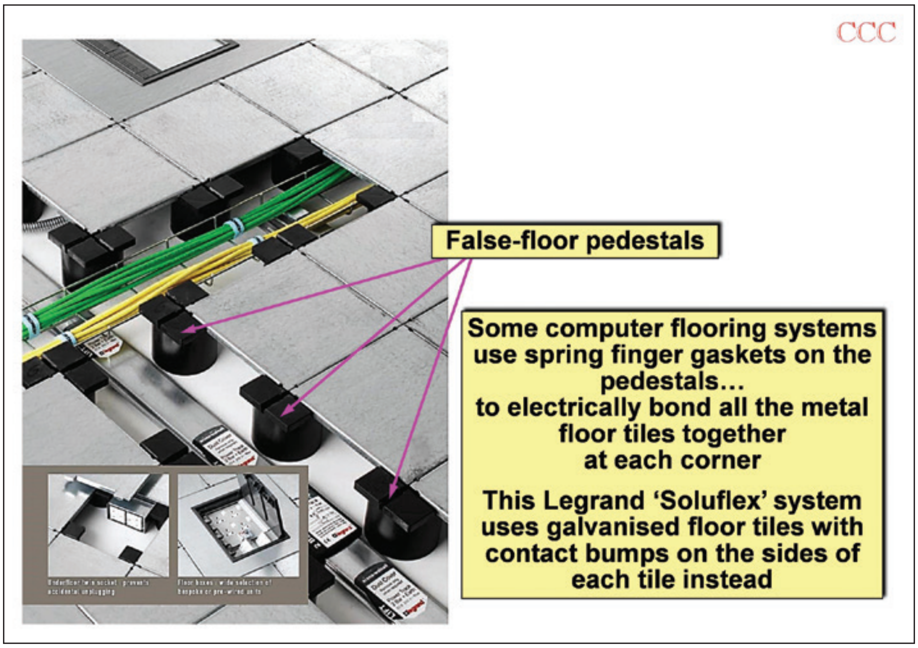


Figure 6: A proprietary system for constructing SRPPs using false-floor tiles themselves

as shown in Figure 8. Modern computer systems may require meshes to control 100MHz or more.

The VSD technology that was new in the early 1990s could excite structural resonances in installations up to a few MHz, and this frequency has been steadily rising as power switching devices have developed. These frequencies are lower than those used by computer data, but on the other hand, their levels are much higher, so the sizing of a mesh size could depend more on the VSDs used on the site than on its computers. This issue will become much more important as the next generation of power switching devices replaces IGBTs and silicon powerFETS during the 2020s.[4]

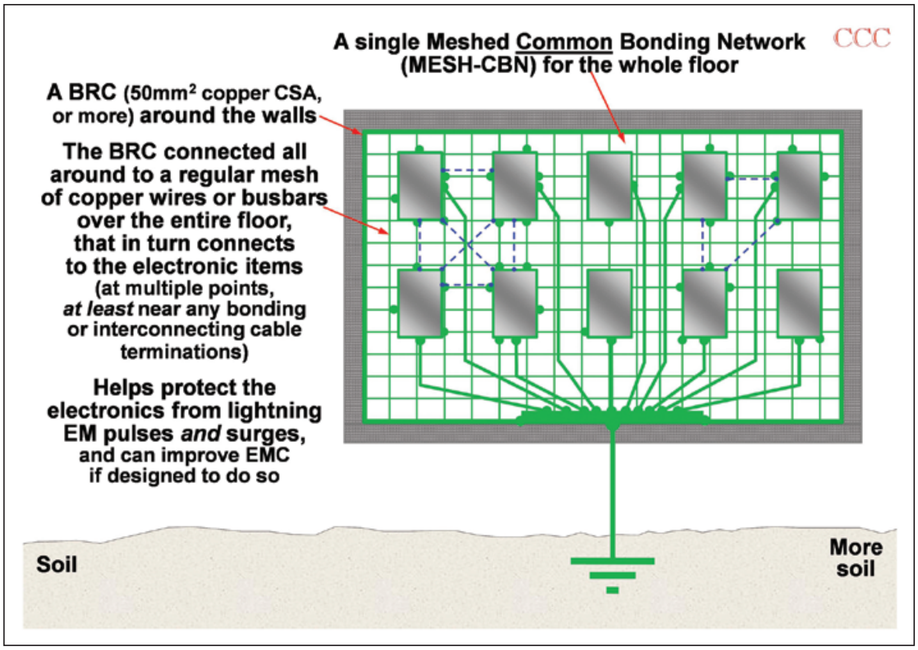


Figure 7: A sketch of a MESH-CBN

Clearly, to be able to easily and quickly install new electronic systems or VSDs these days, it helps if you don't have to first modify a building's protective equipotential bonding structure (whether it is grounded to rods in the soil, or not) to create MESH-BNs, IBNs or CBNs. Modifying existing installations to create meshed bonding networks for new equipment can easily cost more than the new equipment itself! After all, you often have to cut into floors or walls to get at the conductors that need to be meshed together.

Also, in industrial applications it has long been a simple matter to use existing metal cable support structures and/or cable armor as PECs. But this clever cost-saving measure is very vulnerable to changes and modifications being carried out by people who are not aware that these metal structures have any functionality other than mechanical. Creating a well-meshed CBN helps avoid problems of unreliability and/or EMC arising for such reasons.

So, since the mid-1990s, the general recommendation for all systems or installations is that "new-builds" should install MESH-CBNs right from the start. It is also generally recommended that legacy buildings convert to MESH-CBNs as soon as practical, usually a gradual process as new equipment is installed.

These recommendations are set to become much more important during the next few years, as the new generation of power switching converters and variable-speed motor drives based on HEMTs and SiC powerFETS discussed in Part 1 of this article become readily available in high power ratings.

Figure 7 shows a MESH-CBN covering an entire floor of a building, but of course, we may need to extend them in three dimensions to other floors too, and Figures 8 - 10 on pages 78 and 79) are copies of relevant slides from my training course on EMC for Systems and Installations.[5]

SPECULATION ON 3G, 4G, 5G, ETC., AND FIBRE-OPTICS

What if low-cost high-rate digital wireless comms had been available back in the 1970s? Even 3G cellular systems would have made data cables unnecessary back then, making BNs, IBNs and CBNs unnecessary. As the complexity of the electronic systems grew, wireless datacomms would have kept pace, first with 4G and then 5G.

Perhaps when 5G is mature and proven to be robust in industrial applications (despite the high levels of interference often associated with industrial processes), we will simply be plugging 5G modems into USB 3 sockets to carry industrial Ethernets, with no longer any need for data cables, hence no need for costly MESH-BNs, -IBNs, or -CBNs. Protective equipotential bonding/grounding networks would still be required for human safety, but nothing more complex than the original types sketched in Figure 1 of Part 1 of this article – a big reduction in the use of costly copper.

A similar speculation concerns low-cost fibre-optics. If we had had modern low-cost fibre-optics running at 25Mb/s in the 1970s, they would have been preferable to copper cables (with all the EMC problems created by their unavoidable "accidental antenna" behaviours).

These days, when people ask me for help in fixing data interference problems with cables between items of equipment in scientific/industrial systems/installations, I am increasingly recommending that they replace their copper data cables with fibre-optic "modems" connected by (metal-free) fibre-optical cables. The cost of fibre-optic systems is steadily falling, and their data rates are steadily increasing, and using them instead of copper cables avoids the need to create MESH-BNs, -IBNs, or -CBNs.

Even though the cost of a fibre-optic solution may be a few hundred or thousand U.S. dollars, very little time is required for installation. Although creating a MESH-BN, MESH-IBN, or MESH-CBN might appear at first to cost less, it will almost certainly cost a lot more overall when labour costs are taken into account, never mind the costs of the lost production while these intrusive modifications are being undertaken.

Also, while the fibre-optic solution is almost guaranteed to work first time (no one with any real experience

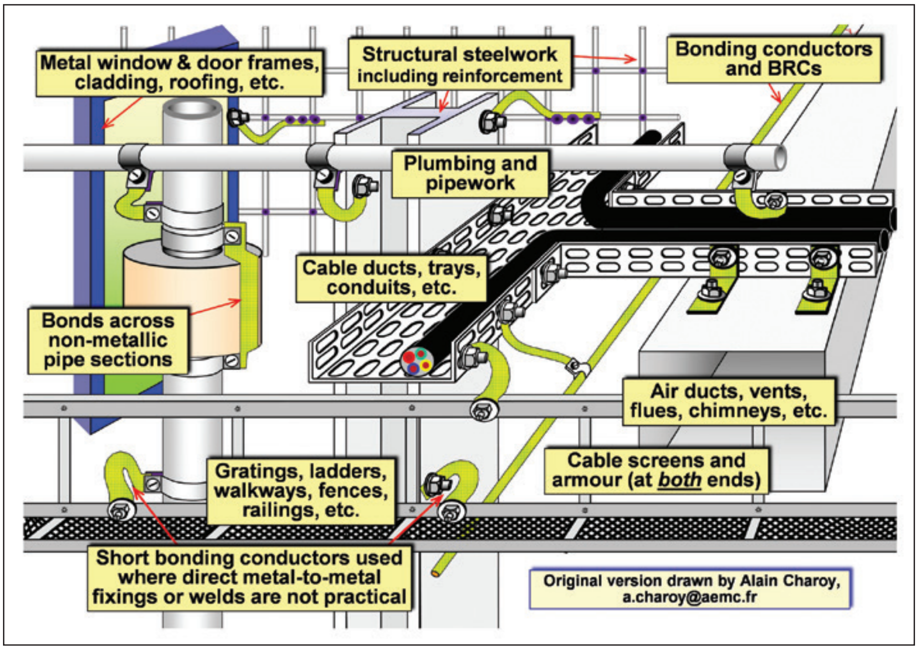


Figure 8: Using "natural" metalwork in a building-wide 3-D MESH-CBN

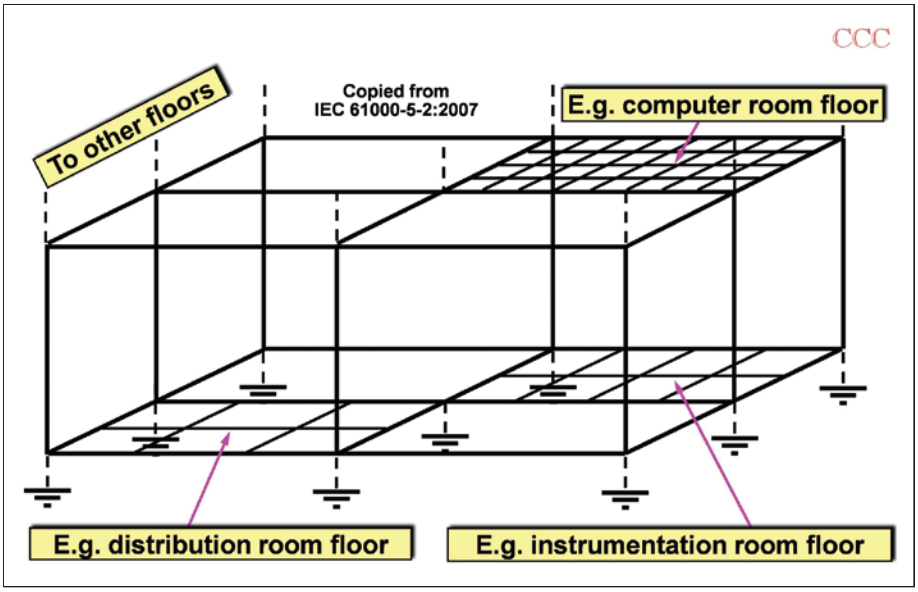


Figure 9: A sketch developed from a Figure in IEC 61000-5-2, showing the vertical bonding between MESH-CBNs on different floors of a building

ever guarantees anything where EMI is concerned!), converting a legacy installation into a MESH-BN, -IBN, or -CBN can be a bit of a gamble. Installing meshed bonding in legacy buildings is very labor intensive and time consuming, but going for a least-cost option might well only result in having to do it all over again! For example, the mesh size depends upon how low the overall impedance needs to be, and the highest frequency it needs to control, and these are often not understood as well as they might be.

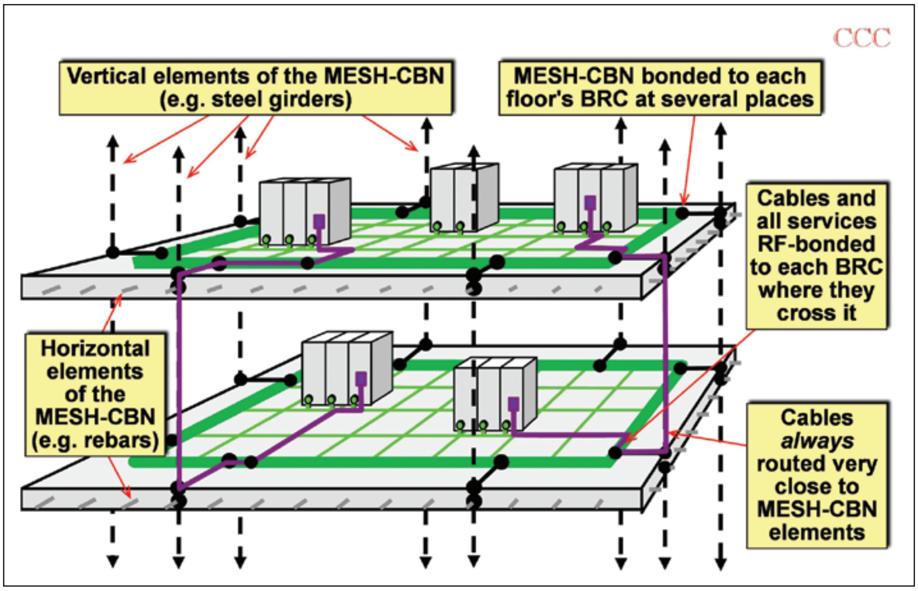


Figure 10: A sketch of using "natural" metalwork to vertically bond between MESH-CBNs on different floors of a building

Also, will the resulting meshed structure be future-proof, or will it need to be modified again when the existing equipment is upgraded or replaced, or when new equipment is installed nearby in a few years' time? Even replacing failed equipment with new versions of the exact same product from the same manufacturer inevitably causes ever-increasing noise problems at ever-higher frequencies.

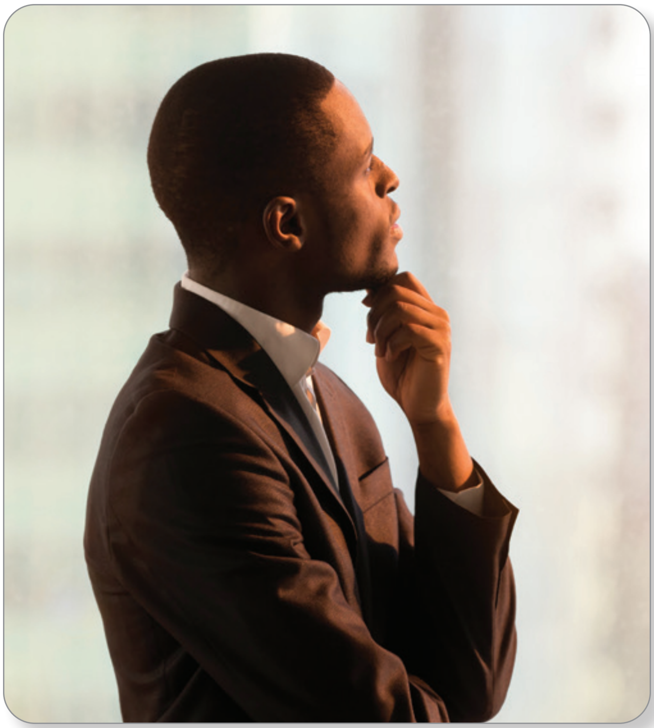
This problem arises because the newer versions inevitably use newer power switching devices and newer microprocessors that switch more quickly – whether we want or need them to, or not! The original, slower semiconductors are simply no longer available to manufacturers, whose products therefore tend to become ever noisier at ever-increasing frequencies – even when they remain fully compliant with the relevant emissions standards.

Generally speaking, for the best EMC with the lowest overall costs, now and in the future, copper cables should only be used for (well-filtered!) AC or DC power. And all signals, data, and controls should use either (metal-free) fibre-optic cables or proven-industrially-robust and reliable wireless datalinks.

ENDNOTES

1. It is always a problem in a brief article like this for an author to know how far to go into the detail, especially where safety issues are concerned. I have to assume that my readers understand that testing an IBN by isolating it and charging it up to 10kVDC has the potential to injure people due to electric shock – therefore such tests should only be carried out by people independently certified as being competent to perform them, and who regularly perform such tests. The high-voltage test generators must be current-limited to help prevent dangerous shocks, and the area of the IBN and near to it kept reliably off-limits to all personnel not directly involved.
2. All conductors (including any metalwork) are "accidental antennas," whether we want them to be or not. See https://www.emcstandards.co.uk/the-physical-basis-of-emc for more details on this.
3. For example, I have seen such a guide from the 1970s that said the SRPP for a computer room had to maintain an 'equipotential voltage' from one corner to another that should not exceed 0.7V at frequencies up to 30MHz.
4. This article is not the place to discuss mesh sizing in detail. But, for more information about EMC, see *EMC for Systems and Installations*, Tim Williams and Keith Armstrong (available at https://www.emcstandards.co.uk/emc-for-systems-and-installations). Also see section 5 of "Good EMC Engineering Practices for Fixed Installation" at https://www.emcstandards.co.uk/good-emc-engineering-practices-for-fixed-instal2 for information on using rebar meshes and the like to help protect installations from the powerful electromagnetic pulses (EMP) that can be created by lightning and nuclear explosions (e.g.: LEMP, HEMP, NEMP, etc.).
5. Available at https://www.emcstandards.co.uk/good-enc-engineering-practices-for-electricalel.

So You're a New EMC Engineer… Now What?



Looking to master the world of EMC?

Here are some tips from an industry veteran.

BY DARYL GERKE, PE

It's been said that nobody grows up wanting to be an EMC engineer. Rather, it usually just happens. Maybe you had incriminating information on your resume, such as being a radio ham. "You've created interference, so you must know how to stop it, right?" Maybe you showed a knack for EMC troubleshooting, and suddenly you're now the company expert – whether you want to be or not. Or maybe you just zigged when you should have zagged.

In any event, you're now in the EMC trenches. In this article, we'll discuss what to do next. It won't happen overnight, but with a plan (and some work), you can move from EMC-novice to EMC-expert.

FIRST, FIND A MENTOR…

If you are in a big company with an established EMC group, this may be your boss or a colleague. You need someone who has experience and who is willing and able to share it. Fortunately, most EMC engineers are happy to help – particularly the older ones, so don't be afraid to approach the more senior members of your engineering staff.

If you are in a smaller company, identifying a mentor may be more difficult, particularly if you are the sole EMC practitioner. In this case, you may need to look outside the company. Good candidates for mentors are your local EMC test lab, or perhaps an EMC consultant. Since both sell their time, fees may or may not be involved, but your company should be willing to invest in your education. After all, they put you in this position, and they want you to do well.

GET SOME EXPERIENCE – FAST…

If you are responsible for the front-end design work, get to know the design teams. Participate in design reviews even if you don't feel you know a lot about EMC. Trust me, this is a quick way to accelerate learning, particularly if you are a young engineer.

Be curious, and ask questions. Don't worry that you don't know the answers – you are in learning mode. And don't limit yourself to EMC engineers. Designers in specialized areas like power electronics, RF or analog circuits often have valuable insights applicable to EMC issues.

Witness EMC tests. If you are hired into an EMC lab, you'll be doing this anyway under the supervision of an experienced EMC test engineer. If you're doing design work, get in as much test time as you reasonably can. It is amazing how much you can learn by just watching an EMC test. An added advantage – you'll also get to know the good folks at the test lab.

Daryl Gerke, PE, has been a successful consulting engineer for 41 years (http://www.emiguru.com). In 1978, Daryl and his business partner (the late Bill Kimmel, PE) co-founded Kimmel Gerke Associates as a part time electrical engineering consulting firm. In 1987, they went full time specializing in EMI/EMC design, troubleshooting, and training. Daryl has a BSEE (Electrical Engineering) degree from the University of Nebraska, is a Registered Professional Engineer (PE), and a NARTE Certified EMC Engineer (NCEE). He can be reached at dgerke@emiguru.com.

START ON YOUR SELF-EDUCATION…

Unfortunately, undergraduate engineering classes on EMC are few and far between. Graduate programs are even more rare, and those that do exist usually focus on specific research. As a result, you may need to set up your own self-training program. Here are some ideas.

Books

While I have over a hundred EMC books on my bookshelf, there are four I regularly recommend for newcomers to EMC.

- EDN Magazine Designer's Guide to EMC – written by my late business partner Bill Kimmel and me as a beginner's guide for non-EMC engineers. Simple explanations and recommendations, with no equations or complex math. A good place to start if you are new to EMC. Available in PDF and hard copy. Published by Kimmel Gerke Associates.
- Electromagnetic Compatibility Engineering – written by Henry Ott as a major update to his previous book (Noise Reduction Techniques in Electronics Systems). Well written, with all the equations you need without field theory or complex calculus. Published by Wiley & Sons.
- Introduction to Electromagnetic Compatibility, 2nd Edition – written by Clayton Paul, primarily as a college text, so it has lots of technical depth with all the field theory details. At the same time, very readable and practical. Published by Wiley Interscience.
- High Speed Digital Design – A Handbook of Black Magic – written by Howard Johnson as the definitive guide on Signal Integrity. Easy to read, with all the great design advice applies to EMC too. Published by Prentice Hall.

Magazines

There are several publications serving the EMC community. The good news is that two are free, and all are filled with practical articles.

- *In Compliance* (you are reading it now) – monthly, with an annual buyers guide. Design, test and regulatory issues. Focus on commercial electronics, blanketing compliance related topics. Free on-line, free hard copy in North America. Same Page Publishing Co.
- *Interference Technology* (formerly ITEM) – annual buyers guide with additional guides throughout the year.

Primarily test and regulatory issues, with an emphasis on EMC. Free. ITEM Publications.

- *IEEE Electromagnetic Compatibility Magazine* - Quarterly publication of the IEEE EMC Society. Included with membership the EMC Society.

Courses

These are excellent ways to gain focused practical information in a short time. They typically run from 2-5 days in duration and are offered throughout the US. In house classes are another option. Here are three major providers of EMC training.

- Kimmel Gerke Associates Ltd – EMC Design classes now offered primarily in-house, with schedule by mutual agreement. Over 12,000 past students.
- Wyatt Technical Services LLC - EMC Design classes offered both in-house and public. Part of an annual EMC Week in Las Vegas, NV.
- Washington Labs Academy – various EMC issues (length varies), with an emphasis on test and regulatory topics. Classes on-line and throughout the year at Washington Labs in Maryland.

Regulations

Last, but not least, you want to get copies of the EMC regulations applicable to your industry.

Most are copyrighted and have a fee, but government regulations such as MIL-STD-461 and MIL-STD-464 are in the public domain and are free. The latter also have detailed appendices that are great tutorials on the "why" along with the "how" of the various tests.

Here are the main EMC requirement by industry (with web sites.) Many of these are tailored by individual companies as internal EMC requirements.

- Military – MIL-STD-461 & MIL-STD-464 (https://quicksearch.dla.mil/qsSearch.aspx)
- Avionics – RTCA DO-160 (http://www.rtca.org)
- Automotive – SAE J551 & SAE J1113 (http://www.sae.org)
- Commercial/Industrial – FCC Part 15, EN55022/55011, EN61000-4-x (http://www.fcc.gov, http://www.ansi.org)
- Telecommunications – Telcordia (formerly Bellcore) GR-1089 (http://telecom-info.telcordia.com)
- Medical – EN60601-1-2, FDA "Reviewer Guidance" (http://www.ansi.org, http://www.fda.gov)

PARTICIPATE IN THE EMC COMMUNITY…

The community is small, but tight. Don't worry – fresh recruits are always welcome. Maybe it is a case of "misery likes company", but you will find most EMC folks are friendly to newcomers.

This is especially true of many EMC old-timers. Most of us have enjoyed the journey and are happy to share what we have learned. Since little of this is taught in schools, most of us learned (and continue to learn) directly from colleagues and those before us. So if you are a new EMC engineer, don't hesitate to ask for help.

The IEEE EMC Society is probably the biggest community resource. Among the smallest of the IEEE professional societies, the EMC Society is very active. It hosts chapters throughout the world, along with annual symposiums. Both provide excellent opportunities for ongoing education and professional networking.

If you have graduated within the last 15 years, check out the IEEE EMC Young Professionals, which has their own IEEE affinity group. (If you are an old coot like me, just hang out at the bar at the next EMC symposium — you will be in good company.)

Join an EMC Chapter

My first recommendation is to join your local IEEE EMC chapter. Go to http://www.emcs.org for a list of chapters, many with links to their local pages. Most chapters host at least four meetings a year, and usually include a speaker discussing a technical topic. Finally, you don't need to be an IEEE member to attend – if you are interested in EMC, you are always welcome.

If you don't have a local chapter, consider forming your own. Upon moving to Phoenix 22 years ago, I missed the camaraderie of the Minnesota chapter. So two other EMC engineers and I reactivated the local chapter, which had been defunct for years. It is still active 22 years later.

And, you are not alone. The EMC Society will help with its Angel and Distinguished Lecturer programs.

Attend EMC Symposiums

My next recommendation is to attend an IEEE EMC Symposium. These are held annually around the US, with additional international symposiums around the world.

A word of caution – you may need to convince your management of the value of attending. Trade shows are often seen as a boondoggle, but this can be an excellent educational opportunity. Even after almost 50 years in this business, I learn something new from every show.

Here are some suggestions for attending the symposium:

- Attend all five days. While the main technical sessions are Tuesday through Thursday, tutorial sessions are held on

Monday and Friday. These tutorials sessions are often aimed at the new EMC engineer, but I find them useful too.

- The Tuesday through Thursday technical sessions are usually heavy on analysis and modeling, so make these a lower priority. Now this may irk the academics, but you can always read the papers later. If a particular paper interests you, by all means attend. Sometimes there are special sessions, and we've found those to be very useful. The point is – don't spend all your time in the meeting rooms.
- Spend time on the show floor. Talk with the vendors to find out about new products, and attend the special tutorial demos. Both can be particularly beneficial to the new EMC engineer.
- Attend the social events. Remember, "All work and no play…" Besides, this is a chance to rub shoulders with those in the business. Although many engineers are introverts, try to mingle, meet and ask questions. Most of those you meet will be fellow engineers.

Use LinkedIn

Finally, use your on-line resources. At this time, LinkedIn is the preferred venue for professional activities. There are several EMC special interest groups which you can join. Your participation can be as much or as little as you prefer. These are also great places to post those perplexing EMC questions.

MAKE A PLAN, AND THEN WORK IT…

First, be patient. It may take a couple of years until you feel like you have really mastered the craft. If you are new, there is a lot to learn. Often this learning is piecemeal, like working a puzzle. But if you study, learn and participate, one day in the not too distant future the overall picture will make sense.

At that point, you'll realize you are finally there – you're no longer an EMC-novice, but have become an EMC-expert.

A final piece of advice. When you reach that point, don't stop learning. Even after almost 50 years, I still learn new things about EMC. It keeps the game interesting. What weird problem will crop up next? Welcome to the wild and wacky world of EMC!

Accessing the Growing Market for Drones in the U.S.

The Regulatory Landscape

BY DAVID SCHRAMM

It was recently reported that one U.S. retailer had been ordered to pay a fine of nearly $3 million in connection with the marketing of drone transmitters that operated in unauthorized radio frequency bands. The severity of the fine demonstrates why manufacturers and retailers of drones need to be certain that the products they place on the market are safe and comply with relevant legislation.

DRONE MARKET GROWTH

The "anthropause" – the period when many countries have gone into lockdown because of COVID-19 – has been a chance for all of us to re-evaluate our lives. Many of us have appreciated the temporary respite from the noise, pollution and congestion of modern life. And, as our lives slowly begin to return to normal, we are wondering if technology can be used to make these changes more permanent.

One area that has shown considerable promise in recent years has been the expanded use of unmanned aircraft systems (UAS), more commonly known as drones. Until recently, commercially available drones were little more than toys. But that has all changed. By the time the COVID-19 lockdown began, drone technology had advanced to a point where it could successfully and safely deliver life-saving medicines to hospitals while allowing the operators to maintain strict social distancing rules.

Utilizing drones in this way is not just a response to the COVID-19 Pandemic. Indeed, these developments have been in the works for a number of years. One multinational company is so keen to exploit the potential of drones for delivering packages that they already have drone development sites operating in the U.S., United Kingdom, Austria, France and Israel.

Companies are keen to exploit the utility and cost-effectiveness of drones in a number of different theaters. Photography was the initial commercial use because it allowed companies to take photographs in places that would have previously been either prohibitively expensive or impossible. Since then, commercial drone use has expanded to include surveying and mapping, inspecting

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pipelines, gathering data, search and rescue, tracking criminals, and for checking insurance claims. The agricultural sector has been particularly keen to exploit this technology, using it to monitor animal health, determine weight and movement, survey crops, plan irrigation schemes, and manage pasture and hydration.

Demonstrative of the growth of commercial drone use is the fact that the U.S. Federal Aviation Authority (FAA) originally estimated it would take until 2022 to reach 450,000 commercial drones in the U.S. a number that was actually matched and exceeded by 2019. Contributing factors towards the exponential growth of this emerging technology include:

- Rapid technological advances mean drone users have been able to quickly exploit different commercial opportunities;
- Compactness and relative simplicity make them an attractive option for businesses operating in a wide variety of environments; and
- Cost-effective – analysts have estimated cost savings could easily reach $100 billion.

It is hardly surprising therefore that the market for commercial drones is predicted to grow from $4 billion to $40 billion in the next five years.

NEED FOR REGULATION

In recent years, the drone industry has received unwelcome attention because of the actions of a few individuals. As often happens with many emerging technologies, the fast pace of development means legislation and regulation often fail to keep pace.

There are several ways drones have been misused, including spying, flying contraband over borders or into prisons, and damaging property. What really brought drone misuse to the attention of the public, however, was the threat they present to commercial airplanes. Stories of drones being used to disrupt airports have appeared in newspapers all over the world, for example, Newark Airport (U.S.) in January 2019 and Heathrow Airport (UK) in September 2019.

In response to this threat, several countries have introduced, or are preparing to introduce, regulations to curb this misuse. In June 2019, the European Union (EU) became the first region to publish a comprehensive set of rules for ensuring the safe, secure and sustainable use of drones. Regulation (EU) 2019/945 and Implementing Regulation (EU) 2019/947 cover both commercial and leisure use. And, while they do cover product safety, they are equally concerned with the operational use of the drone.

This is something that we see in a number of markets – the conjunction of regulations to control use with additional safety and performance requirements. Perhaps this is a characteristic of all emerging technologies as advances in capability initially outstrip the ability of jurisdictions to regulate them. In many ways, what we are seeing is that these concerns are not related to technology but rather to how the technology is being used. Rather than abandon the technology, we need to rewrite the instruction manual!

It is clear that the authorities drafting regulations have been unable to match the fast rate of growth in the drone sector. For manufacturers of drones looking to operate in these markets, it should be understood that any review of the current regulatory landscape is just a snapshot. As the technology transforms and advances, we can expect new regulations to be introduced to define what is a safe product, and what represents safe and sustainable use.

U.S. DRONE MARKET

Greater commercial use has been the driving force behind the U.S. drone market's exponential growth. We, therefore, need to start by looking at workplace requirements applicable to drones.

In the U.S., workplace health and safety are controlled and monitored by the Occupational Safety and Health Administration (OSHA). OSHA has the right to enter any business and can if its inspectors deem the workplace to be unsafe, close it with immediate effect.

When OSHA investigates a business, among the things they will want to see is whether all electrical products are certified by a Nationally Recognized Testing Laboratory (NRTL). However, while the U.S. does have a standard for drones – UL 3030 – it has not yet been adopted by OSHA.

Further, drones do not currently fall under the scope of the Consumer Product Safety Commission (CPSC). However, it is a salutary lesson for drone manufacturers and suppliers to remember that, until a few years ago, hoverboards were also not covered by the CPSC. It then began to emerge that hoverboards were the cause of multiple incidents, including burns and, in one particularly awful incident, a house fire that caused the death of a young girl. It is now a mandatory requirement of the CPSC that all hoverboards supplied in the U.S. must conform to UL 2272.

Therefore, it is not impossible to imagine that the CPSC may require compliance with UL 3030 at some point in the future. At the moment, though, this seems unlikely because much of the debate surrounding drones relates to usage and not product safety.

FAA REGULATIONS

Since many of the reported drone incidents relate to misuse, it is probable that any immediate regulatory interdictions relating to drones would come via the FAA. Part 107 of FAA regulations relates to UAS, covering drones weighing less than 55 pounds but excluding model aircraft. These are operational requirements and include conditions relating to:

- Flying safely
- Minimum visibility when flying
- Maximum speed
- Maximum height

The regulations make it clear that drones must be flown within unaided sight.

Part 107 also covers drone registration, but it does not include requirements that are directly relevant to manufacturers, beyond the limitations it places upon operators in terms of maximum and minimum capabilities.

FCC REGULATIONS

The only regulatory requirements with which a manufacturer or importer must conform for access to the U.S. market come from the Federal Communications Commission (FCC) and are related to radio frequency functions. And, as the nearly $3 million fine levied on the retailer we referenced at the beginning of this article demonstrates, the cost of failing to conform to these requirements can be high.

In that case, the FCC found that the video link between the drone and the operator functioned outside of the frequency bands designated for amateur use. The FCC's investigation found that the company had marketed at least 65 different transmitter models, none of which had been certified. These products were found to be operating in restricted frequencies, which could cause interference with critical FAA systems. In addition, some models were also found to operate at power levels that exceeded FCC limits, meaning they could interfere with FAA terminal doppler weather radar.

The FCC prohibits drones from using the following radio frequency technologies:

- 6 GHz U-NII devices (a new frequency band, similar to WLAN 5 GHz)

- Ultra-wideband and wideband transmission systems
- 57-71 GHz and 92-95 GHz frequency bands

The most commonly used radio frequency technologies used in drones for the U.S. market are:

- ISM bands: 915 MHz, 2.4 GHz, 5.8 GHz
- GPS
- Wi-Fi (WLAN 2.4 GHz and 5 GHz)
- Bluetooth and other 2.4 GHz technologies

Additionally, it should be noted that radio frequency technologies using UHF 433 MHz, 1.3 GHz, 3.4 GHz, require the operator to hold an amateur (HAM) radio license.

LOOKING TO THE FUTURE

It is always dangerous to try to predict the future. Who, for example, would have predicted a global pandemic shutting down entire countries back in October 2019? It is always safer to look at the here and now. When looking at drone regulations, the problem we have is that the history of this technology is defined by rapid advances that outpace the ability of authorities to regulate. In essence, they are always playing catchup.

However, manufacturers should consider two important points when trying to predict the future direction of regulations in relation to this emerging technology. First, much of the growth in this sector is related to commercial operations and this brings it closer to being adopted by OSHA. Second, as the example of the hoverboard demonstrates, it is not without precedent that the CPSC will mandate a standard if it should prove necessary to protect consumers. In either of these scenarios, it is easy to see that UL 3030 (a standard we currently recommend to clients) might well become mandatory.

UL 3030

Published in September, 2018, UL 3030:2018, Standard for Unmanned Aircraft Systems, covers the electrical system of unmanned aircraft systems used in flight for commercial applications or flight incidental to business applications for both the U.S. and Canadian markets. The drones covered by the standard are intended for use by certified UAS pilots, as identified in Federal regulations.

UAS, or drones, are defined in the standard as being:

- For outdoor use;
- Less than 55 lbs. (24 kg);
- Provided with an internal lithium ion battery that is charged from an external source; and
- Operating at a voltage of no greater than 100 V dc

Commercial applications include, but are not limited to:

- Agricultural applications
- Scientific or research applications
- Government or local police applications
- Search and rescue applications
- Video applications for the film industry or news broadcasts

A subset of commercial applications, "flight incidental to business," covers things like roof inspections by insurance agents or construction workers, or real estate photography.

UL 3030 does not cover:

- Model or hobby UASs which are marketed to and intended to be operated by the general public;
- Aspects of control associated with the human pilot (pilot error), UAS handling, contact or impact of the UAS with external objects, people or structures, adverse weather conditions such as high winds that may affect operation, or the general airworthiness of the aircraft;
- The ability of the UAS to correctly or adequately perform its intended operation;
- The ability of the UAS to land safely if the battery is discharged in flight;
- Physiological effects associated with the use of UASs;
- Devices intended for use in hazardous (classified) locations, which are subject to additional requirements to mitigate risks of fire and explosion;
- UASs used for any military or similar tactical operations;
- The efficacy of UAS communications or the effects of the loss of UAS communication during flight.

The standard covers the requirements associated with electrical shock, fire and explosion hazards relating to the inherent features of the UAS, as well as the battery and charger system combinations provided for recharging the UAS.

BATTERY REQUIREMENTS

UL 3030 allows for UAS batteries to be provided as either individual cells, configured around the design of the UAS, or as complete battery packs. The standard provides the following provisions:

- Section 17.2.2 – Individual lithium ion or other lithium-based cells must comply with the requirements for secondary lithium cells in UL 2580, Standard for Batteries for Use in Electric Vehicles, or UL 1642, Standard for Lithium Batteries
- Section 17.2.3 – Battery packs must conform to one of the following:
    - UL 2580 – Standard for Batteries for Use in Electric Vehicles
    - UL 2271 – Standard for Batteries for Use in Light Electric Vehicle (LEV) Applications
    - UL 62133 – Standard for Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications

Manufacturers should also note that, if the battery pack can be replaced by the user or can be removed for charging, it must be marked or designed to ensure that the battery can only be replaced in one direction. If this is not the case, then an internal battery reverse polarity test must be performed (Section 32.5).

MOTOR REQUIREMENTS

According to UL 3030, the motor in a UAS must be safe under normal conditions and should not be hazardous under overload conditions. It must be capable of carrying the maximum normal anticipated load without exceeding temperatures on insulation and windings as determined during the temperature test.

UL 3030 states that motors located in hazardous voltage circuits must comply with the requirements of both of the following standards:

- UL 1004-1 – Standard for Rotating Electrical Machines – General Requirements
- CSA C22.2 No. 100 – Motors and Generators

"Hazardous voltage" is defined as voltage exceeding 30 V rms/42.4 V ac peak or 60 V dc.

Motors that are located in low voltage circuits should either comply with the requirements of UL 3030 or either of the above standards.

In addition to these provisions, UL 3030 also covers a wide range of other construction criteria, including:

- Metallic and non-metallic materials

- Enclosures
- Assembly
- Internal wiring and terminals
- Chargers
- Insulation levels and protective grounding
- Protection circuits and safety analysis
- Printed wiring boards
- Spacings and separation of circuits
- Fuses

As a comprehensive standard, UL 3030 also contains provisions relating to performance testing:

- Temperature test (charging and flying)
- Dielectric voltage withstand
- Isolation resistance
- Capacitor discharge
- Vibration
- Strength of enclosures
- Water exposure
- Motor overload

There are also a wide variety of provisions relating to abnormal operations including, inter alia, overcharge, disconnected fans/blocked vents, relay and solenoid burnout, and imbalanced charging.

MOVING FORWARD

The global COVID-19 Pandemic has helped to highlight the benefits of commercial drone use in terms of cost effectiveness and utility. As we return to normality, it is clear this is an emerging technology that has proven itself and is here to stay.

The U.S., like other countries, may soon find that their current legislation is inadequate for this growing market. Its mandatory FAA and FCC requirements only relate to operation and radio frequency technology, but it is possible to see that, as the market expands and new suppliers come online, product safety may become an issue that requires more comprehensive regulation.

UL 3030 is currently only a recommended standard for manufacturers operating in the United States. But there is a real possibility that growth in commercial drone use may lead to its adoption by OSHA. If this happens, then all drones used in the workplace would require NRTL certification.

In theory, this would not affect the sale of non-commercial drones because OSHA has no jurisdiction over the home or the retailer. However, the boundaries between home and workplace are increasingly becoming blurred and electrical products sold in the high street can often be found in both settings. If a non-commercial drone is accidentally supplied for commercial use, then it would need to be NRTL certified and it does not matter where it was purchased.

Manufacturers are therefore advised to consider adopting the UL 3030 standard as part of a pre-emptive risk management strategy to avoid possible future legislative non-compliance.

Why You Should Pay Attention to Cable Discharge Events (CDE)

CDE, the Re-Discovered Barrier in the ESD Landscape?

BY MART COENEN

Cable discharge events (CDE) occur when a cable is plugged into an electrical system and when the cable and the system are at different potentials. CDE can cause system failures such as system lock up, requiring a reboot, and even physical damage.

There have been numerous technical papers on the subject, and ESDA Working Group 14, System Level ESD (http://www.esda.org), has been considering the development of a test standard to screen for this issue for some time. The problem is that there is no single "worst-case" event that is CDE. There are many types and qualities of cable, multiple ways that cables and system can get to different potentials before being connected, and the far end of the cable may or may not be connected to another electrical system or device.

In this article we will review our current understanding of some of the issues with CDE. At the same time, we welcome your help in developing a CDE test method (or methods) to address the issues you have encountered. Please contact us to share your own experiences with CDE, and the real-world problems you believe we need to consider in this process.

INTRODUCTION

A signal interface cable is considered as a point-to-point connection between two ports. The side where the cable-to-port connection is to be made is called the near-end port. The far-end port may be left open or connected to some other system/device, which itself might also be connected to something else.

For the signal interface, there are three cable options, shielded, non-shielded and double shielded. The shielded cable options include cables for microphones, coaxial, USB-2/-3 or (S)STP connections. Non-shielded cable options include cables for loudspeakers, earphones, UTP, USB-1, USB-x for charging, etc. Double shielded cable options include cables such as HDMI and Firewire (see Figure 1), where the inner high-speed signal wires are screened by an inner shield and separated from an outer shield that is typically connected to the metal outer shell of the connector.

We'll discuss three interface use-cases, as follows: 1) unconnected charged cables (Use Case #1); 2) charged cables which are at their far-end already connected to some

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other circuitry, without protective earth (PE) connection (Use Case #2a); or 3) charged cables connected to some other circuitry with a PE connection (Use Case #2b).

Use Case #1

In the unconnected charged cable case, typically, the outer cable screen (for shielded cable) or the (unshielded) wires will be charged up: Q = C.V. After a while, all inner wires will obtain the same potential against their (conductive) surroundings (for example, the outer shield). The total charge becomes distributed, that is, there is almost no potential difference among the inner wires or between the inner wires against the outer screen.

However, how the discharge event will occur is determined by the first contacted terminal at the connector versus socket and/or screen of the cable. Due to the contacting, the charge distribution in the cable as well as on the outside of the cable towards the surroundings will change rapidly but with different impedance paths and different time constants.

Due to the mini- and micro-pitch spacing between connector terminal contacts, the maximum static voltage that may occur between the separate wires and/or the wires and the outer screen will be limited to less than 1 kV.

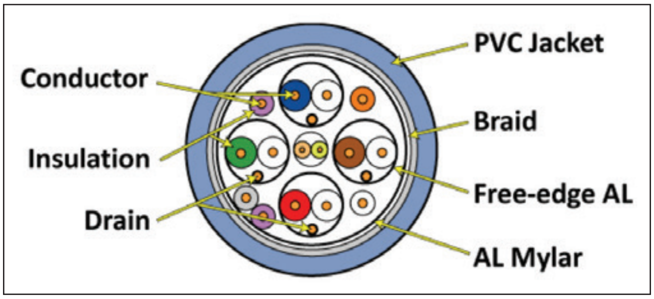

Figure 1: HDMI cable cross-section showing inner and outer shields. With HDMI, (FireWire) the inner and outer shields remain separated between shell and pins.

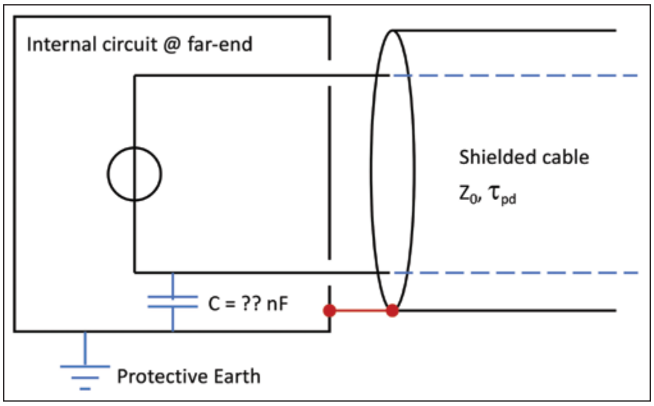

Figure 2: Unknown far-end capacitance (Use Case #2b) between floating circuitry and PE

However, an unconnected cable can be charged up to several kVs. Short lasting pulses may have higher voltages without causing instant breakdown.

Cable charge build-up may arise from dielectric friction, rubbing, airflow and many man-made kinds of disturbances. Potential changes also arise from lifting up the charged cable, thereby lowering the capacitance → increased voltage: V = Q/C.

Use Case #2

In the case where the far-end of the cable is (already) connected to some circuitry (for example, a mouse, keyboard, display, beamer, storage device, tablet, laptop, PC, charger, supply, server, switch, router, test and measurement equipment, etc.), the charge storage will be determined by whether that far-end system/device is connected to PE. The internal electronic circuitry connected to the signal interface wires is either floating (Use Case #2a) or intentionally kept insulated (Use Case #2b, see Figure 2) from the conductive enclosure, which is electrically coupled to that PE terminal.

For battery or interface wire supplied devices (Use Case #2a), the far-end termination will be capacitively coupled to its surroundings. In this case, the (conductive) exterior of the far-end device is not connected to PE. When the far-end system/device is locally supplied, while the inner electronics are kept insulated (e.g., Class-II electric devices; without PE, or Class-I electric devices with PE), a "Faraday cup" is created. The maximum potential is limited by the creepage and clearance distances used or by the break-down voltage of the capacitors used, crossing that insulation barrier. This far-end floating circuitry is connected to the inner wire of the cable. Any retention voltage may be stored in-between that floating circuitry (that is, inner wires) against the outer shield (i.e., AC mains and/or PE). Making "shell contact first" will affect the CDE, such that the maximum discharge current will result due to the low(er) impedance path which closes the loop.

If the device at the far-end is affected by an EMC transient threat (e.g., EFT, Surge), it will couple immediately onto the cable interface in either Use Case #2a or #2b. With the regulatory EMC tests, coupling is done to the cable's exterior at the near-end port while the cable is fixed to the equipment under test (EUT), not while the cable is in the process of making its contact. True, the probability of the coincidence of an EMC related threat while plugging in a cable is low, but this combination will be very harsh.

(It is important to note that EMC immunity tests are intended to show recoverable functional behavior of a system rather than physical damage at the component level!)

THE CAUSE FOR OVERSTRESS IS IN THE DETAIL

When a "floating" charged signal cable is plugged into a port, the internal discharge event will initially look like a regular transmission line pulse (TLP), starting at t = 0 ns, of which the pulse duration is determined by twice the propagation delay of that cable for all far-end load conditions (see Figure 3). The typical duration of a TLP test pulse according to applicable ESDA, JEDEC and IEC standards is 100 ns. The maximum cable length is determined by the interface (for example, 5 meters for USB-2, 15 meters for HDMI, etc.).

Considering the propagation speed in cables of ~ 7 ns/m, 15 meters HDMI cable would yield a pulse length of 210 ns. The exterior propagation speed on a cable will be equal to the speed of light, that is 3.3 ns/m. The rise time of the pulse while making contact will be in the sub-nanosecond region, considering a metal-to-metal contact. The maximum voltage to be expected on the cable may be high for the cable as a whole (up to several kVs) but will be internally limited considering screen-to-wire or wire-to-wire, typically less than 1 kV.

The discharge "source" impedance, voltage-over-current ratio, will be determined by the cable cross-sectional topology and whether the impedance is determined in the cable itself (that is, wire-to-wire(s) or wire(s)-to-screen) or from the whole cable towards its surroundings. The exterior cable to surroundings' impedance is 100 to 300 Ω. The inner wire-to-wire or wire to screen impedance is 50 to 100 Ω. At worse, the characteristic impedance of the inner-to-outer shield transmission line (HDMI, FireWire, etc., see Figure 1) can be below 10 Ω.

From a formal TLP source, the peak current can be directly calculated from the initial charge voltage on the line and the characteristic impedance. For a 1 kV charged up 50 Ω transmission-line, the peak current will be 20 Amps initially. A TLP source with an additional capacitance at the far-end means that the initial current will again resemble the TLP characteristics. After twice the propagation delay of the cable is used, the charge as stored in the far-end circuitry will show up too.

As an example, the 100 pF case results when a USB cable with a mobile phone attached at one end is plugged into a computer (to perform a backup, for example). In case the phone is already electrically connected to a sound system (headphone) while the USB cable is plugged in, values of 1 nF or higher occur. Issues like these can be circumvented by using wireless BT interfaces instead. This might also answer the question of why new mobile phones no longer include a headphone socket and use contactless charging.

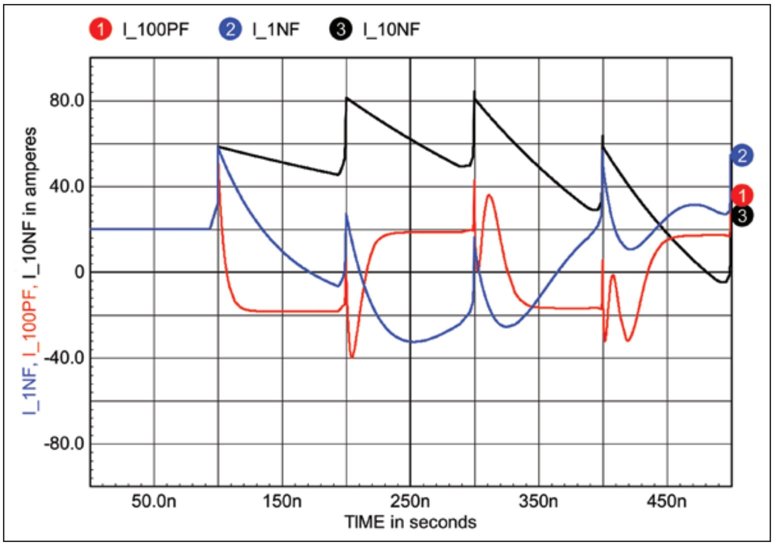

Figure 3: Discharge current (voltage across 1 Ω) of a 50 Ω TLP (100 ns) charged up to 1 kV (initially 20 Amps) while far-end loaded by 100 pF; lower red curve, 1 nF; blue curve and 10 nF; black curve).

If there are no accessible ports, the likelihood of CDE vanishes too.

This article may prompt other questions. But, after the initial hang-up or damage to a port, it's unlikely that you have conducted your own experiments to learn what went wrong and why. In many cases, when the product is still under warranty, the product will be sent back to the supplier for repair. But repairing the damage alone contributes nothing to our understanding of the application condition that caused it.

CONCLUSIONS

CDEs are likely to occur anytime a cable is plugged into a port (in particular, when the cable is loaded capacitively at the far-end), though they often go unrecognized.

An unconnected cable may collect charge such that its potential towards its surroundings becomes over 1 kV and will increase when being lifted up. In-between the wires and/or the wires and a screen, CDE will remain less than 1 kV due to the mini- and micro-pitch of the connector pins.

However, if the far-end of a cable is loaded by some insulated circuitry, the total capacitance for charge storage will increase towards the outer shield. The maximum potential will be limited as described above. The total charge energy ($E = \frac{1}{2}C.V^2$) will be substantially higher than with "formal," non-far-end loaded TLP test cases.

Do you have an increase in unexplained ESD/EOS failures on your connector ports? Do you think that you have suffered a CDE leading to soft- or hard-failures that have not shown-up with regular ESD compliance testing? Or have you passed IEC system and other ESD qualifications but fail miserably when working with certain cables from a new supplier or other connected far-end devices? If so, you may suffer from CDE, a rediscovered interaction between cables and systems that can cause profit loss, WIP repair and retention, and unsightly internet product reviews.

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Why Resistance Requirements Differ by Industry and Why Standards Matter

BY DAVID LONG

An access floor contractor was bidding a project calling for "static dissipative" flooring. Like many contractors, the project manager viewed the terminology from a generic perspective. Most laymen equate the term static dissipative (SD) with any flooring type that is marketed for the purposes of mitigating the discharge of static electricity. They do not realize there is a distinction between a conductive floor and a dissipative floor and that there may be a practical reason for choosing one over the other.

Since the architectural specs did not include electrical resistance parameters, cite-specific industry standards, or require that resistive properties be tested before final acceptance, the project manager felt comfortable bidding any type of ESD flooring. In this instance, she proposed a conductive floor for an FAA flight tower, when in fact the FAA requires flooring to measure in the static-dissipative range.

Similar scenarios occur every day. The root causes almost always involve semantics, with specifiers citing incorrect standards for a specific industry, as well as a general lack of understanding about electricity and static-control flooring.

This creates multiple problems encompassing product liability, economic loss, failure to perform and in compliance with industry standards.

CONFUSING CONDUCTIVITY AND SPECIFICATIONS

To investigate this dilemma, we need to explore the history of floors used to prevent static-discharge problems.

The roots of the ESD flooring industry hark back to the need for preventing static sparks in medical environments where flammable and explosive gases were administered as anesthesia. Like the static-control wrist straps used in electronics manufacturing today, early versions of static-control products involved some form of single-point grounding and bonding (via tethering) to maintain a single potential between all conductors that came in contact with one another. In general, this was achieved by placing wet towels across the floor to connect the anesthesiologist's foot with the base of a steel operating table. (Yes, this is real!)

Dave Long is the CEO and founder of Staticworx, Inc., a leading provider of flooring solutions for static-free environments. He has 30-plus years of industry experience and combines his comprehensive technical knowledge of electrostatics and concrete substrate testing with a practical understanding of how materials perform in real-world environments. Dave can be reached at dave@staticworx.com.

In an article published in 1926, titled "How Can We Eliminate Static from Operating Rooms," Dr. E. McKesson writes:

> *"Hence the simplest method of preventing static sparks is to keep the objects concerned in the administration of combustible mixtures in contact—i.e., the patient, the anesthetist and the inhaler. This is usually done and accounts for the relative infrequency of fires from static sparks in the operating room."*[1]

As throughout the electronics industry today, McKesson recognized that full reliance on a multi-step human process of tethering and un-tethering of personnel and fixtures with cords and wires assumes a perfectly executed process every time. He writes, "But errors of technique are made, and if the conditions are 'right,' a fire occurs."

McKesson recognized the need for a passive grounding system that does not rely solely on a series of connections that may not always occur. McKesson writes:

> *"An effort has been made at one hospital to make errors impossible by grounding a mosaic floor, consisting of alternate block of tile and bronze in one or two rooms and a solid metal floor in another. That is, when one steps upon this floor the charge on his body flows through a thick wire to the ground. The operating table, apparatus, instruments, anesthetists, surgeons and all are thus grounded or their charges neutralised."*

McKesson wrote this paper for the British Journal of Anaesthesia – advocating for what we now call ESD flooring - all the way back in 1926. And yet, into the 1960s, there continue to be records of hospitals placing wet towels on the floor to provide electrical bonding between the anesthesiologist and the operating table.

Late in 1950, a Wisconsin company called Natural Products began work on plastic conductive flooring. The following year they would introduce Statmate and rename the company Vinyl Plastics Inc (VPI). VPI's non-metallic conductive floors gained immediate and widespread acceptance as a highly effective grounded flooring solution in hospitals. Unlike metal, these early conductive plastic floors could be made with inherent and controlled electrical resistive properties. This was and is critical to electrical safety.

Circa 1950, the NFPA had determined that floors in hospitals should not measure below 25,000 (2.5×10^4) ohms or in excess of 1,000,000 ohms (1.0×10^6). Vinyl floors could be manufactured to meet this requirement. This ohms range of 2.5×10^4 to $< 1.0 \times 10^6$ marks the launching point at which today's confusion about conductivity, resistance ranges, and the suitability of conductive floors begins.

RESISTANCE TESTS PER NFPA GUIDELINES ARE NOT EQUIVALENT TO ESD/STM 7.1 TESTS

Although metal floors were durable and provided effective conductivity, they offered absolutely no safety in the presence of alternating current (A/C). To ensure safety along with a reliable level of conductivity, NFPA bulletin 56 (issued in the 1940s) required a specific electrical resistance range for conductive floors. Electrical resistance was to be tested using an ohmmeter, with 500 volts of applied current. This was because, in 1950, meters – 500 volts was chosen to test for resistance with an emphasis on electrical safety. Wall-mounted meters, such as the Conductometer were installed in ORs and tested both flooring and footwear at 500 volts. Today we test with 10 volts of applied current.

Why does this matter? Ohm's Law: the higher the applied voltage, the lower the resistance. Likewise, the lower the applied voltage, the higher the resistance.

Since ANSI STM 7.1 requires 10-volt electrification, resistance tests of the same material will measure much higher than an NFPA test using 500 V of applied current. Likewise, the results of an NFPA test using 500 V of applied current will be much lower than the results of a test following guidelines of 7.1 applying 10 V. The point is that the test methods are not equivalent; therefore, measurements are not equivalent.

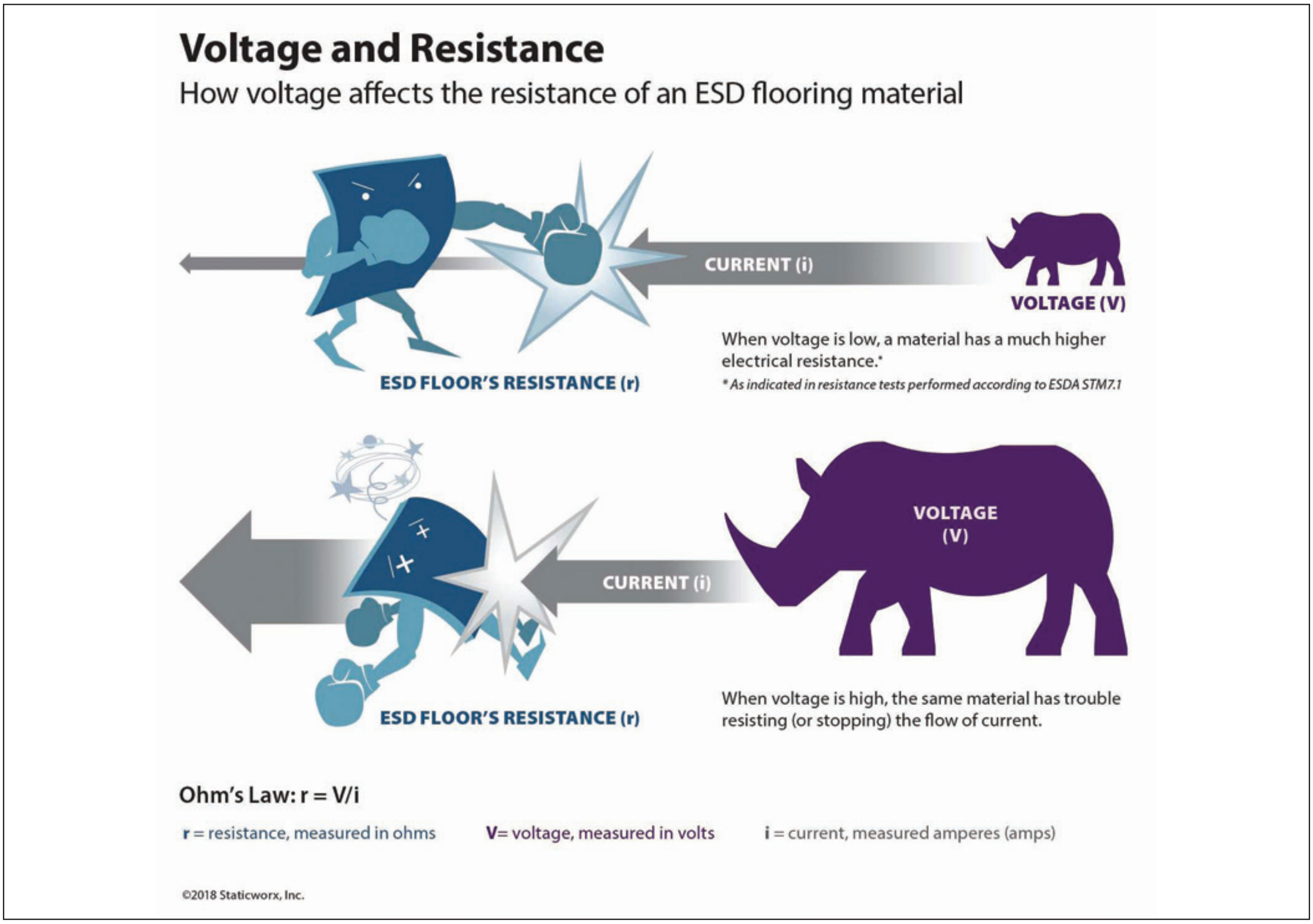

Figure 1: How voltage affects the resistance of an ESD flooring material

The Electrostatic Discharge Association (ESDA) and the electronics community have chosen an upper limit of less than 1,000,000 ohms for defining a conductive floor.[2] This conductive range is quite different from the range set by the NFPA. Yet many floorings suppliers state that their floors measure above 25k ohms per NFPA - but also market their floors as measuring between 25k and one million ohms per the current ANSI/ESD STM 7.1 10-volt test method.

This is not possible. A floor measuring 25,000 ohms at 500 volts will present as a much less conductive surface with 10-volt electrification. The chart in Table 1 shows measurements taken by an independent lab. As indicated in the chart, gray ESD carpet measuring 75,000 ohms with 10 volts of applied current measured only 16,000 ohms at 500 volts. While the floor tested per S7.1 measured slightly above the stated 25,000 ohms, when tested at 500 volts, it failed to meet the NFPA's requirement for resistance.

Table 1 shows examples of the discrepancy between resistance test results performed per NFPA and ANSI/ESD test methods.

WHAT IS A STATIC-DISSIPATIVE OR CONDUCTIVE FLOOR?

This history of conductive flooring and evolving resistance test methods brings us to the concerns we face today. What is a static-dissipative floor, what is a conductive floor, and which version should be referenced in a specification?

The first answer is actually a question. What are the test methods you're using to measure resistance and what standards do you need to meet for compliance in your industry? One example is NFPA 99. Almost every flooring manufacturer mentions NFPA 99 compliance; NFPA 99 deleted any mention of floor testing years ago due to the elimination of flammable anesthesia. Unless the manufacturer specifications account for and incorporate test data obtained at 500 volts, they are misapplying a defunct test method.

The perhaps bigger problem is that different industries have different resistance standards. We often see ANSI/ESD S20.20 cited in specifications for ESD floors for 9-1-1 dispatch centers. ANSI/ESD 20.20 relates specifically to electronics manufacturing and handling environments and requires the use of ESD footwear in the qualification of ESD flooring. ESD footwear is never used in call centers and dispatch areas. In these applications, the mention of 20.20 is irrelevant and potentially misleading. Floors in these environments should reference either Motorola R56 or ATIS 0600321, both of which require floors to measure between 1.0×10^6 and $1.0 \text{ X } 10^{10}$. Many airport flight towers are also equipped with static-control floors. Like Motorola R56 and ATIS 0600321, FAA-STD-019f, Lightning and Surge Protection, Grounding, Bonding, and Shielding Requirements for Facilities and Electronic Equipment, prohibits the use of flooring measuring below $1.0 \text{ X } 10^6$ due to concerns for the safety of people working near energized equipment.[3]

Unlike end-user spaces, there is no lower resistance limit for flooring used in an ANSI/ESD S20.20 ESD program. Conductive floors are an important element in an ANSI/ESD 20.20 program due to the need for worker mobility, rapid charge decay, prevention of tribocharging, effective grounding of mobile workstations and the ability of personnel to handle highly sensitive products without the use of wrist straps. ANSI/ESD S20.20 states that the resistance measurements obtained through the use

Carpet Tile Test Results for product marketed as measuring 2.5×10^4 – 1.0×10^8:		
Color	***ANSI/ESD STM 7.1 @10 volts***	***NFPA @500 volts***
Grey	7.5×10^4	1.6×10^4
	$7.2 \text{ X } 10^4$	$1.4 \text{ X } 10^4$
Silver	7.5×10^4	1.4×10^4
	$6.9 \text{ X } 10^4$	$1.3 \text{ X } 10^4$
Dark grey pattern	5.0×10^4	1.4×10^4
	$6.0 \text{ X } 10^4$	$1.0 \text{ X } 10^4$
Carpet Tile Test Results for product marketed as measuring $1.0 \text{ X} 10^6$ – $1.0 \text{ X } 10^9$:		
Color	***10 volts***	***500 volts***
Patterned carpet	1.8×10^6	1.1×10^6
Blue Carpet	1.5×10^6	8.0×10^5

Table 1: Carpet tile resistance test results showing the discrepancy between NFPA and ANSI/ESD test methods

of ANSI test methods are not to be used to determine the relative safety of personnel exposed to high AC or DC voltages. Although most flooring manufacturers do not produce flooring measuring below 25,000 ohms it is imperative that the end-user understands that the burden of liability involving both safety compliance and product suitability of electrically grounded flooring rests on both the manufacturer's and specifier's shoulders.

It should not be implied that conductive flooring is unsafe when appropriately utilized in an ANSI/ESD S20.20 certified program. These programs require regular testing of both floor conductivity and footwear conductivity, these spaces are accessed only by trained personnel and conductive flooring should never be installed in areas where high potential testing or equipment is in operation. However, before any conductive floor is installed, buyers should understand that a conductive or static dissipative floor is a system that requires multiple installation materials, special footwear and specific steps during the qualification and verification processes. As further confirmation that flooring should not be viewed as a discreet component, we need to look no further than the newly proposed tile in the 2020 draft of test method ANSI/ESD STM 7.1., Flooring Systems – Resistive Characterization.

TEST METHODS VERSUS PERFORMANCE STANDARDS

Most ESD flooring specifications reference some type of resistance testing procedure, such as those found in ANSI/ESD STM7.1, ASTM F150, DOD 4145.26 or NFPA 99 (formerly NFPA pamphlet 56). Many buyers mistake these test methods as representing performance standards. Performance standards guide the specifier in determining what test results are acceptable. Test methods tell us how to determine if we have compliant products.

For example, FAA-STD-019f states that a floor must measure between 10^6 and 10^9 ohms. Motorola R56 states that the floor should measure between 10^6 and 10^{10} ohms when tested per ANSI/ESD S7.1. ATIS 0600321 cites the same resistance requirements as Motorola R56. Although not an actual standard, IBM's Physical Site Planning document states:

> *"For safety, the floor covering, and flooring system should provide a resistance of no less than 150 kilohms when measured between any two points on the floor space 1 m (3 ft.) apart. They require a test instrument similar to an AEMC-1000 megohmmeter for measuring floor conductivity."*[4]

Like the hand crank meggers and other instruments used to test insulation resistance, the AEMC-1000 does not offer a 10-volt output but it does allow testing up to 500 volts. Since IBM's upper recommended resistance is 10^{10} and no test voltage is mentioned, one might believe that this test was intended to ensure a minimum amount of insulation resistance. By contrast, the ESD industry requires simply that conductive floors measure below 1.0×10^6 at 10 volts.

Again, resistance measurements alone should not be used to determine the safety of a particular floor. There are multiple reasons for this that are beyond the scope of this article. However, as an experiment, we solicited a third-party lab to apply both AC and DC voltages to various ESD floors and measure the resulting current at the floor-ground connection. The results of this testing are shown in Table 2.

As the chart illustrates, some conductive floors appear to enable significantly more electrical current than others. The amount of current is not accurately predicted mathematically by using electrical resistance measured

Carpet Tiles with Black Backing - 2.5×10^4 - 1.0×10^8	
AC Volts Volts ac	**AC Amperes mili Amps ac**
4	1
11.5	3
18	5
30.5	**10**
52.3	**20**
117	**50**
EC Rubber Tiles - 2.5×10^4 - 1.0×10^6	
AC Volts Volts ac	**AC Amperes mili Amps ac**
31	0.1
40	0.4
66	2
80	4
93	5
120	7.6
Static Dissipative Carpet Tiles - 10^6 - 10^9	
AC Volts Volts ac	**AC Amperes mili Amps ac**
5	**<0.1**
10	**<0.1**
25	**<0.1**
50	**<0.1**
100	**<0.1**
120	**<0.1**

Table 2: Results of testing applying AC and DC voltages to various floor types

with an ohm meter. In part this is due to the construction of conductive floors, whether they are comprised of composite layers, if they are fully conductive on the surface or constructed of the same material throughout the thickness of the material.

However, the experiment clearly illustrates what we already know: a floor with an inherent resistance over 1,000,000 ohms is less likely than a very conductive floor to enable a dangerous leakage current. This fact drives recommendations for using dissipative flooring in data centers, flight towers, dispatch operations and areas where energized equipment is used. Whereas we need to control static generation and charge decay to an extremely low threshold in electronics manufacturing, we do not need the same level of performance in end-user spaces like data centers, etc. While the electronics in these end-user spaces can be damaged by electrostatic discharge, they're less sensitive than components in manufacturing and handling facilities.

According to an ASHRAE white paper, the data center industry views 500 volts as an upper threshold compared with the 100 volt upper limit for meeting ANSI/ESD S20.20 in electronics manufacturing.

THE SEMANTICS PROBLEM

The ESDA has produced a glossary of terms. Three newly proposed terms referencing flooring include flooring systems, conductive flooring systems and dissipative flooring systems. But terms like dissipative and conductive are frequently misunderstood and misapplied. In some cases, the misapplication leads to problems in the field. In many cases, specifiers don't know which electrical range is the correct one for their client's specific industry. In other cases, specifications are copied from previous static-control projects even though the application may be entirely different.

For example, per DOD 4145-26-M, DOD explosives-handling applications require conductive floors as defined by resistance testing at 500 volts. Per ANSI/ESD STM 7.1, the same floor tested at 10 volts might actually measure in the very low part of the static-dissipative range. As previously noted, resistance is predicated by the applied voltage.

> *"To avoid any confusion and future liability due to misunderstandings about conductivity and test method, we recommend that explosives handling specifications always be cowritten by the end-user and the specifier."*

Let's look at the definition of a dissipative flooring system. A static-dissipative flooring system, measured with a full combination of components, including surface material, adhesive, grounding mechanism, substrate and any other material in the system, is considered static dissipative as long as the system has a resistance greater than or equal to 1.0×10^6 ohms and less than 1.0×10^9 ohms.

This sounds like a comprehensive definition with no room for misunderstanding. However, if an installer laminated the highly conductive bronze tiles (mentioned in McKesson's 1926 article) with a static-dissipative adhesive, it would appear in a typical ANSI/ESD STM 7.1 resistance to ground field test that the bronze floor was not conductive, but, in fact, static dissipative. How?

Because we would be grounding bronze through a series resistor network. The dissipative adhesive, not the bronze surface, would be the groundable point, and the adhesive would represent a false indication of the resistance to ground if the dissipative ground were bypassed due to an inadvertent connection to ground. Relying upon a less conductive surface as the groundable point below a more conductive surface is an imprudent concept for multiple reasons.

This may seem like a ridiculous example, except for the fact that many concrete on-grade substrates retain a high concentration of water due to the local water table. Water saturates adhesives, lowering the conductivity of the system, and changes the path to ground. This scenario occurs so often that flooring installers test concrete per ASTM 2170 for moisture, in part, to determine how vapor content and emissions in the substrate might negatively affect the adhesive.

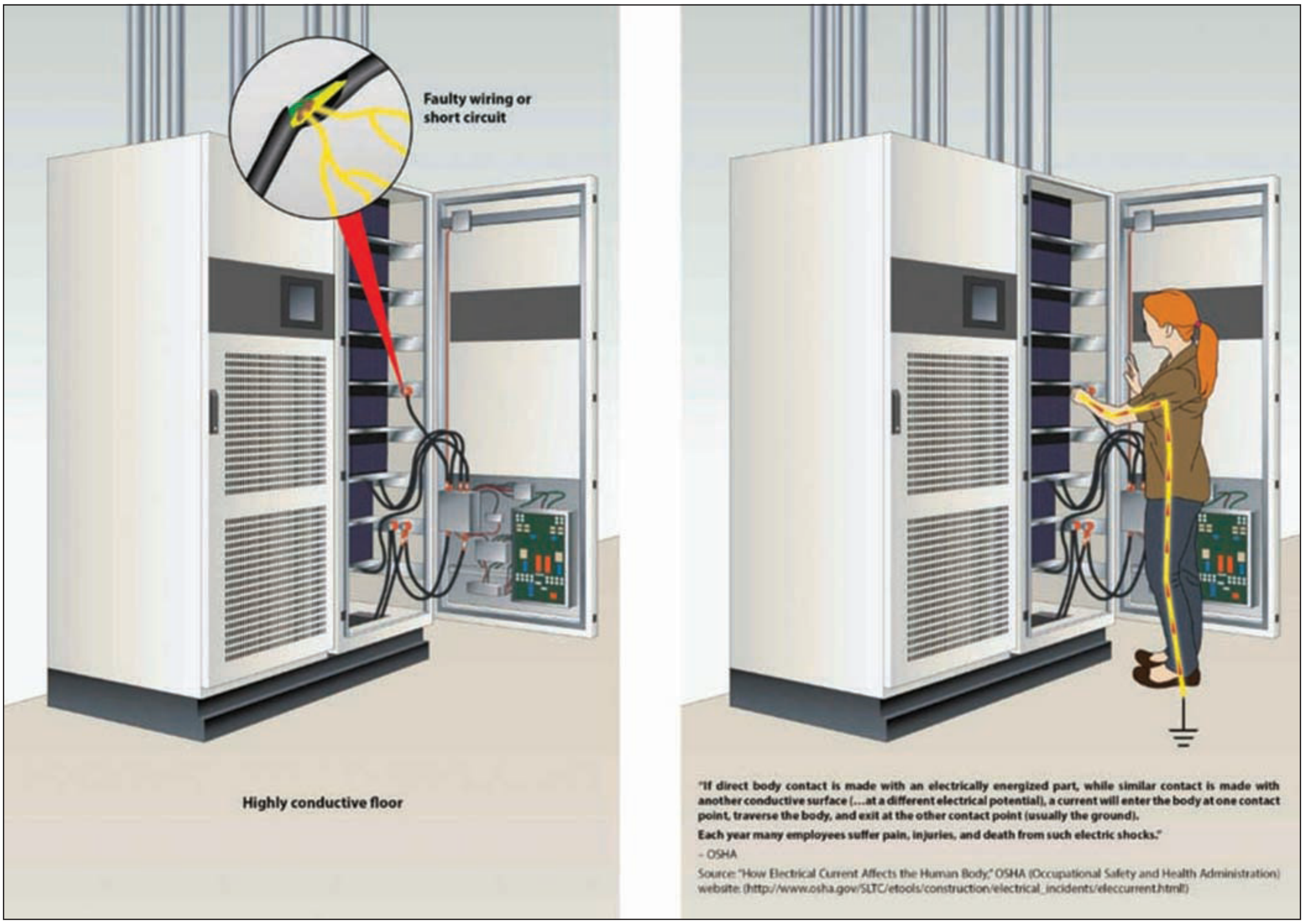

Figure 2: Large systems positioned on the surface of an ESD floor can inadvertently act as a surface ground connection.

What if this floor system were installed in a space where energized systems were resting on the floor while operating at 480 volts, three-phase. Obviously, any electro-mechanical system resting on the floor would become the groundable contact point and bypass the series resistor (dissipative adhesive) below the bronze tiles.

Another misstatement is the claim that "Flooring meets or exceeds ANSI/ESD S20.20." The first error is the failure to recognize that flooring is only one component of a system within a program that must comply with all aspects of a standard, which typically includes many items unrelated to the flooring itself. For example, ESD flooring, whether conductive or dissipative, is often mistaken as having only to ground people and prevent charge generation on people wearing ESD footwear.

This is not the case. Most users of ESD flooring rely on the floor to ground and prevent charges on people, carts, shelves, benches and chairs. Due to surface hardness or spacing of conductive surface particles, a particular design conductive floor may do an excellent job of grounding and charge prevention on personnel but fail at grounding mobile carts and shelving. If a circuit board manufacturer expects the floor to provide a path to ground for workstations and carts and the floor fails in this task, it cannot be described as meeting S20.20, whether or not the root cause of failure is the drag chain on the cart, the contact area of the conductive casters, or the arrangement of conductive layers or conductive particles embedded into the flooring.

If we remove the question of which standards are better or more valid or more clear, we are left with the most important question: Why would one write a specification for a specific industry and fail to mention the standard for that industry? Now we are back to the beginning: semantics, incorrect standards cited for a specific industry, and a general lack of understanding about electricity and static-control flooring.

What happens when an industry or entity like the FAA publishes a frequently updated 500-page grounding standard and specifiers, installers or facilities managers neglect to follow the standard? This question may be one for the product liability attorneys, but over the course of several discussions, liability attorneys tell me that meeting standards is a "minimum expectation." In the case of ESD flooring and electricity, this means privileging safety equal to or greater than potential performance enhancements from increased conductivity.

In the construction trade, there is an old saying, "electricity always follows the path of least resistance." The saying is only partially true. Electricity flows through all paths – intended and unintended. We must keep this in mind when we verify the resistance of installed ESD vinyl or carpet tiles.

If we only follow test method ANSI/ESD STM 7.1, we might overlook an unintended path to ground. STM 7.1 only requires testing the resistance of floor tiles to the ground connection specified by the manufacturer. But what if that ground connection relies on resistors or high resistance adhesive as part of its path to ground, even though the equipment racks on top of certain floor tiles are also grounding the floor?

For this reason, always test the resistance connections between the surface of tiles directly under equipment, and the connection to either the equipment racks or the pedestals of the equipment sitting on the surface. This is a case of prudently exceeding standards and test methods when those standards emphatically warn that they are not intended for evaluating safety.

The bottom line? To be safe and to protect yourself or company from liability, be sure you know what the terms mean and follow the standards specific to the industry. If you're not sure, do your homework, ask questions or enlist an expert to help.

ENDNOTES

1. "How Can We Eliminate Static From Operating Rooms to Avoid Accidents with Anaesthetics?," E.I. McKesson, published in the British Journal of Anaesthesia, April 1926. Available at https://academic.oup.com/bja/article/3/4/178/271645.
2. Note that proposed changes in ANSI/ESD STM7.1 would address the need to mitigate the hard line between the conductive and dissipative range.
3. According to FAA-STD-019f, "conductive ESD control materials shall not be used for ESD control work surfaces, tabletop mats, floor mats, flooring, or carpeting where the risk of personnel contact with energized electrical or electronic equipment exists." FAA-STD-019f, Lightning and Surge Protection, Grounding, Bonding, and Shielding Requirements for Facilities and Electronic Equipment, Federal Aviation Administration, published October 18, 2017.
4. "Static electricity and floor resistance," posting to the IBM Knowledge Center website, https://www.ibm.com/support/knowledgecenter/en/SSWLYD/p7eek_staticelectricity_standard.html.

Defining Product Grounding in the Automotive EMC Test Plan

BY STEVE MASIAK

One of the more overlooked elements of an automotive EMC test plan is defining the grounding for the device under test (DUT) case and its load simulator. These are critical items that will not only affect the test results, but also the test repeatability. Even if the DUT and load simulator have a non-conductive case with no customer grounding installation requirements, this still needs to be defined for the EMC test lab.

WHY IS GROUNDING IMPORTANT?

Military EMC standards historically helped form the basis from which the international automotive EMC standards were developed. From military EMC standard MIL-STD-461G [1]:

> *"Adequacy of bonding is usually one of the first areas reviewed when platform problems develop. Electrical bonding controls common mode voltages that develop between the equipment enclosures and the ground plane. Voltages potentially affecting the equipment will appear across the bonding interface when RF stresses are applied during susceptibility testing. Voltages will also develop due to internal circuit operation and will contribute to radiated emission profiles. Therefore, it is important that the test setup use actual bonding provisions so that test results are representative of the intended installation."*

DOES THE DUT CASE NEED TO BE GROUNDED?

The EMC test plan needs to be written with the understanding that the test lab does not know the product to be tested. The DUT description must include how its case is grounded based on customer installation requirements. In the automotive world, the vehicle architecture determines this. The DUT case can have either no connection to vehicle ground or be connected to vehicle ground (either directly or through a metal bracket). Therefore, the customer must be consulted to determine proper DUT case grounding during testing. Some customers may also allow or require a product be tested with its mounting bracket.

DOES THE LOAD SIMULATOR NEED TO BE GROUNDED?

The load simulator is defined in ISO 11452-1 [2] as: "physical device including real and/or simulated peripheral loads which are necessary to ensure DUT nominal and/or representative operation mode."

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Customer requirements typically determine how the load simulator is grounded. The customer may require either a non-conductive plastic or metallic enclosure be used for the load simulator. In some cases, actual loads may be allowed without an enclosure. Actual loads may be a seat motor, parking brake switch, wheel speed sensors, etc. This must be defined in the EMC test plan.

TYPICAL AUTOMOTIVE INDUSTRY STANDARDS GROUNDING REQUIREMENTS

If the customer does not have defined grounding requirements, then automotive industry standards such as ISO and CISPR may be allowed by the customer.

DUT Case

This DUT case definition below is commonized between the ISO and CISPR standards.

> *"The DUT shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material (εr ≤ 1,4), at (50 ± 5) mm above the ground plane. The case of the DUT shall not be grounded to the ground plane unless it is intended to simulate the actual vehicle configuration." [3], [4], [5], [6].*

Typically, EMC labs use foam insulation board to meet the non-conductive, low relative permittivity material requirement.

Load Simulator

This load simulator definition below is commonized between the ISO and CISPR standards.

> *"Preferably, the load simulator shall be placed directly on the ground plane. If the load simulator has a metallic case, this case shall be bonded to the ground plane. Alternatively, the load simulator may be located adjacent to the ground plane (with the case of the load simulator bonded to the ground plane) or outside of the test chamber, provided the test harness from the DUT passes through an RF boundary bonded to the ground plane." [3], [4], [5], [6]*

PROPER GROUNDING STARTS WITH A GOOD BONDED CONNECTION

From international automotive standard ISO 11452-1 – General Principles and Terminology [2]:

> *"Bonded – grounded connection providing the lowest possible impedance (resistance and inductance) connection between two metallic parts with a d.c. resistance which shall not exceed 2,5 mΩ.*

Note 1 to entry: A low current (≤100 mA) 4-wire milliohm metre is recommended for this measurement."

MIL-STD-461G also defines ground potential as 2.5 milliohms or less [1]. As stated in ISO "Note 1 to entry," this resistance needs to be verified with a milliohm meter (or micro-ohmmeter), not a standard digital multimeter (DMM). A standard DMM can typically only measure resistance as low as 0.1 ohm.

Figure 1: Standard copper tape

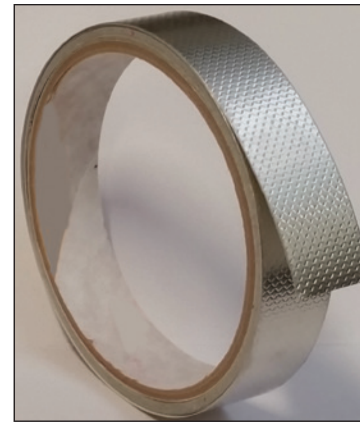


Figure 2: Embossed tin-plated copper tape

GROUNDING TECHNOLOGIES

Copper Tape (if customer allowed)

One type of grounding technology is a flexible copper foil tape with adhesive backing (caution: not all tapes have conductive adhesive). The copper colored tape is the standard used in most EMC labs. However, the embossed tin-plated copper tape (silver colored) has a few advantages over the standard copper tape. The adhesive is pressure sensitive which allows for better contact, and the tin-plating allows for soldering the tape directly to the ground plane and it has better resistance to corrosion.

Figure 3: Braided metal straps found in a typical EMC lab

	Grounding Technology Variables
Shared by Both Grounding Technologies	• Material is variable (e.g. copper, copper/tin, etc.) • Multiple widths available • Length is variable based on test operator • Impedance at high frequencies affected by length to width ratio
Copper Tape (easy to use and readily available in most EMC labs)	• Adhesive may not be conductive Should only be used once • Repeated use affects adhesion which can decrease conductivity • Oxidation can affect the tape if used for long periods of time • Embossed tin-plated copper tape has better conductivity and adhesion than standard copper tape • Embossed tin-plated copper tape can be soldered to ground plane
<BEST CHOICE> Braided Metal Strap (most reliable when used with bolts, screws, c-clamps, etc.)	• Can be bonded to DUT case (or ground plane) with copper tape or mechanically (e.g. bolt, screw, c-clamp, soldered, etc.) • Can be soldered directly to ground plane • Modifications to the braid (adding banana jacks, eyelets, etc.) can affect the impedance at high frequencies

Table 1: Grounding technology variables

Braided Metal Strap

Another type of grounding technology is a bonding strap made from a semi-rigid flat metallic braid/weave that is copper tinned (or untinned). Bonding straps are better than wires since their length to width ratio has lower inductance per unit length. A good practice is to define in the EMC test plan that any ground straps used maintain a "5:1 length to width ratio or less" (recommended in MIL-STD-464C [7]).

The ground straps shown in Figure 3 are an example of what an EMC test lab may choose for your product if not defined in the EMC test plan. Note, the impedance at high frequencies will be different due to the width, length and addition of connectors (e.g., banana plugs, eyelets, etc.). As shown in Figure 3, the ends of the braid may fray. This can be remedied by soldering the ends of the braid. Also, if adding a hole for a fastener (e.g., bolt, screw, etc.), the edges of the hole should be soldered to prevent fraying. Alternatively, the braid can be soldered directly to the ground plane.

Once it is determined that the DUT case and/or load simulator requires grounding to the ground plane, then the grounding technology variables can be controlled by defining them in the EMC test plan. The 5:1 length to width ratio (or less) is a good guideline to also include in the EMC test plan.

WHERE AND HOW TO GROUND THE DUT CASE?

It is not enough to simply state that the DUT case needs to be grounded. For test repeatability and to avoid misleading test results, where and how to ground the DUT case must be answered in the test plan.

Where to Ground?

"Where to ground" should be clear based on customer installation requirements. In some cases, a customer may require that the DUT be tested as case grounded and ungrounded. An example of this would be an automotive customer that may use the DUT on multiple vehicles with different architectures.

If uncontrolled by the EMC test plan, the EMC test lab will typically use copper tape and place it on the conductive area of the DUT case where most convenient for the test setup. The lab also needs to be notified if the conductive area has a coating that needs to be sanded/removed. Therefore, it should be defined if the DUT case has a mounting foot, threaded hole or other designated area to attach the copper tape/grounding strap.

How to Ground?

"How to ground" is controllable through the EMC test plan. The most common grounding methods are copper tape or braided metal strap. To maintain test repeatability, the grounding method needs to be defined.

WHERE AND HOW TO GROUND THE LOAD SIMULATOR?

Fortunately, the "where" and "how" to ground discussion also applies to the load simulator. Just like the DUT, the load simulator needs to have a defined "where to ground" location and "how to ground." The load simulator can be in a plastic enclosure, metal enclosure or no enclosure depending on customer requirements and DUT needs. The load simulator system may also involve more than one enclosure. Therefore, each enclosure must have its grounding defined in the EMC test plan.

GROUNDING METHODS

Refer to Figures 4-7 for descriptions of the different "how to ground" methods for the DUT case and/or load simulator.

As shown in Figure 8, there are various combinations of grounding methods and technologies available for the lab to use. When testing is not repeatable or unexpected results are found, one of the first troubleshooting questions asked is: "how was it grounded?"

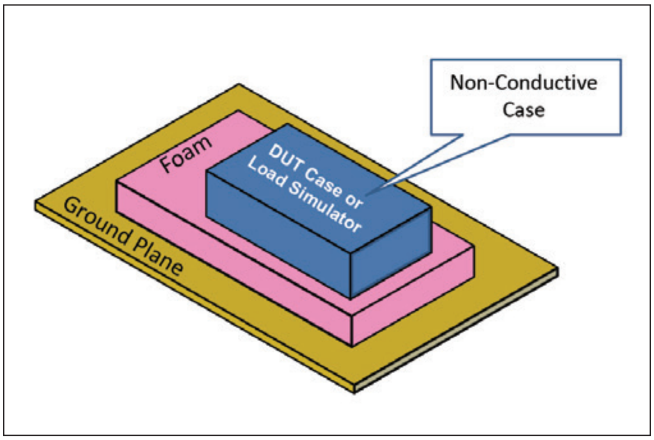


Figure 4: DUT case or load simulator with a non-conductive case isolated from the ground plane on foam.

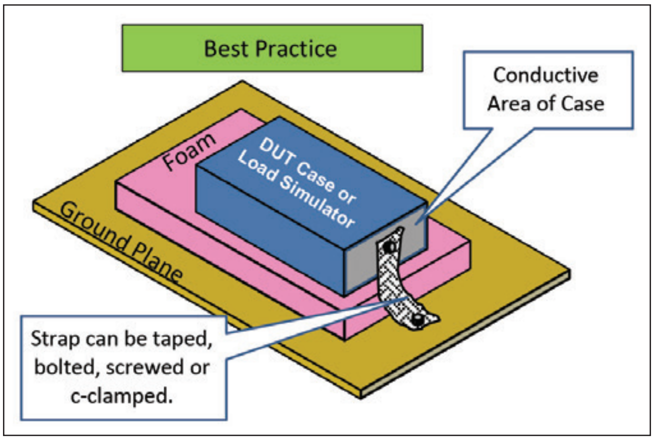


Figure 6: DUT case or load simulator isolated from the ground plane on foam and bonded with a metal braided strap from the conductive area of the case to the ground plane. Fastening the strap with a bolt or screw is best.

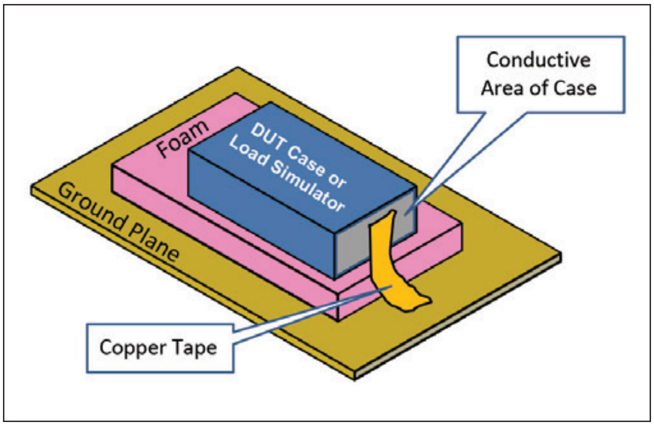


Figure 5: DUT case or load simulator isolated from the ground plane on foam and bonded with copper tape from the conductive area of the case to the ground plane.

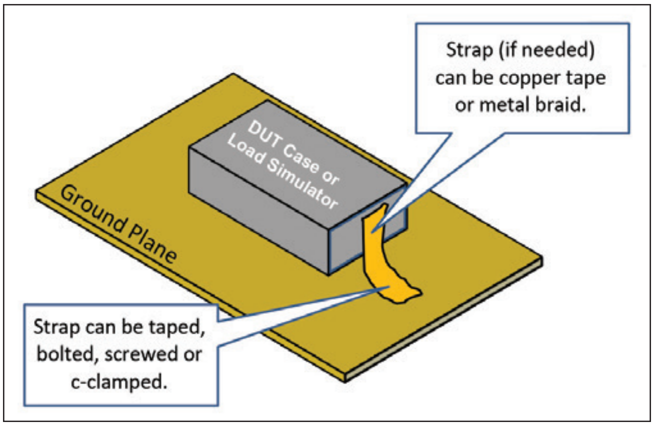


Figure 7: DUT case or load simulator conductive case placed directly on the ground plane. Can be resting on ground plane or bonded to ground plane using copper tape, metal braid or fasteners (e.g., bolts, screws or c-clamp).

WHAT ELSE?

In addition to defining the grounding in the EMC test plan, what else can be done to provide test repeatability and to prevent misleading test results? Instruct the lab to clean the ground plane prior to grounding. Due to oxidation and tape residue, the ground plane surface may have reduced conductivity. Therefore, require the lab to clean the grounding area with a scrubbing pad or emery cloth sandpaper until the metal is shiny again. Use a cloth or vacuum to remove the fine metal dust, then wipe clean with rubbing alcohol.

SUMMARY

Know the customer requirements for grounding the DUT case and/or load simulator. Defining the grounding in the EMC test plan for the DUT case and load simulator is an easy insurance policy for maintaining test repeatability between test operators and test labs. Otherwise, test results may be affected which could cause unnecessary repeat testing or misleading results.

The braided metal grounding strap (maintaining the 5:1 length to width ratio) with fasteners (e.g., bolts, screws, etc.) is the best practice and should be provided to the EMC lab as part of the DUT setup. As an added measure of security, require the EMC test lab to clean the grounding area of the ground plane prior to grounding the DUT case and load simulator.

REFERENCES

1. *Department of Defense Interface Standard – Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*, MIL-STD-461G, 11 December 2015.
2. *Road vehicles - Component test methods for electrical disturbances from narrowband radiated electromagnetic energy - Part 1: General principles and terminology,* ISO 11452-1, 2015-06-01.
3. *Road vehicles - Component test methods for electrical disturbances from narrowband radiated electromagnetic energy - Part 2: Absorber-lined shielded enclosure,* ISO 11452-2, 2004-11-01.
4. *Road vehicles - Component test methods for electrical disturbances from narrowband radiated electromagnetic energy - Part 4: Harness excitation methods,* ISO 11452-4, 2011-12-15.
5. *Road vehicles - Electrical disturbances from conduction and coupling - Part 2: Electrical transient conduction along supply lines only,* ISO 7637-2, 2011-03-01.
6. *Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers,* CISPR 25, 2016-10-27.
7. *Department of Defense Interface Standard – Electromagnetic Environmental Effects Requirements for Systems*, MIL-STD-464C, 1 December 2010.

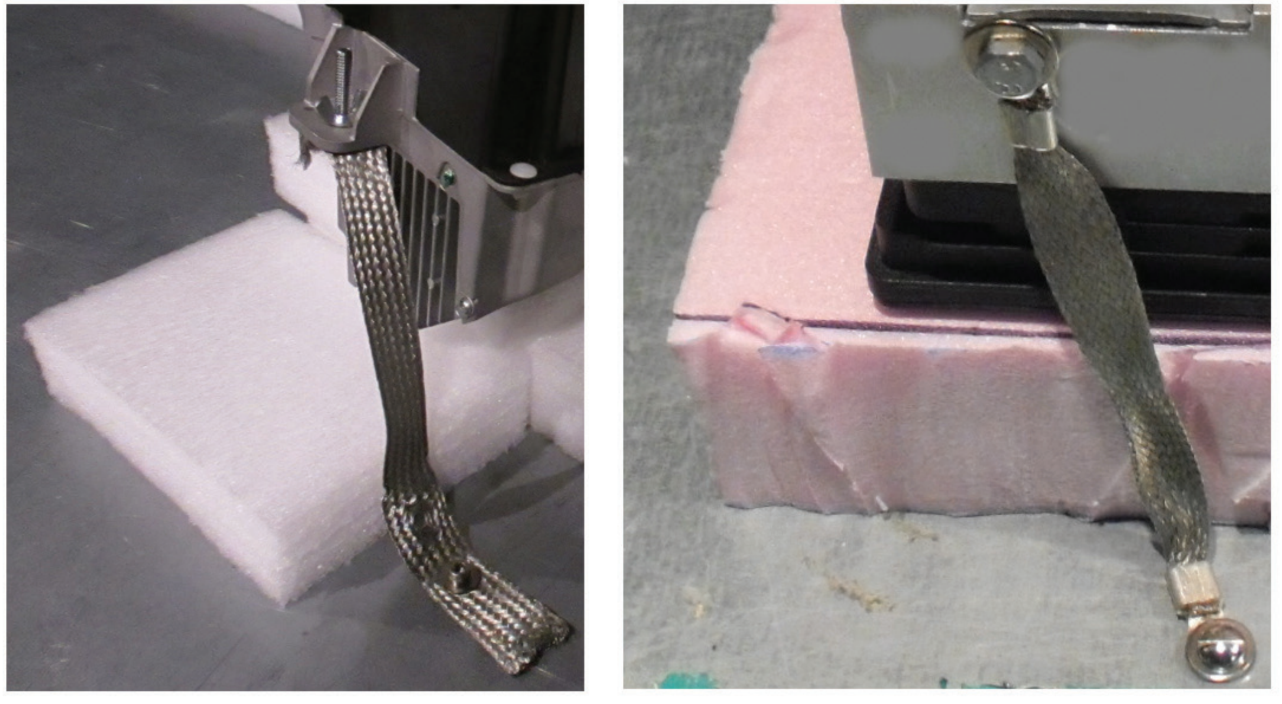
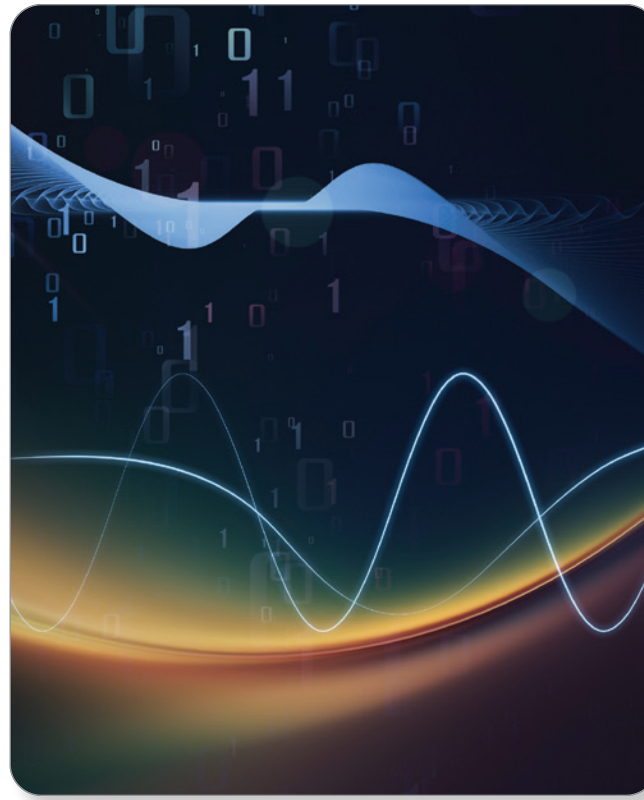


Figure 8: Best practice grounding examples

Measurements of Conducted EMI in the Manufacturing Environment

Practical Guide for Factory Engineers and Technicians

BY VLADIMIR KRAZ



WHY MEASURE EMI IN REAL-LIFE APPLICATIONS?

For EMC practitioners the most important EMI measurements are in the test laboratory to verify EMC compliance of an individual piece of equipment with applicable Standards. However, there is a life after the laboratory, one full of real-life EMI adventures. The whole reason for an EMC test in the lab is to assure low, or acceptable enough, levels of EMI in the actual product's use.

The problem is that the lab measurements have very little to do with real-life applications[1]. This article will focus on measurements of EMI levels in that actual use, more specifically, conducted EMI.

Semantics: while EMI is often defined as a process of interference with, or disruption of, operation caused by high-frequency signals, in this article we will bend this definition a bit for brevity sake and use it as a convenient abbreviation for high-frequency signals that cause such problems.

MANUFACTURING PROCESS

What are the EMI-related needs of manufacturing, or, for that matter, most of real-life applications? The key concerns are the throughput, high yield, low cost, and product's reliability. Strong EMI presents at least the following impediments to the above:

- Equipment downtime, i.e. interruptions in operation of production equipment;
- Errors in measurements, often leading to altered process parameters in automated production;
- Errors in data communication; and
- Exposure of sensitive devices to electrical overstress (EOS)[2] which lowers yield and increases probability of product failure in the field (latent damage).

EMI performance of any one particular tool isn't as important as the overall EMI environment in the process which encompasses all the equipment in the process plus EMI from the facility mains and ground. We will focus on the complete approach to EMI that is focused on the process, not on individual equipment.

Most EMI signatures in real-life applications are transients, i.e., short pulses, periodic or not. Our instrumentation and methodology will be focused on this type of signal.

Vladimir Kraz is President and Founder of OnFILTER, a California manufacturer of high-performance U.S.-made EMI filters and instrumentation. Vladimir holds numerous U.S. patents on the subjects of EMI and ESD. He is a leader of EMC Standards Task Force at SEMI, member of ESD Standards Association and an author of many technical papers in publications and International Symposiums. Vladimir can be reached at vkraz@onfilter.com.

WORST CASE

EMI is generated by operation of equipment in which operation is likely to be intermittent and/or seemingly random. One needs to practice patience and determination to capture the highest signals. Make sure that your equipment is fully operational when making measurements. Set your oscilloscope's triggering to Normal and keep raising the trigger level until triggering stops; then wait for a minute or two just to make sure that you didn't miss a big event. The worst case will eventually happen whether you tried to capture it or not, so you may as well make an effort to capture it.

CONDUCTED EMISSION

This article focuses on conducted emission - any type of unwanted high-frequency signals present on wires and other conductors in equipment or a facility with all equipment operational. For EMC practitioners this is a departure from traditional conducted EMC tests that focus solely on EMI on power lines of individual equipment. So, if EMC regulations are zeroed in on only power lines, why then would we want to measure EMI on anything else than power lines?

One of the key sources of EMI-caused problems resides not on live and neutral wires of AC mains but on ground. This includes both facility ground and grounding inside the equipment. At high frequencies there can be voltage differences between different grounded points inside equipment even if the resistance at DC or impedance at the mains' frequencies (50/60 Hz) is very low. This paper[3] shows high-frequency signals with peak amplitude exceeding 1V between grounded points with impedance of just 0.2 Ohms between them. At high frequencies impedance is quite a bit higher than at 50/60Hz due to parasitic inductance of wires and skin effect. High impedance at high frequencies inevitably leads to voltage difference causing problems with reference points for electric circuits and electrical overstress exposure for sensitive devices assumed to be safe when contacting grounded surfaces. Another conducted EMI problem – high-frequency voltages and currents on data lines – is often caused by induced signals on runs of data cables.

EMI ON POWER LINES

First and foremost, mind safety! Any measurements on live power lines carries risk. If you don't have proper qualification on working with the mains' voltage, please take appropriate courses and/or involve a licensed electrician to assist you.

Measurements of EMI on facility power lines reflect total EMI "dumped" on the shared facility power by a combination of all equipment in the facility. Measuring EMI presents several challenges.

High Voltage Problem

Connecting your oscilloscope or a spectrum analyzer directly to a live power line is never a good idea. The peak voltage on a 250VAC line reached 353V in each polarity, requiring at least a 100:1 probe. Even with such a probe, strong power line surge can still damage your instrument. EMC laboratories use a specialized tool – LISN (line impedance stabilization network)[4]– that is supposed to emulate a real-life power line in the laboratory conditions. LISNs have a high-pass filter (just an L-C network) to provide signal output free of mains' frequency. One of the problems is that we are already working with real power lines and the LISN will cause errors in frequency response by unnecessarily "doctoring" line impedance[5]. Another problem is that the LISN provides hard connection to ground which causes ground loops in measurements and a potential safety hazard. This makes a LISN unsuitable for use in our applications.

Ground Loops

Most oscilloscopes and spectrum analyzers are AC powered and thus grounded via their electrical plugs. If during measurements the ground lead of your scope probe touches live wire, this would cause a catastrophic short via your instrument; if the scope probe's ground touches any other ground in wiring or equipment, this would create ground loop with serious measurement errors as the best outcome. Battery-powered instruments alleviate most of these problems, but not all.

Measurement Problem

When connecting your instrument directly to a power line using 100:1 probe, this probe attenuates not only power line mains voltage, but all signals on power lines. High-frequency signal will also be reduced 100 times making it difficult to measure. If you are concerned with noise of 0.3V as specified in IPC-A-610 (see further in the text)[6], now you would have to deal with looking for a 3mV signal with dubious certainty.

Triggering Problem

If the above is not enough, it is unlikely that you will be able to trigger your oscilloscope on the elusive high frequency signal because your oscilloscope will be latching on an overpowering 50/60Hz signal. Even the oscilloscopes with high-pass filter on trigger are unlikely to succeed because the ratio between peak level of AC mains and high frequency noise is just too high.

Impedance Matching

A 100:1 probe coupled with the scope would inevitably have high input impedance which is a poor match for the impedance of high-frequencies source on power and ground wires. This would cause ringing of high-frequency signals and amplitude errors.

A Better Way to Measure EMI on Live Power Lines

These problems can be solved with specialized power line EMI adapters (an example is shown in Figure 1). Such adaptors typically provide the following features:

- Galvanic separation from power line
- Balanced input
- 50 Ohms output
- Flat frequency response within the required range
- Overload limiter to protect other instruments

With these adapters one can safely measure EMI on live power lines without any artifacts.

GROUND EMI MEASUREMENTS

When measuring EMI on AC power lines the first check is whether the outlet is wired properly – all too often ground and neutral are reversed (regular three-LED checker doesn't check for that) and return current flows through ground, not through the neutral. Besides being a safety violation, this facilitates strong EMI. To identify this problem, take a regular AC clamp meter and measure current through ground conductor in an electrical distribution box. There is always some AC leakage current,

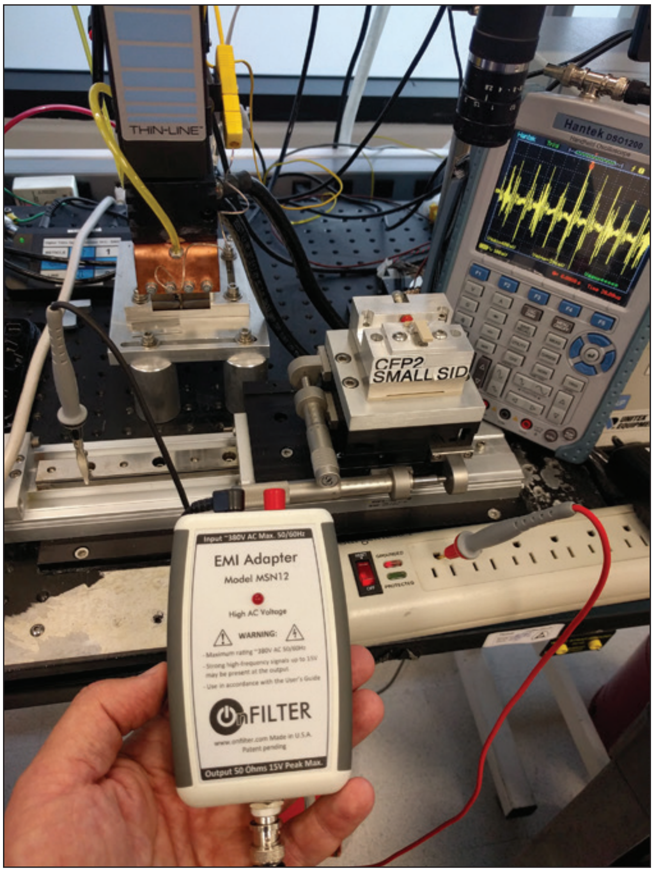


Figure 1: Power line EMI adapter[7]

but it should be limited. If you see AC current over ~0.5A on ground, start asking questions. If this current reaches several Amperes, you can be certain that at least one piece of equipment connected to this power branch has neutral and ground reversed. You can diagnose it by measuring current in ground leading to one machine at a time. Involve a safety specialist at your company and correct this problem before addressing any EMI-specific issues.

We already know that there can be significant high frequency voltage between two otherwise well-grounded points. Why is this bad? In short, problematic reference voltage for electronic circuits and a possibility of electrical overstress. This is well covered in literature[2,8]. In this paper we will focus on measurements. Measurements of voltage between different grounded points using an AC-powered oscilloscope are worthless because an oscilloscope's own ground connected via its AC cable to the mains' ground adds yet another variable to this equation. A battery-powered oscilloscope or any oscilloscope with the EMI adapter described above is a better way of measuring EMI between different grounds. User should be careful when using just the battery-powered oscilloscope alone because sometimes the presumably grounded object isn't really connected to ground and has rather high AC voltage – it pays to check before connecting your oscilloscope. If you are using an EMI adapter this is not a problem because it galvanically separates mains' voltage from its output.

Where to Measure?

In short, where it matters. Traditional EMC tests cover emissions only on the outside of equipment – this is by far insufficient for real-life use. EMI causes problems everywhere, mostly inside the equipment. We will consider as examples the following cases: AC mains, facility ground, automated handling process, and manual soldering.

AC Mains

Please review notes about measurements on EMI on mains earlier in this article for safe and accurate results.

EMI on power lines can be differential (between Live and Neutral) and common mode (between Live or Neutral and Ground). The nature and the pattern of such emission are different – both need to be measured. You may find situations with plenty of differential EMI and very little common mode one, or just the opposite. A good portion of EMI on mains (except occasional commutation events – On/Off) are synchronized with the waveform of the mains' voltage.

Make sure that the equipment is fully operational when performing the measurements – equipment in "Off" state produces no EMI.

As an illustration, Figure 2 shows EMI at the output of uninterruptable power supply (UPS)[9]. In short, this is EMI from operation of a switched mode power supply (SMPS). Note how it is synchronized with 60Hz mains.

EMI on Ground

Some factories have separate facility ground - either a separate ground cable or ground bars. One of the reasons for such separate ground is potential reduction of EMI. This assumption sometimes fails spectacularly. Figure 3 shows EMI voltage between such "special" ground and the mains' ground. A piece of equipment or a workbench connected to both grounds may have a hard time with reference voltages for its electronics and with exposure of devices to EOS.

In manufacturing, different tools often are conjoined for performing a task. It helps if there is no EMI voltage between grounds of these tools. AC powered oscilloscope by itself, of course, is not the right tool for such measurements.

Measurements of EMI on ground or between grounds of different tools can also be done using a current probe, but only after verifying that both grounds are actual grounds.

Automated Handling Process

Figure 4 shows points of measurements of EMI between the robotic arm and the chassis of an IC handler (same applies to other tools handling semiconductor devices such

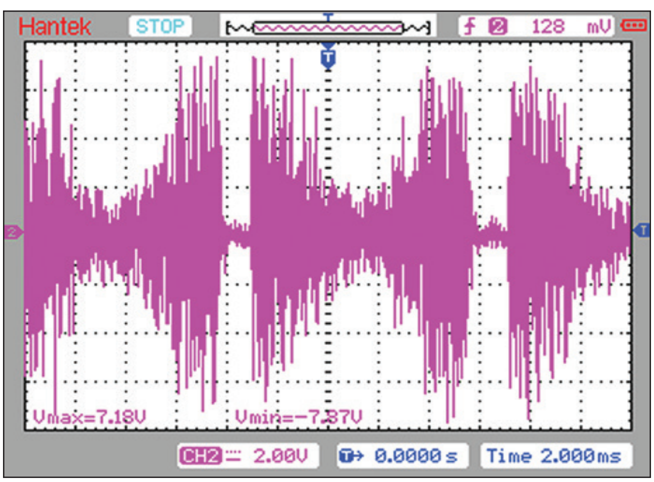


Figure 2: AC mains' EMI after UPS

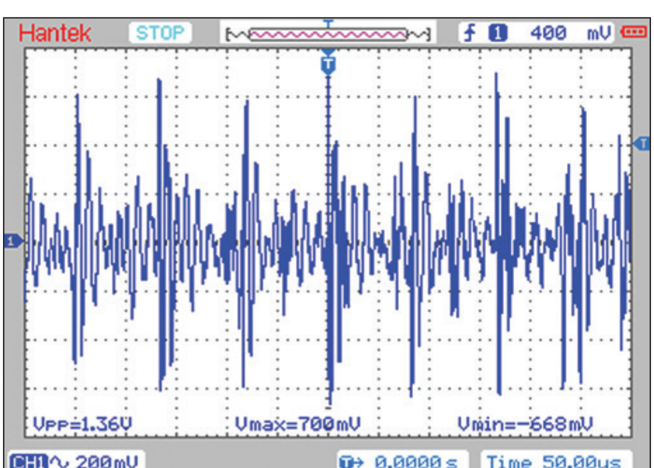


Figure 3: EMI voltage between "special" and mains' grounds

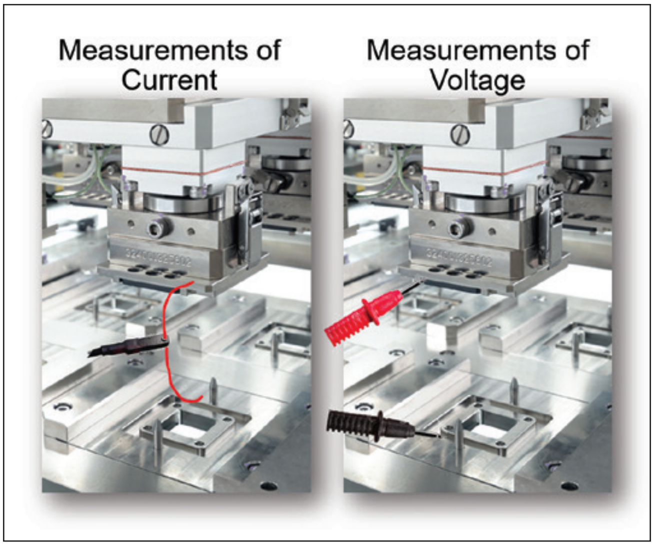


Figure 4: Actual voltage between robotic arm and chassis in IC handler

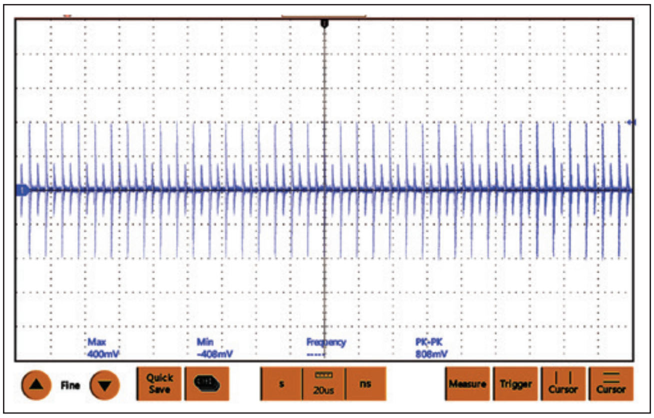


Figure 5: EMI measurements in IC handler

as SMT pick-and-place machines, wire bonders, die attach, etc.). The assumption that a device is "safe" when in contact with ground and nothing else fails a basic equipotentiality test – the voltage difference between different grounded points at high frequencies may not be zero[10].

Figure 4 depicts actual voltage measured in the setup of Figure 5. As seen, the peak voltage (the one that matters – not RMS) is 400mV – higher than applicable Standards – we will look at these Standards further in this article.

Manual Soldering

From an electrical overstress aspect, soldering is one of the worst processes one could imagine – a metal tip of the soldering iron makes a galvanic connection to the pins of the devices which are connected to a potentially different voltage point. The soldering iron tip is grounded via AC outlet; PCB is coupled to the bench ground which is often connected to so-called "ESD" ground. When the tip of the iron touches the component, resulting current can easily subject device to electrical overstress. Whether the PCB is galvanically connected to ground or capacitively coupled to it, this can still happen because capacitive coupling offers very low impedance to high frequency signals[11].

How should we test for EMI-caused EOS in a soldering process? Figure 6 provides some suggestions – voltage (a) and current (b and c) measurements. A user is advised to put together a kind of a fixture as shown to avoid burning fingers or melting test probes. The resistor in Figure 6c is 10 Ohms (any value between 10 and 50 Ohms will do).

The left terminal of the fixture should be attached to either AC ground via power plug or to the ground bar on the workbench (verify first that it is indeed grounded).

The probes shown belong to an EMI adapter that resolves ground loop issues. An oscilloscope without it would work only if it is battery-powered, otherwise the measurements would be completely meaningless.

What if the EMI is caused by a soldering iron itself? Absolute majority of professional grade soldering irons do not introduce high-frequency artifacts by themselves. The problem lies in EMI on the facility's AC power and ground.

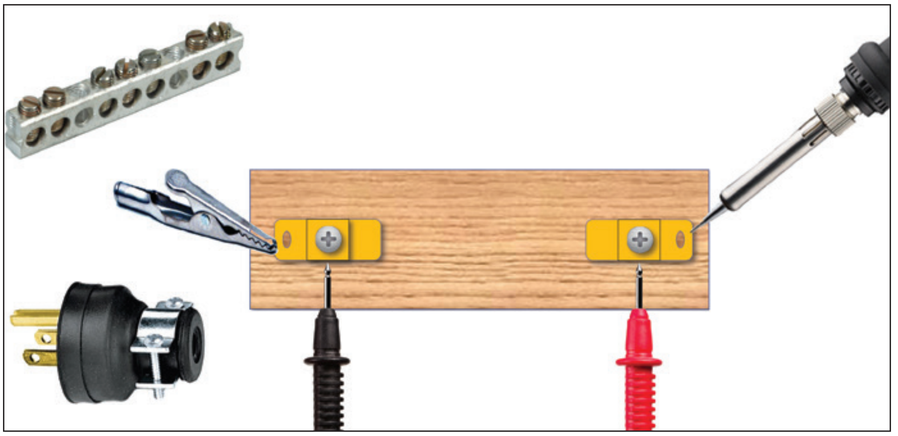


Figure 6a: Measuring EMI voltage

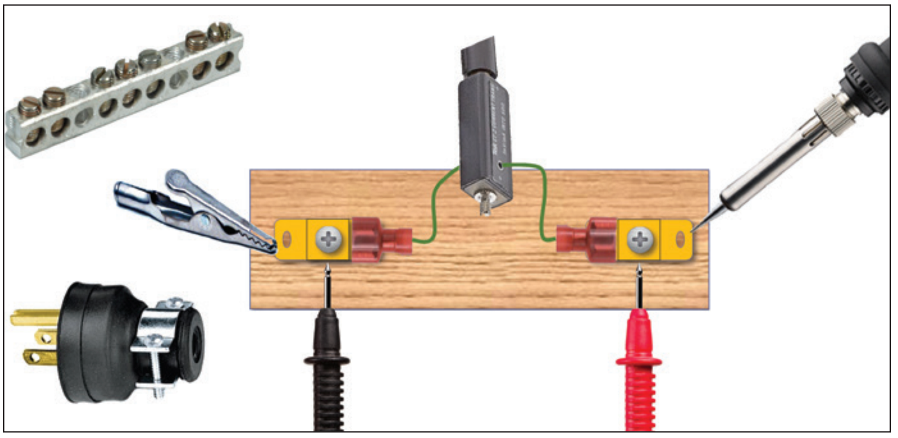


Figure 6b: Measuring EMI current using probe

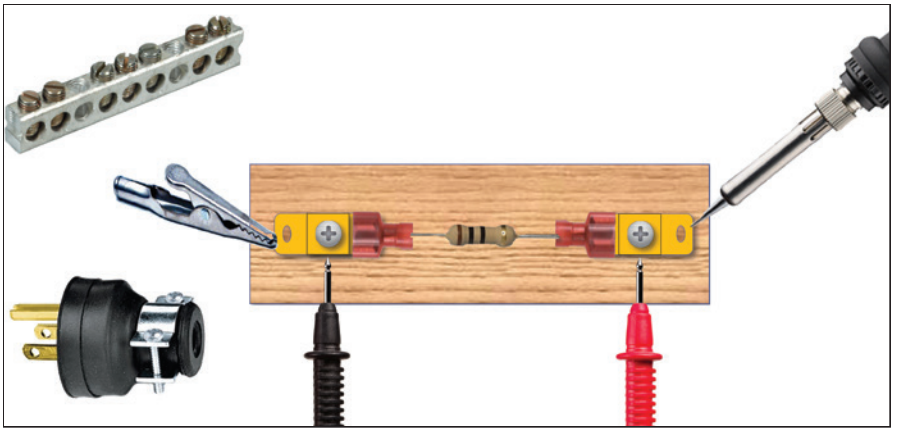


Figure 6c: Measuring EMI current using voltage drop

Figure 7 demonstrates this cause-and-effect. The current spike from the tip of the iron is well-synchronized with the corresponding spike on the mains (as measured with an EMI adapter so that the oscilloscope is well-insulated from the mains).

Is what we see in Figure 7 safe for the devices? This will be discussed further in this article.

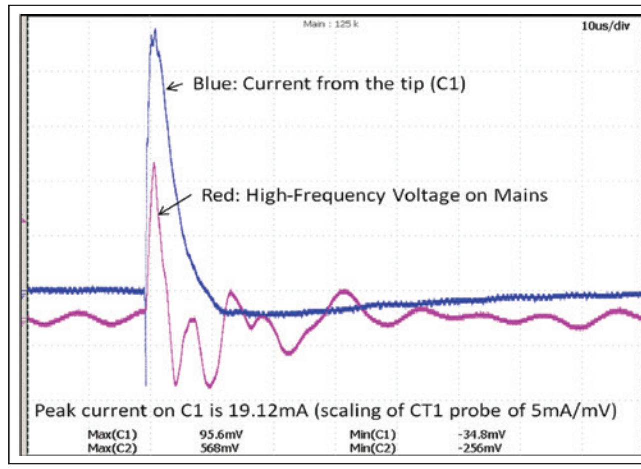


Figure 7: Current from the tip of the iron to a component on the PCB synchronized with the spike on power line

Measurements of Voltage vs. Current in Ground

For operation of electronic circuits, having identical voltage reference in a distributed architecture is most important. For EOS exposure, both voltage and current measurements are meaningful, although, ultimately, it is the current that causes EOS damage, voltage measurements are also quite adequate. From the safety point of view, current measurements between two unverified grounds may cause short circuit should one of the presumed "grounds" be not a ground at all – always verify that assumed "ground" is indeed ground.

Figure 5 shows how to measure current between robotic arm and the tool's chassis. A special current probe should be used for this purpose. The bandwidth of such a probe should start at low kHz and extend to at least 30MHz. The probe's sensitivity to 50/60 Hz is a detriment as it masks the signals of interest.

How to Measure

The only meaningful measurements can be obtained on a working tool. This presents both safety and functionality problems. It is not only unwise but outright dangerous to have your hands in the midst of moving robotics. When performing measurements inside equipment always work together with the person in charge of that particular tool. Instead of putting your hands inside the working tool, utilize jumper wires with alligator clips with enough service slack that won't interfere with movement.

A metrology purist at this point would note that all these wires will adversely affect the measurements and will be highly susceptible to radiated emission which is always plenty in a manufacturing environment, especially inside the equipment. That purist would be correct. But the only alternative would be not doing the measurements, so we will accept inherent unevenness in frequency response and signal ringing as a "fact of life."

Dealing with Radiated Emission Interference

High-frequency signals on wires and metal objects mean corresponding high frequency radiated emission as well. Such electromagnetic fields induce unwanted signals into test leads and corrupt measurement results. To see if your measurements are affected by radiated emission grab the test lead with the palm of your hand – if the readings change, radiated emission is certainly a factor and is likely added some mV or mA to your data. Allow for it when analyzing your results.

INSTRUMENTATION

While from EMC regulations' point of view, signal levels at a particular frequency are a measure of either passing or failing the requirements, for most cases in the field it is the peak value of a total signal that is of importance. A transient signal most common on power lines may have wide spectrum with signal amplitude spread across it, but this is not what matters – the peak value of the pulse does. Therefore, in absolute majority of cases frequency-domain measurements are not as important as time-domain measurements. And the best tool for that is a digital storage oscilloscope. Some real-time spectrum analyzers offer ability to analyze some transients, but are still too slow for the task. Conducted emission do not require high end oscilloscopes – 200MHz bandwidth with at least 1GS/sec is quite sufficient.

Settings of Oscilloscope for EMI Measurements

Incorrect measurements may lead to decisions that could be expensive and difficult to correct. Let's assure that our measurements are done well. Proper settings of an oscilloscope improve our chances of doing so. The majority of EMI signals on power lines and ground are transients, i.e. pulses, therefore we need to set the scope up to capture and correctly measure such signals.

Vertical Scale

Figure 8 shows a signal displayed using different vertical scales. Not only the visual waveforms are quite different, measured numbers are different as well. Yet, it is the very same signal. Why such a difference?

A digital oscilloscope has finite resolution – both its A/D converter and its screen, with typical resolution of 8-bit, or 256 steps. When the measured signal is in the lowest few bits, the oscilloscope adds to it its own noise and A/D dither, inflating the signal value. Unless the vertical scale is pegged up to maximum sensitivity already, the data in Figure 8a offers little value. In the ideal case the signal should occupy ~2/3 of the screen as shown in Figure 8b. The signal, the very same signal as in Figure 8a, but is now

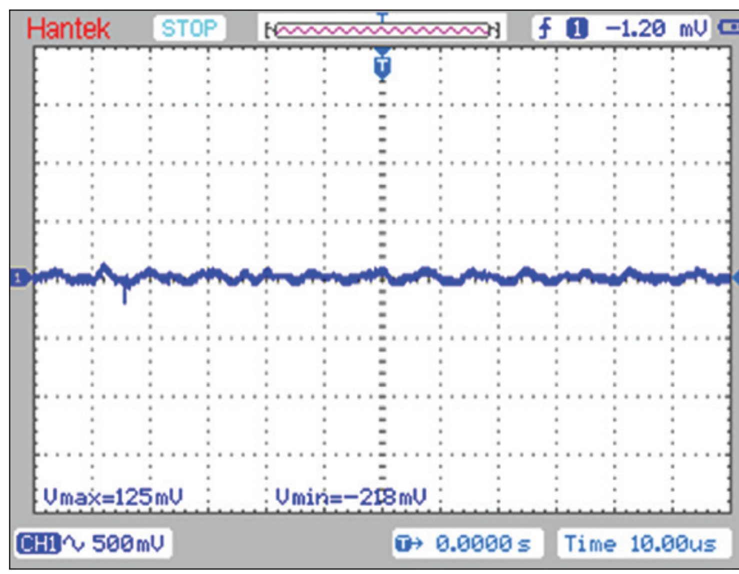


Figure 8a: Incorrect vertical scale

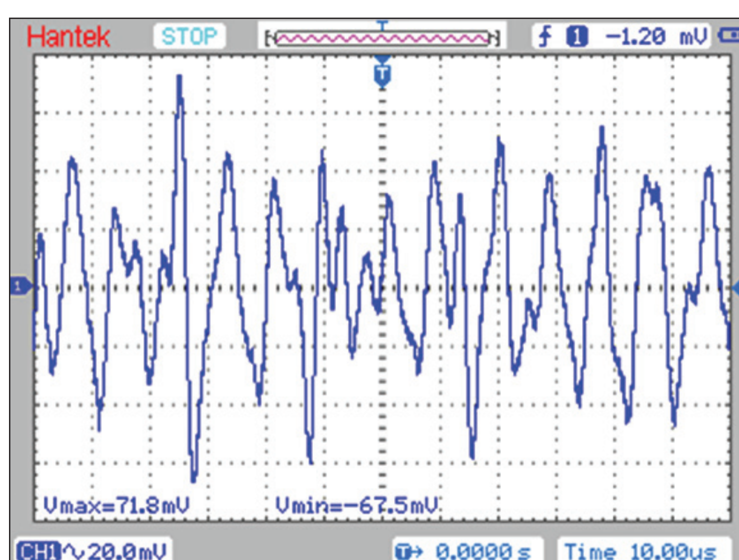


Figure 8b: Correct vertical scale

clearly visible and with more believable values. Watch for overload – if the signal is clipped on the screen, the front stage of the oscilloscope may be distorting the waveform and the measurements are no longer accurate.

Figure 9 further illustrates importance of selecting the correct scale. In this case the signal is very low and is, essentially, flatlining. If one is to estimate the amplitude of the signal, Figure 9a would show an order of magnitude higher "noise level" than the much more realistic Figure 9b.

Time Base

No less important than the vertical scale is the time scale. The same signal is shown in Figure 10. For a full evaluation of the signal any one of the screenshots of the same signal is insufficient. One needs all three screenshots

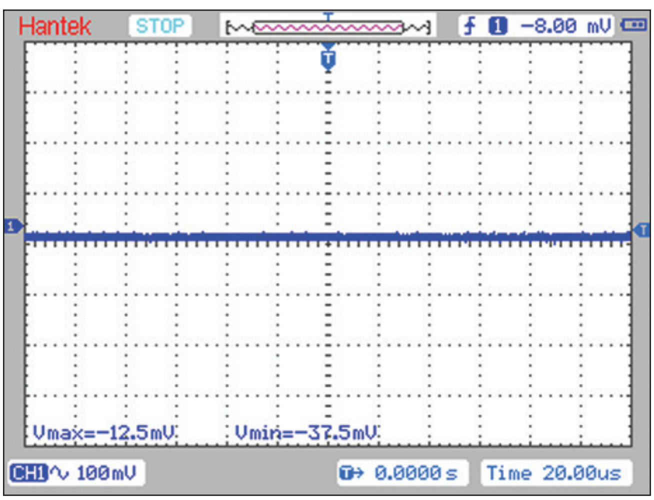


Figure 9a: Incorrect vertical scale

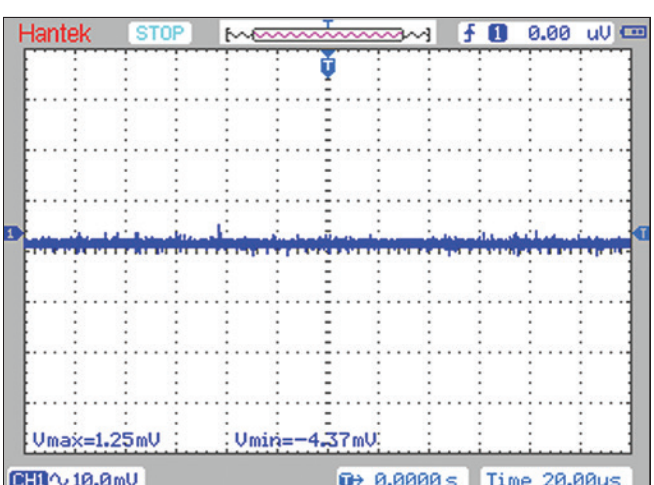


Figure 9b: Correct vertical scale

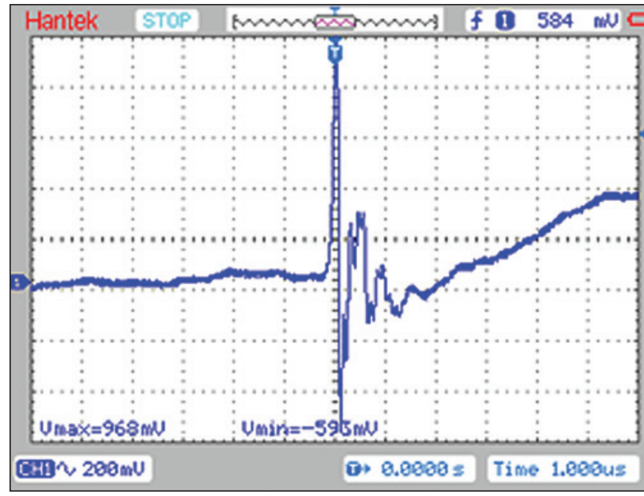


Figure 10a: Can see rise time

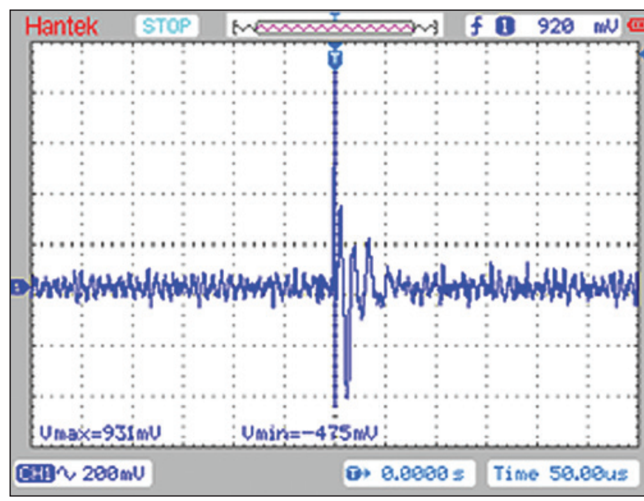


Figure 10b: Can see the entire pulse

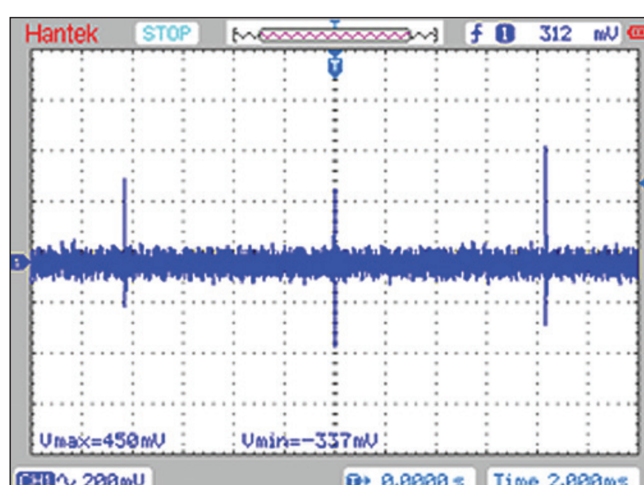


Figure 10c: Can see pulse pattern

to have a complete picture. One can see the rise time of the pulse in Figure 10a; the ringing of the signal in Figure 10b, and the repetition rate of the signal in Figure 10c (which in this case corresponds with the frequency of AC mains). The attentive reader would notice that the wider the time base, the lower the displayed amplitude of the signal. The oscilloscope resolution provides limitations not only on vertical scale but on horizontal (time) scale as well. The more we compress the signal on the screen, the fewer bits would represent the signal and the signal peak can be missed, lowering its perceived amplitude.

Triggering of an Oscilloscope

Triggering is perhaps the most important function in capturing the right signal. Figure 11 provides an illustration of that. A typical EMI signal consists of "important" parts such as A and B, "secondary" part C, and rather unimportant part D. If your trigger is set to "auto" you would see mostly signals D, occasionally C. The best trigger mode to use for EMI signals is "normal." Initially, set the trigger level low and gradually raise it until the triggering stops and the waveform on the screen freezes.

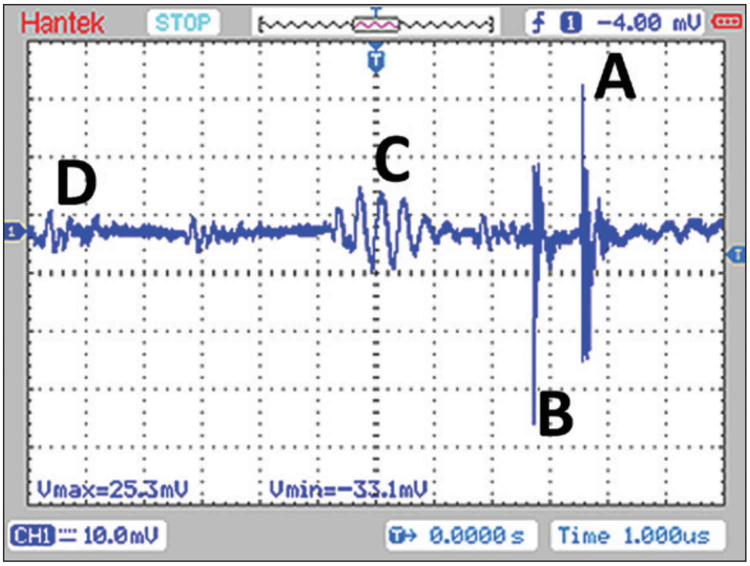


Figure 11: Triggering

Note that signals A and B have similar maximum amplitude but different polarity. These peaks can be both positive and negative, therefore it is important to repeat capture with different trigger polarity.

WE HAVE DONE THE MEASUREMENTS – NOW WHAT?

The data by itself is of little consequence unless it is actionable. First, we need to know what the acceptable levels of EMI are and whether we need to do anything about our findings.

To the author's knowledge, there is no IEC-level standard addressing broad industry needs for low levels of EMI. There are, however, some industry-specific documents specifying acceptable levels of EMI.

SEMI E176-1017 Guide to Assessing and Minimizing Electromagnetic Interference in a Semiconductor Manufacturing Environment

SEMI[12] is an international consortium of semiconductor manufacturing and related companies working on improvements of productivity and advancing technology. Among other activities, SEMI sets standards for the industry covering many aspects of semiconductor manufacturing. The author is a co-chair of Metrics Committee of SEMI Standards overseeing, among other task forces, EMC Task Force, where he serves as a Task Force Leader. SEMI E176 Standard[13] was well covered in this publication.[14] Depending on the internal geometry of the semiconductor devices in the process allowable levels of EMI vary – the smaller the geometry the lower the allowable EMI levels. The same limits apply to adjacent industries – PCB assembly is not much different from semiconductor device manufacturing when it comes to device handling. Table 1 shows selected recommended EMI levels for different geometries of the devices.

According to this table, the voltage between the robotic arm and the chassis shown in Figure 9 (400mV) exceeds

Category	Geometry	Radiated Near Field	Radiated Far Field	Conducted Emission	Ground Current
1	≥28.3 nm	2 V/m	1 V/m	0.3 V	50 mA
2	14.2 - 28.3 nm	1.5 V/m	0.8 V/m	0.2 V	20 mA
3	10 - 14.2 nm	1 V/m	0.7 V/m	0.1 V	10 mA
4	7.7 - 10 nm	0.7 V/m	0.5 V/m	0.1 V	5 mA

Table 1: SEMI E176-1017 recommended emission levels in semiconductor manufacturing (partial data)

even the most generous level of conducted emission – 0.3V. If you are reading this article, most likely your devices have smaller geometry and are consequently more sensitive and demanding lower levels of EMI.

IPC-A-610 Acceptability of Electronic Assemblies

IPC, an organization[6] that governs the quality of electronic assemblies worldwide, publishes limits on electrical overstress in its Standard IPC-A-610[6]: "extremely sensitive components require that soldering irons, solder extractors, test instruments and other equipment must never generate spikes greater than 0.3 volt." Note the emphasis on "spikes" in recognition that even a short transient can irreversibly damage a device. SEMI E176 Standard is also applicable for PCBA since there is very little difference, from an EMI point of view, in handling devices in an IC handler and in SMT pick-and-place machine

ANSI/ESD STM13.1 Electrical Soldering/Desoldering Hand Tools

This Standard Test Method (STM)[15] created by EOS/ESD Association defines limits for AC and DC voltages on the tip of the iron itself, not in any application. The document is used to qualify soldering irons, not the soldering process including workbench. The only practical value we can use from this document is maximum allowed current of 10 mA.

CONCLUSION

Without proper measurements it is impossible to establish satisfactory EMI control. This article merely touches some key points of EMI measurements. The author hopes that this article demystifies EMI often considered a "black art" and makes it possible to use by anyone familiar with an oscilloscope.

Even if you are not overly concerned with EMI today, tomorrow you may be – sensitivity of components and of electronic circuits to EMI is continually increasing. You may be at a place where resolving EMI issues presents an urgent need rather than academic curiosity. The next step is mitigation of EMI in your process, but this is outside of the scope of this article.

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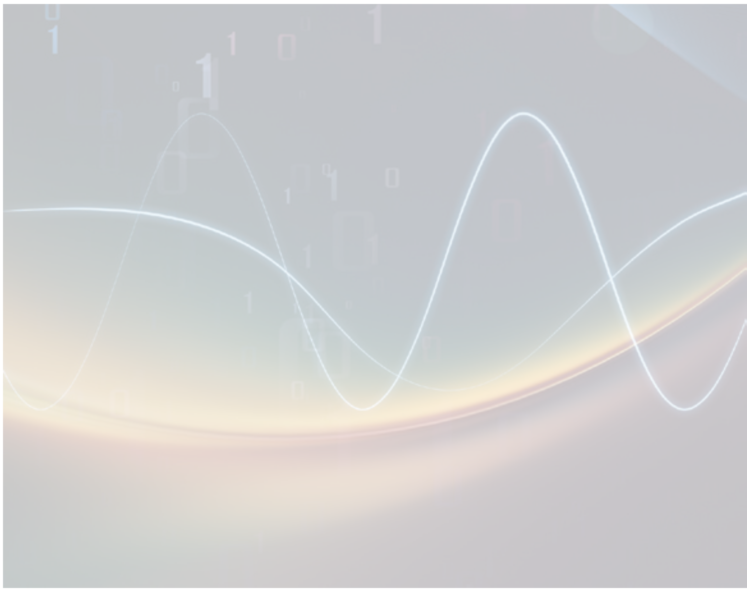

There's an "R" in "Varistor"

A Voltage or Current Dependent Resistor?

BY MICK MAYTUM

The article title is not a spelling test, but an attempt to explain the properties of the neglected varistor resistance parameter, R. Resistance, in this case, is the varistor voltage at a point in the V-I characteristic divided by the varistor current at that point.

A nominal 275 V rms, 14 mm diameter varistor will be used as an example. Manufacturers usually provide a single V-I graph of all the varistor characteristics of a given type. Figure 1 shows the extracted characteristic for a nominal 275 V rms varistor of 14 mm diameter. The characteristic 20% upward step at 1 mA is when the curve changes from the lowest component voltage to the highest component voltage. To form a single curve for the highest voltage component, the curve below 1 mA needs to be lifted by the value of the step. The characteristic normally ends at the rated single 8/20 impulse peak current level.

Turning Figure 1 into a line of data points involved several steps. An enlarged Figure 1 was printed and voltage values taken at the current vertical grid lines. Using a logarithmic reference, such logarithmic graph paper or the slider of a slide rule, enabled accurate measurement of the voltage values. Figure 1 shows a step increase of about 20% in the characteristic at 1 mA as the characteristic changes from minimum voltage (384 V @ 1 mA) characteristic to maximum voltage characteristic (474 V @ 1 mA).

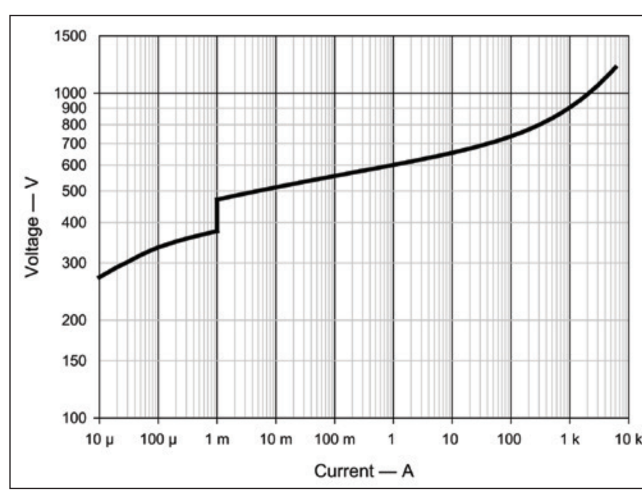

Figure 1: 14 mm varistor data sheet V-I characteristic for a 275 V rms component

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The step was removed by increasing the lowest voltage characteristic by the multiplier of 474/384 = 1.23. Figure 2 shows the result of removing the step and plotting the recorded data points taken as described.

Varistor V-I curves depend on the test current waveform used, a classic case of "It ain't what you do it's the way that you do it." Figure 3 shows the effects of DC, AC, pulse and impulse currents on the shape of the V-I characteristic. At low currents DC is a continuous condition whereas the AC current value will vary over the AC voltage cycle. At high currents the voltage will have a dependence on the impulse rate of current rise. At a given peak current for 1/5, 4/10 and 8/20 impulses, the 1/5 impulse will have the fastest di/dt and, as a result, the highest voltage. These effects need to be born in mind when working from the manufacturers published V-I curves.

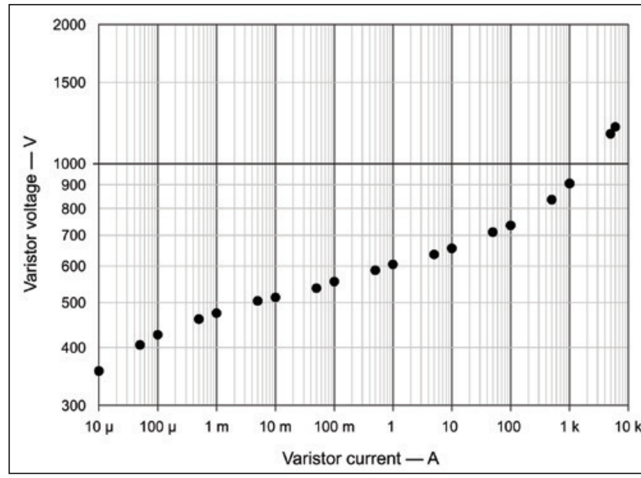

Figure 2: 14 mm 275 V rms varistor V-I characteristic data plot

VARISTOR RESISTANCE R

Dividing the voltage by the current of each data point gives the point resistance value. Plots of resistance versus voltage (Figure 4) or current (Figure 5) can then be made.
Figure 4 does not show any particular relationship between resistance and voltage. Remarkably, Figure 5 shows nearly a straight-line relationship between resistance and current of the form $r = 10^{(A + B \times \log(i))}$, where r is the resistance value, i is the current value and A and B are constants.

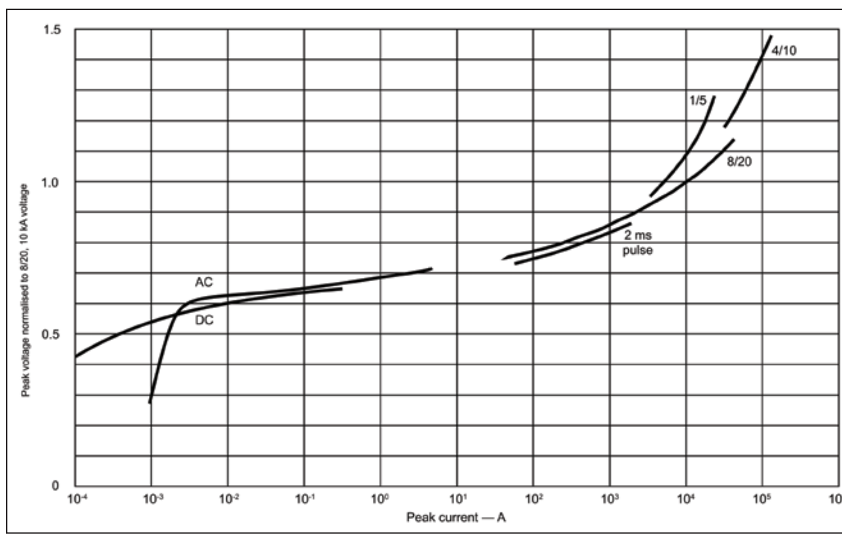

Figure 3: Example of DC, AC, pulse and impulse test currents on the shape of the varistor V-I characteristic

RESISTANCE-CURRENT RELATIONSHIP

A straight-line equation fit to the data points is $r = 10^{(2.8 - 0.95 \times \log(i))}$, but

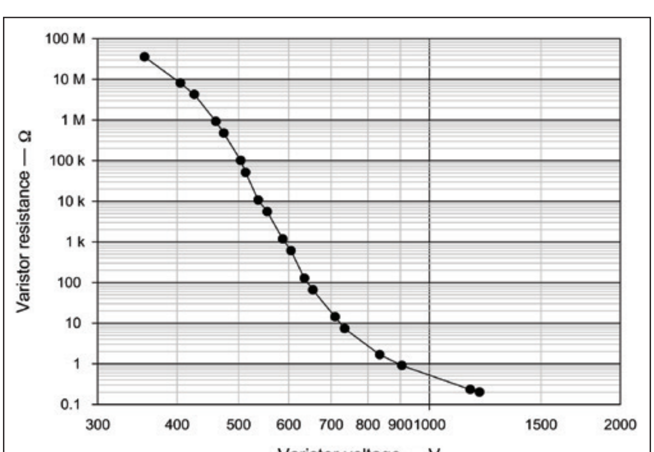

Figure 4: 14 mm 275 V rms varistor resistance versus voltage

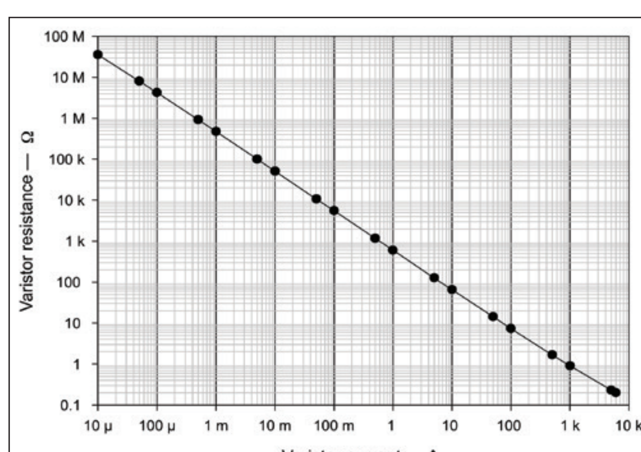

Figure 5: 14 mm 275 V rms varistor resistance versus current

the plot line shows a 16% error at the 5 kA and 6 kA points and the calculated resistance needs to be increased by 0.035 W. The resultant equation would then be $r = 0.035+10^{(2.8-0.95\times\log(i))}$ and is shown in Figure 6. Although the equation has less than 5% error over most of the current range, in the 5 A to 100 A region there is about a 10 % error. These errors could be caused by incorrect data point values and the error may not matter if only the high impulse current operation is important.

Using curve-fitting software resulted in the more complex equation of $r = 5.793\times(i)^{-0.5} + (595.5 + 18\times\mathrm{LN}(i))/i - 1/(1.953\mathrm{E}{-7} + 871\times((i)^2))$, which reduces the maximum error to 1%. One needs to be careful in using such software as outside the data current range some crazy results may occur that causes circuit simulations to fail. The fit quality of this equation (multiplied by current) to the data point set is shown in Figure 7.

These results are not the full story as factors like di/dt have not been taken into account. Figure 8 shows the di/dt resistance effect on a 100 A peak current pulse initiating with di/dt applied values of 1.25A/µs, 12.5A/µs and 250A/µs. In Figure 8, the varistor resistance is normalised to the 12.5 A/µs value because the current rise time will be 8 µs and hence be similar to the virtual front time of an 8/20 impulse. Plotting di/dt on a logarithmic axis shows the measured values are in straight line with a relationship of $R_N = 0.9 + 0.4 \times \mathrm{LN}(di/dt)$, where R_N is the resistance normalised to the 12.5 A/µs value. For the tested di/dt values the varistor R-I characteristic is modified by -9% and +12% depending on the di/dt limit values.

VARISTOR CLAMPING VOLTAGE TEST CURRENT

The clamping voltage is normally measured with an 8/20 current waveshape, but the current amplitude used can differ between manufacturers. The IEC 61051-1:2018 seeks to standardise the test current by defining the 8/20 class current, which is 1/10 of the maximum peak current rating for 100 pulses of 8/20 current. A class current value of 1/10 translates to a repetitive rating of over 100,000 pulses of 8/20 current. Although manufacturers quote the single maximum peak 8/20 current rating and possibly the 2 or 15 impulse 8/20 current rating as well, the maximum peak 8/20 current rating for 100 impulses may only be determined from the derating curves for repetitive surge current. Examining several varistor data sheets with a single maximum peak 8/20 current rated 6 kA, 8/20 component showed 100 pulse ratings of 650 A to 800 A at 8/20, which would give 8/20 class currents between 65 A and 80 A. If manufacturers conformed to using IEC 61051-1:2018 class currents for clamping voltage determination, designers could work out the 100 pulses current rating as being ten times larger.

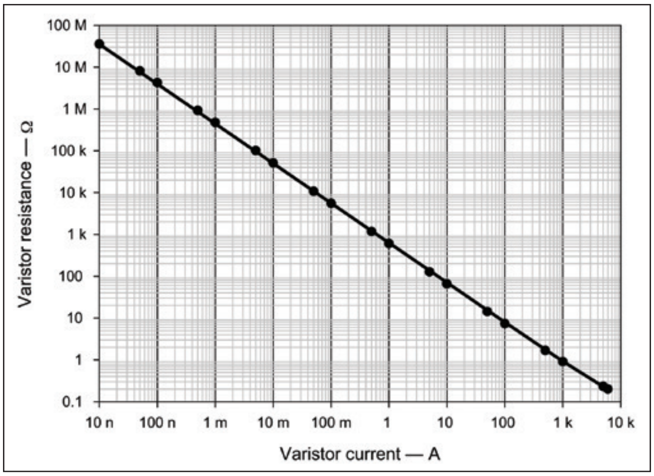

Figure 6: Figure 4 with r = 0.035+10^(2.8-0.95×log(i)) plot

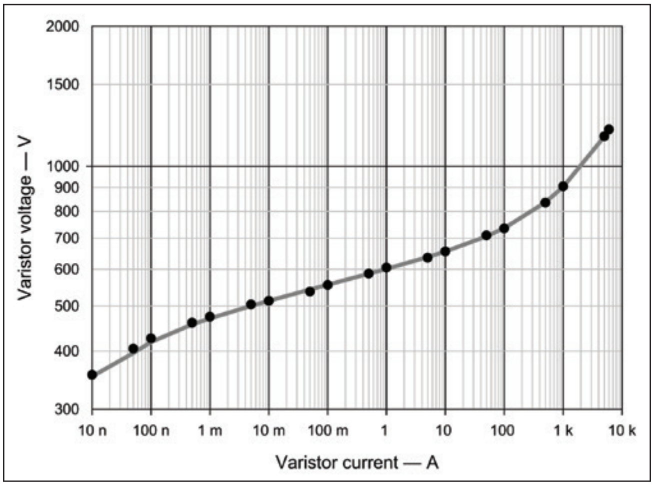

Figure 7: Figure 2 with curve-fitted equation plot

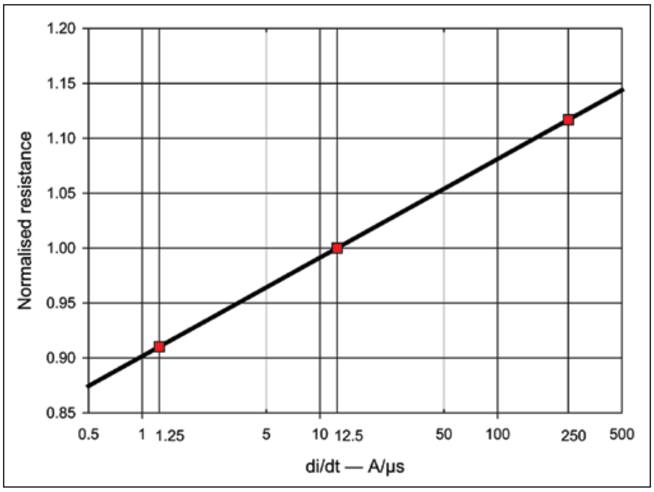

Figure 8: Variation of normalised varistor resistance with di/dt for a peak current of 100 A

RATED MAINS TRANSIENT 8/20 CURRENT

IEC 60664-1 deals with insulation coordination for mains-powered equipment and defines overvoltage categories I to IV with rated 1.2/50 voltage impulse withstand levels for various mains distribution systems. IEC 62368-1 allocates these overvoltage categories to various locations in a building. Added to that IEC 61051-2 varistor standard translates these overvoltage categories into short-circuit currents resulting from a 1.2/50-8/20 surge generator. Table 1 summarises the results from these three standards.

In testing a varistor with a 1.2/50-8/20 generator, the varistor voltage will reduce the delivered current. Using the 275 V rms varistor with a 1.2/50-8/20 generator set to 2.5 kV and 4.0 kV results in peak currents of 720 A and 1.4 kA. According to the data sheet maximum peak current derating characteristic, the rated number of impulses at these peak current levels are 80 and 50.

VARISTOR TERM AND DEFINITION

The standard varistor definition tells us that the varistor is a voltage dependent resistor, not a current dependent resistor, yet clearly these results show it is a current dependent resistor. Article 3.3 of the latest IEC 61051-1:2018 states:

varistor

voltage dependent resistor (VDR)

component, whose conductance, at a given temperature range, increases rapidly with voltage within a given current range.

Note 1 to entry: Varistor is graphically symbolized as Z.

Note 2 to entry: This property is expressed by either of the following formulae:

$$U = CI^{\beta} \quad (1)$$

or

$$I = AU^{\gamma} \quad (2)$$

Standard	Overvoltage category			
IEC 60664-1	I	II	III	IV
	1.5 kV	2.5 kV	4 kV	6 kV
IEC 62368-1	special mains with measures to reduce voltage transients	Pluggable items to building wiring	integral to building wiring	mains supply entry to building
IEC 61051-2	1.5 kV/750 A	2.5 kV/1.25 kA	4 kV/2 kA	

Table 1: Impulse withstand voltages and currents for mains voltages between 150 V rms and 300 V rms

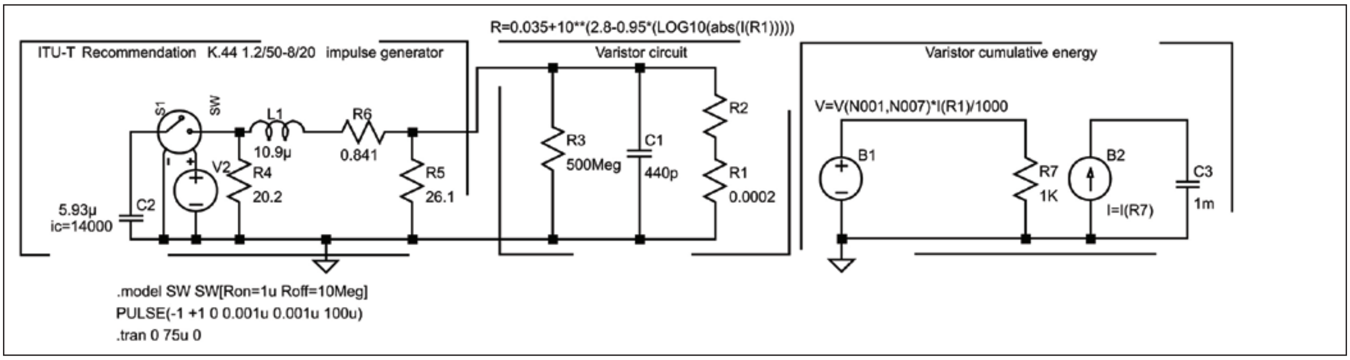

Figure 9: LTspice 1.2/50-8/20 impulse generator with connected varistor simulation circuit

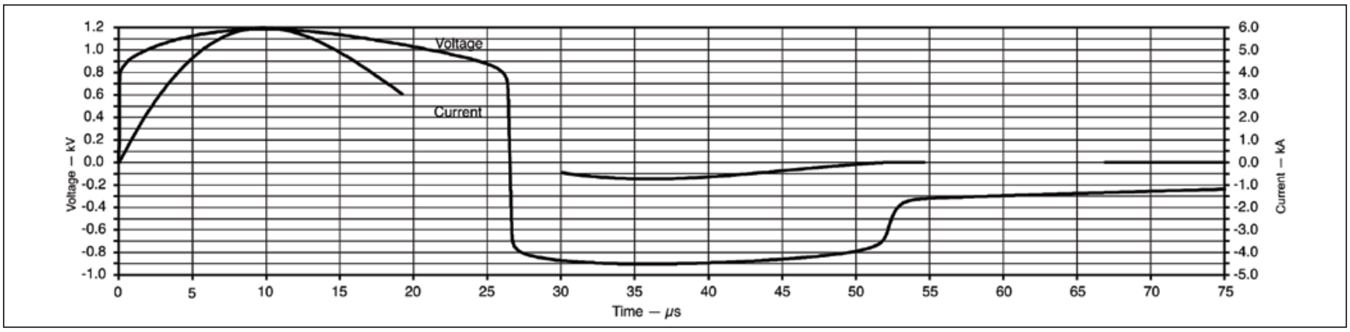

Figure 10: Figure 9 varistor voltage and current

Where:

- I is the current flowing through the varistor;
- U is the voltage applied across the varistor;
- β is the non-linearity current index (see 3.4);
- γ is the non-linearity voltage index (see 3.5);
- A and C are constants

Although the term, definition and circuit symbol are technically wrong, these items will not be discussed here. ITU-T Recommendation K.77, *Characteristics of metal oxide varistors for the protection of telecommunication installations*, solves the problem by using the different term of "metal oxide varistor" rather than "varistor" and gives a completely different definition:

> *"**metal oxide varistor (MOV):** non-linear resistor made of a sintered mixture of zinc oxide and other metal oxides whose resistance (R), at a given temperature, decreases rapidly with current (i), and increases with current rate (di/dt), i.e. R = f(i, di/dt)."*

Examples of impulse di/dt influence on varistor voltage were given in Figures 3 and 8.

USING THE VARISTOR EQUATION

In spice simulation software it is possible to make a fixed resistor into a variable resistor controlled by a function that is dependent on another quantity. We have seen that the varistor resistance is dependent on the current through it and Figure 9 shows the simulation of a varistor connected to a 1.2/50-8/20 impulse generator. The 1.2/50-8/20 impulse generator circuit is reproduced from ITU-T Recommendation K.44. The varistor circuit consists of varistor resistance R2, controlled by the equation at the diagram top, which, in turn, is dependent on the current in series current-sensing resistor R1. Parallel elements representing varistor capacitance, C1, and insulation resistance, R3 are included. The cumulative energy circuit is an add-on to determine the varistor energy. Voltage source, B1, drives resistor, R7, with the product of the varistor voltage, V(N001, N007), and current, I(R1), divided by 1000. Current source, B2, drives the integration capacitor, C3, with the current in resistor R7. Circuit values are dimensioned such that each 1 mV of capacitor C3 voltage represents 1 J of energy.

Figure 10 shows how the Figure 9 varistor voltage varies from positive to negative during the impulse and likewise for the current.

Figure 11 shows that the varistor accumulates energy in two steps; in the positive polarity the step is 107 J and in the negative polarity a further 10 J is added making 117 J in total.

This has been a simple example; the real benefit of an accurate varistor model is when more complex circuits are analyzed. For example, the addition of two more varistors in parallel with the single varistor of Figure 9. When three similar varistors are connected in parallel the lowest voltage one will take most current, set in this case to the maximum single 8/20 rated current of 6.0 kA. Table 2 shows what the individual peak currents and energies would be for three varistors that have the highest, nominal and lowest voltages of a selection. An alternative analytical approach would be to work to a maximum energy criterion as the lowest voltage varistor would develop less energy than the highest voltage varistor at the same rated peak current.

SUMMARY

After years of being taught a varistor is a voltage dependent resistor, it turns out to be actually a current dependent resistor with a well-defined resistance-current relationship. Whether the standards makers rewrite their varistor definitions to comprehend this fact remains to be seen. For engineers, the varistor resistance-current equation can be useful in tolerancing circuits containing multiple surge protective components.

ACKNOWLEDGEMENT

Many thanks go to Zhang Nanfa, for mentorship on the "R" in varistor.

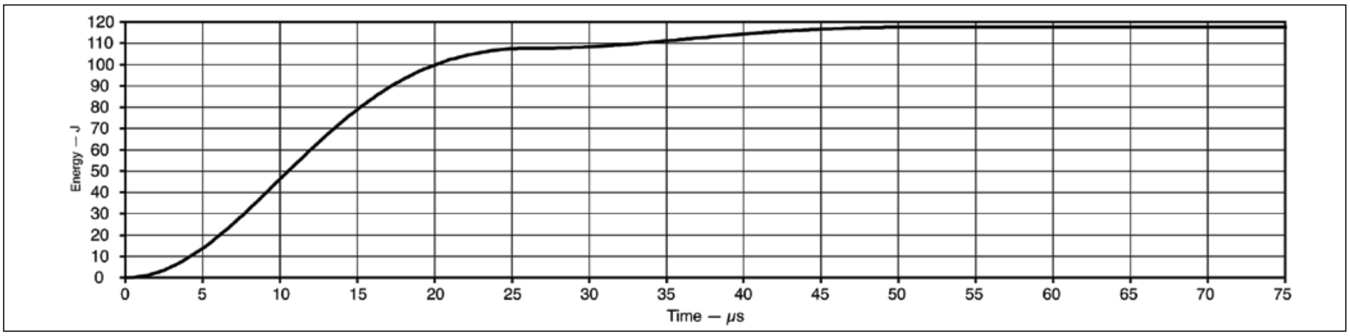

Figure 11: Figure 9 varistor cumulative energy

Certifications for the Korean Market: An Overview

BY JULIAN BUSCH

After being the world's fastest growing economy between 1980 and 1990, and especially after its successful democratization after 1987, South Korea has become a highly developed nation and an industrial and technological leader in many fields as well as a member of the G20 in a matter of just a few decades. Providing its citizens with the fastest internet connection speeds and being home to many large technology companies, South Korea is a global leader in many innovation-driven industries. As the world's 8th largest importer, it is also a very attractive market for many international businesses intending to sell technology and other sophisticated products.

Before being allowed to import and sell products in South Korea, conformity with local regulations must be ensured. For many manufacturers or importers, this often means a certification is required to verify compliance with the requirements of applicable consumer safety standards.

The Korean government has drastically consolidated their certification systems in the last decade, so that the following certification schemes can be highlighted as the most important ones:

- KC certification for many different products, like consumer goods, electronics or children's products;
- KC EMC certification for electromagnetic compatibility and wireless products; and
- KC certification for machines and industrial robots.

This article provides an overview of these different certification systems.

KC CERTIFICATION

In the past, Korea had a complex setup of 13 different certification systems and 140 different test marks, all regulated by different governmental organizations, sometimes even with partial overlaps. In 2009 all these certifications were consolidated after the government introduced the KC certification system to replace the multitude of different certification marks.

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More than 730 types of products are now being regulated under the KC certification umbrella, with consumer goods and especially electronic products being a major contributing factor. KC certification confirms that the products are in compliance with the relevant Korean Safety Standards, the so-called K standards or special governmental ordinances. Even though these standards are usually similar to comparable IEC standards, the KC certification ensures that the products conform with local Korean standards before being allowed to be imported or sold in the country.

The responsibility for the drafting of standards and international standardization efforts in South Korea rests with the Korean Agency for Technology and Standards (KATS). Part of South Korea's Ministry of Trade, Industry and Energy (MOTIE), KATS establishes the general regulatory framework for the KC certification scheme. Products that fall under the KC certification scope have to be checked and certified in accordance with the provisions of South Korea's Quality Management and Safety Control of Industrial Products Act and its Electric Appliances Safety Act.

Accredited as certification bodies and test labs are the Korea Testing Laboratory (KTL), the Korea Testing and Research Institute (KTR) and Korea Testing Certification (KTC). These organizations are permitted to inspect and test the level of product conformity, issue certificates and give permission for marking products with the KC logo.

Generally, the KC certification is manufacturer-based. This means that there is no differentiation between an applicant and the manufacturer. For the KC certification, the actual factory, where a product is produced, must be registered and identified on the certificate.

KC certification covers a wide range of consumer goods, from household appliances to high-visibility clothing, children's products and certain automotive products. However, electric appliances are the most important product category for the KC certification. In addition, most electronic products that use the Korean voltage of 220V AV have to be KC certified. In general, electronic devices with more than 30V (AC) or 42V (DC) usually require a KC certification.

There are three different certification modes and the type of KC certification depends on the product category. The Korean authority defines which products fall under which category and regularly updates these requirements. The three certification types are the following:

- KC Safety Certification
- KC Safety Confirmation
- KC Supplier Confirmation

Under the KC Supplier Confirmation, the applicant's own test results or those from a third-party test lab can be used to show compliance. However, the applicant has to ensure that the tests are conducted according to Korean standards and test methods. No official registration or audit is required, but the manufacturer has to ensure that the labeling requirements are fulfilled. This certification mode is only applicable for electronic products which are classified as not dangerous for users as determined by the certification authority.

The KC Safety Confirmation requires tests in a designated accredited test lab and an official registration with the authority. Electrical equipment that is classified as less dangerous for users usually falls under this category, which for instance includes dish washers, air purifiers and sewing machines. The manufacturer does not have to go through factory audits and the KC certificate is valid for 5 years.

Electrical products that pose a potential danger for users have to obtain a KC Safety Certification. This certification mode requires testing in an accredited lab as well as a factory audit. In order to uphold the validity of the certificate, regular follow-up inspections and product tests are necessary.

Generally, the KC certification process can be simplified and shortened when valid CB certificates and test reports can be presented that verify compliance with the requirements of applicable IEC standards. This documentation must verify that testing has included assessment against Korean voltage of 220V (AC) 60 Hz, or they will not be accepted by the authority.

Certain electrical components of the products that need to be certified also have to be either KC or CB certified. For example, this includes the power plug, switch, AC inlet and circuit breaker. If neither KC certificates nor CB reports demonstrating compliance with IEC standards are available, additional tests of these key components will be required by the certification authority.

As this certification mostly targets products that are intended to be sold to consumers in Korea, the certification authority requires the submission of Korean-language manuals during the certification process. This should be factored in before starting the application process as it can easily lead to unnecessary delays.

Another important product category for KC certification are children's products and especially products intended for use by children under the age of 13. Most children's products require the KC Safety Confirmation at a minimum, including toys or skin care products for children. Products like child restraint systems, for which safety is a crucial design feature, require a KC Safety Certification. However, textiles or leather products for children are only required to go through the KC Supplier Confirmation procedure.

Once a product has been successfully certified, the KC label has to be marked on the product along with certain additional information. Under the KC logo the certification body and certificate number must be displayed. In addition, certain product information must appear on the product label. This includes the product and model name, production date and rated voltage (for electronic products). While the KC logo remains a fixed requirement, actual labeling requirements around specific product information can vary between product categories.

In general, provided product information must be in Korean, except for the name of the manufacturer or the product model, if this information cannot be easily converted into the Korean language.

KC EMC CERTIFICATION

Most electronic devices as well as broadcasting and telecommunication equipment that will be sold in Korea are required to obtain a KC EMC Certification. EMC Certification confirms that a product is electromagnetically compatible with the environment in terms of emissions and interference, and poses no risk to a consumer.

The responsible institutions for KC EMC Certifications are the South Korean National Radio Research Agency (RRA) and the Korean Communication Commission (KCC).

As wireless technologies become more and more prevalent in electronic devices, the KC EMC Certification is further gaining importance.

One essential aspect of KC EMC Certification is that it has two possible components. Apart from general electromagnetic compatibility testing common to many electronic devices, products with wireless and radio technology require separate KC EMC tests. This means that products incorporating Wifi, Bluetooth, RFID and other mobile communication technologies need to obtain two separate test reports when being certified under KC EMC Certification process.

Products which are not equipped with radio technologies consequently only require one test report under KC EMC. In general, the testing requirement for electromagnetic compatibility affects most electric products with frequencies over 9 kHz.

The process for the KC EMC Certification includes the submission of application documents to the authority and subsequent product testing in Korea after the authority has concluded their initial review of the submitted documents. Once testing has been completed and test reports have been issued, the RRA will issue the respective certificates to the applicants.

Upon completion of the certification process, the manufacturer must ensure the correct marking of the certified product. Apart from the KC logo, this also includes a specific identification code as defined by the certification authority. The specific coding varies depend on whether the product has been certified for electromagnetic compatibility, wireless technologies or both. The coding further specifies whether the applicant is the manufacturer, importer or seller of the respective product.

The last two parts of the code include a specific applicant code, issued by the RRA, and a product identification code. The product identification code can be specified by the applicant to include the model name, and can have a length of up to 14 digits.

In contrast to the KC Certification route, there is a distinction between applicant and manufacturer under KC EMC. This becomes especially relevant for foreign manufacturers that use Korean importers and sales organizations. In cases in which the local importer organizes the KC EMC certification and acts as the applicant, there is a certain lock-in effect for the foreign manufacturer. If a manufacturer wants to change their importer who applied for the original KC EMC certificate, that manufacturer must obtain the expressed permission of the named importer to change the certificates. Otherwise, the manufacturer must retest their equipment and obtain a new certification.

KCS CERTIFICATION

The KCs Certification is a special safety certification for machines. This is a certification scheme that is overseen by the Korea Occupational Safety and Health Agency (KOSHA) and requires certain potentially harmful machines or safety equipment to obtain the KCs Mark ("s" for safety).

This certification scheme comprises of two distinct types with different certification processes, namely the Certification of Compliance (CoC) and the Declaration of Conformity (DoC).

The CoC certification requires not only product tests but also an initial factory audit and annual follow-up inspections. In general, machines that are potentially

Staying on top of new developments in the regulatory arena is key to participating in the future growth and development of one of Asia's most advanced and successful economies.

harmful like presses, injection molding machines, sawing machines and pressure vessels fall under this category. Personal protective equipment like safe helmets, shoes, protective gloves or gas masks also require a KCs CoC certification.

Products are usually candidates for the Self-Declaration (DoC) if there is a risk of injury in the event that certain safety-related components fail. This includes products like grinders, mixers, conveyors and industrial robots. For completing the self-declaration process, product tests are usually required and can only be replaced by existing test reports under certain conditions.

Machines with explosion-proof capabilities that are used in hazardous zones can also fall under the KCs certification requirements. Especially when explosion-proof electrical components are built into machines, it is also possible that whole machine as well as the machine's critical individual components will require certification. In such cases, the timeline of a certification process can increase substantially since the certification of the components usually needs to be completed first. Therefore, manufacturers of affected machines should clarify certification requirements with their component suppliers in advance. This can help with avoiding unnecessary delays and discussions over the allocation of responsibilities at later stages.

Normally the KCs certification is a manufacturer certification that also requires factory audits. However, foreign manufacturers of products or components that require a KCs CoC certification can also choose to obtain a so-called import certification via their importer. This allows for a one-time import of a maximum quantity of 10 products. With this certification method, the otherwise necessary factory audit is not required.

Under certain circumstances product tests can also be partially or sometimes even completely replaced with already existing test reports, provided that they are accepted and recognized by KOSHA. Even though replacing product tests could be another way to shorten the certification process, the authority usually requires additional time for a thorough examination of the documentation.

FURTHER CERTIFICATIONS

South Korea also recently reformed its regulations on chemical products by enacting the Household Chemical Products and Biocides Safety Acts (K-BPR) that took effect in 2019. This was an amendment to the existing regulation of chemicals known as Korea REACH (K-REACH), especially for certain products like cleansers, detergents, fabric softeners, deodorants and ink cartridges. These are now classified as household chemical products and regulated under K-BPR.

Certain products not only have to comply to applicable product safety and labelling regulations but are also subject to a safety confirmation. These products have to confirm their conformity by going through testing in designated labs every three years. Some biocidal products must also apply with the South Korean Ministry of Environment (MoE) for pre-market approval.

CONCLUSION

Even after the reform and simplification of the Korean certification system in 2009, it remains a challenge for companies to ensure that their products conform to all the current regulations and requirements and are correctly certified. As the Korean economy is advanced and mature, sudden regulatory changes are uncommon. Normally, sufficient transition periods are granted for companies to adapt their products or obtain necessary certifications (assuming, that is, that they remained informed about the status of requirements applicable to their products, and take timely action to remain compliant).

Staying on top of new developments in the regulatory arena is key to participating in the future growth and development of one of Asia's most advanced and successful economies. And maintaining compliance with relevant consumer safety regulations is an important part of a successful business strategy for taking part in South Korea's innovative marketplace and catering to their sophisticated consumers.

EMC Testing… The EU Experience

Basic Rules for EMC Compliance Self-Testing Techniques

BY DAVID MAWDSLEY

The U.S. has recently changed the rules regarding EMC compliance requirements. Previously, products required accredited test lab measurements in order to claim compliance. Under these rules, the delegation of EMC testing to test labs was understandably standard procedure. Now however, accredited test lab measurements are not mandatory, enabling the practice of self-testing, self-certification by manufacturers.

This has been the situation in the European Union (EU) since 1996.

The experience gained since 1996 in the EU is now relevant to the situation here in the U.S. Self-testing brings many benefits, not all obvious, including:

- Reduced costs paid to the test labs;
- Testing in-house right from early development prototypes through to final product ensures quicker time-to-market;
- Avoidance of expensive re-design phases; and
- Increased in-house expertise, not just in test techniques but in appreciation of how EMC behaves and can be tamed.

EMC measurements are thought of as either a "black art" that requires years of specialist experience to address, or something that can be achieved with very minimal equipment (e.g., near field probes, etc.). Both are far from the truth. Unfortunately, such myths are perpetrated by practitioners and equipment suppliers alike. We had exactly the same happening in the EU. It has taken many years before reality has been established. It is possible that the same "learning curve" will be experienced in the U.S.

Some common myths include:

1. Compliance measurements can be judged/interpreted using near field probes.

   Completely untrue.

2. A standard spectrum analyzer will provide a good tool for measurement of emissions.

   On the contrary, an analyzer can deliver very misleading results, often higher than they should be.

3. Screened rooms are required for measurement of conducted EMC emissions.

   Absolutely not.

David Mawdsley is founder and Managing Director of Laplace Instruments Ltd., and is the originator of innovative techniques for test site calibration and background noise cancelation that enable use of "simple" low-cost EMC test sites. David has travelled worldwide providing training courses which aim to de-mystify the origin and measurement of EMC emissions. He can be reached at tech@laplace.co.uk.

4. Screened rooms are required for radiated emissions measurements.

   A screened room can be useful, but NOT for measuring emissions!

To understand the reasons for the above, an understanding of just two processes are required. These are very simple and basic, and you need nothing more than Ohms law. (I promise!)

Once understood, the EMC measurement techniques specified in the standards become self-evident.

For example:

- Why use an open area test site (OATS), instead of a screened room?
- Why does the antenna have to be at least 3m from the DUT?
- Why use height scanning?
- Why do we measure conducted emissions for frequencies below 30MHz, and why only radiated for 30MHz and above?
- What is the importance of wavelength?
- How is electrical energy actually transformed into radiated RF?
- And, once radiated, how does RF behave?

It is easy to become swamped in the math (Maxwell's equations, etc.) but unless you want to become a specialist in RF, propagation, antenna design etc., there really is no need. Most of us simply want to be able to "see" or visualise and understand the basic principles. These basic principles are surprisingly simple and entirely adequate to explain all you need to know.

On many occasions, I have outlined these simple principles to "EMC experts" at larger companies and consultancies, and have been shocked by their "Aah, now I understand it" response. Clearly, they had simply been following procedures without any real understanding. This means that when confronted by a non-compliant device under test (DUT), they struggled to logically work out how to alleviate the problem.

In this article, I'll focus on radiated rather than conducted emissions. Conducted emissions are more straightforward, but it is important to be aware of and appreciate the importance of dynamic range and detector characteristics, since it is these factors that prevent the use of conventional spectrum analyzers. (I'll more fully address conducted emissions in a future article.)

At the beginning… how is an electrical signal flowing within a conductor magically transformed into an RF signal (airborne emission)? And, once "airborne," how does it behave?

CREATION

Imagine very simple circuit, a battery connected to the power pins of a CMOS digital integrated circuit (IC). The return wire takes a different path, thereby forming a loop. In its dormant state, virtually no current flows. An input from a clock causes the IC to switch at (say) 16MHz. Every time the IC switches, a tiny pulse of current is drawn from the battery.

This current pulse will create a magnetic field around the battery feed wires. We know that current causes magnetic fields around the wire because this is how transformers and electric motors work. The field will be created and then collapsed once the current pulse has passed. (at a 16MHz rate).

Some of the energy involved in creating this field will radiate outwards as magnetic energy. We can think of this as a flow of energy akin to a current flow through a conductor which we call "free space." If free space has an impedance, then Ohms Law dictates that there will be a volt drop.

Indeed, free space has an impedance of 377ohms, so at some distance from the source, we will have a "voltage" (electric field) component related to the "current" (magnetic field) component. This is our electro-magnetic wave (see Figure 1).

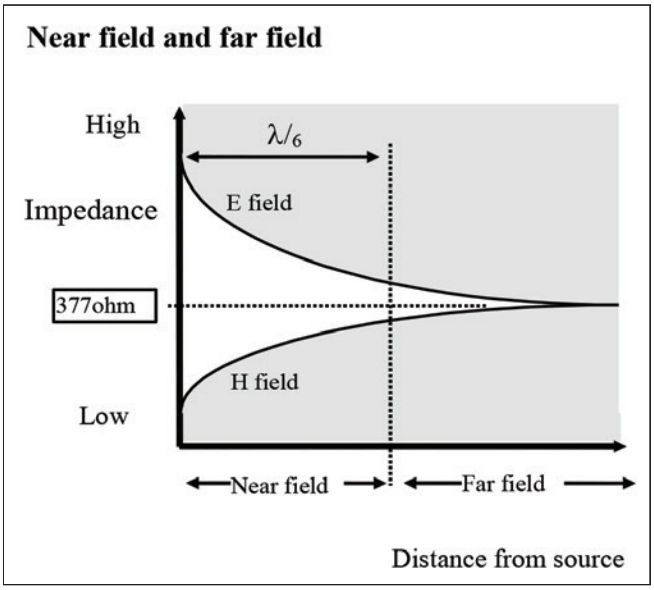


Figure 1: Near field and far field

Close to the source, the wave is entirely magnetic (current) with little voltage component. Again, using Ohms Law, this implies a low impedance wave. If the source was an open circuit stub with a high voltage signal applied to it, an electric field would be created. Its impedance would be high (lots of volts but no current). Again, this field will radiate away into free space and (thanks again to Ohms Law!) a corresponding magnetic (current) flow will be generated, related by the 377ohm term.

3 METERS?

The transition towards the 377ohm wave impedance is gradual, and there is no step change. For practical purposes, this transition is assumed to be at either 1/3rd or 1/6th of a wavelength (depends which textbook you read).

Why is this important?

The "transducer" that we use to measure RF fields is an antenna. Antennas are electric field sensors. If we use an antenna close to the source, which will probably be a magnetic source (most sources are), then the antenna will not measure the field. We need the antenna to be in the far field where the magnetic and electric fields have achieved balance. At the longest wavelength of interest (i.e., that of the lowest radiated emission frequency we need to measure, which is 30MHz), the wavelength is 10m. One third of this is (around) 3m. Hence the standards specify a minimum distance of 3m when measuring emissions.

This also explains why you need two probes for near field work (magnetic and electric).

Some numbers to remember here:

Wavelength (m) = 300/frequency (MHz) in free space.

300MHz = 1m	1GHz = 30cm
100MHz = 3m	3GHz = 10cm
30MHz = 10m	10GHz = 3cm

Impedance of free space = 377ohm.

THE SOURCE?

The energy source of the emission will be a chip/clock/switching circuit or similar component. Although this is the source of energy, it is unlikely to be the source of any emissions. In order to radiate a signal, you need an antenna (as any radio ham or telecoms engineer will confirm). In our case, the antenna will be a wire, a cable or a trace on a printed circuit board. It is this conductor that is the real source of our emissions.

So we have a source of energy (the chip) connected to an antenna (length of conductor). These are typically separate items. The actual radiated emission as measured at 3m will be largely dictated by the antenna, not the energy source.

Near field probes are very good at detecting energy sources, but fail to take account of any antenna, which is why they cannot be used to judge compliance or estimate EMC fields.

To be an effective transmitting antenna, a conductor should ideally be ¼ wavelength long. Other lengths will still "transmit" but will do so with decreasing efficiency. This relationship between wavelength and radiating efficiency is fundamental to the understanding of EMC characteristics of any product. Sometimes, you can just look at a product and know what frequencies will be problematic.

I once tested a golf cart which had some electronics up near the handle and a motor at the base. The distance between the two was around 0.6m, and I amazed the customer by taking one look and predicting that they had a problem around 100 – 150MHz region. Sure enough, they did. (¼ wavelength @ 0,6m = 2.4m full wavelength = 125MHz.)

A golden rule for considering radiated emissions is to think in terms of wavelength…. NOT frequency!

If a product is small, and has no connecting cables, any issues with radiated emissions will be related to higher frequencies. If a product has connecting cables (e.g., mains power feed), use the wavelength criteria, apply to the cables and check the relevant frequencies.

WHY MEASURE ONLY CONDUCTED EMISSIONS UP TO 30MHZ AND RADIATED EMISSIONS ABOVE THAT?

A good question! What is so magical about 30MHz that causes this switch? I mentioned earlier that when a current pulse creates a magnetic field, some of that energy radiates off into space. BUT, some falls back into the conductor in such a way as to oppose further current flow. The shorter the time between the pulses, the more effective this "block" becomes. This is the self-inductance of a wire. If the wire is coiled, the magnetic field becomes more concentrated, and the result is higher inductance.

Reverting to just a plain wire, at DC, its impedance will be very low (mohm). As frequency increases, its impedance increases. So, at 1MHz, impedance may be in the region of some 10s of ohms. Energy flowing through this wire has a choice. Energy will always flow in the path of least impedance, so it will elect to stay in the wire. However, at 30MHz, a typical length of wire reaches an impedance around 377ohm, and above that frequency, the path into "free space" now offers the least resistance, so energy will radiate rather than stay in the wire.

All this is a very generalized "rule of thumb." But it works!

THE EM WAVE

So we now have some emissions from our wonderful product and we place an antenna 3m away. Why 3m? Because that's the minimum distance we are allowed by the standards. Why use the minimum distance? Because that will measure the highest level of DUT emissions and hence provide us the best S/N ratio over the background noise.

The standards will quote class B emission limits at 10m, but in the small print provide a calculation for adjustment of the limit levels for other distances. As a simple rule, changing the limit from 10m to 3m requires a 10dB increase in the limit level.

Officially, we should use an open area test site (OATS). But that creates two problems to address, as follows:

1. Ambient noise
   a. *Find a 'quiet' site for your OATS*—Not so easy in this modern world. Broadcast and telecom services are everywhere!
   b. *Use an ambient cancelation technique*—Definitely an option which works, but only available from certain suppliers.
   c. *Use a screened room*—OK for locating frequencies of interest, but useless for taking measurements (see 2e below). Once you know what frequencies to look for, use an OATS and just select the frequencies of interest.
   d. *Use a test cell that is completely screened from ambient noise*—Good option for small products, but allows higher measurement uncertainties.
   e. *Use an anechoic chamber*—Best option, but expensive.
2. Reflections
   a. EM waves reflect (just like light). They reflect from anything that is conductive. They will pass through any non-conductive and dry obstacles such as brick walls, but will be affected by wet materials.
   b. EM waves interfere with each other such that two coherent waves can cancel out each other, resulting in a much-reduced field strength level.
   c. All waves from a given source will be coherent, that is, they are locked in frequency and phase.
   d. If we have an ideal OATS with just the ground plane causing a reflection, it means that two signals will be received at the antenna, one via the direct path and the other via the reflected path. If the distance to the antenna is 3m, it is quite likely that the ground plane reflected signal will have travelled 3.5m, a path difference of 0.5m. If the emission frequency was 300MHz, wavelength = 1m, the two signals are 180 degrees out of phase and will cancel out each other. This is not just a theoretical nicety, it actually happens!

      The solution is height scanning. It can be shown that, for every frequency in the range 30 – 1000MHz, there is an antenna height at which the two signals are in phase, roughly resulting in a 5dB increase in signal strength. This increase is allowed for in the limit levels specified in the standards.
   e. The above is an account of what happens with just one reflection. Any kind of screened room (not anechoic) is literally a box of reflections and resonances which will make any measurement of signal strength quite meaningless. *Do not use a screened room!*

SOLUTIONS

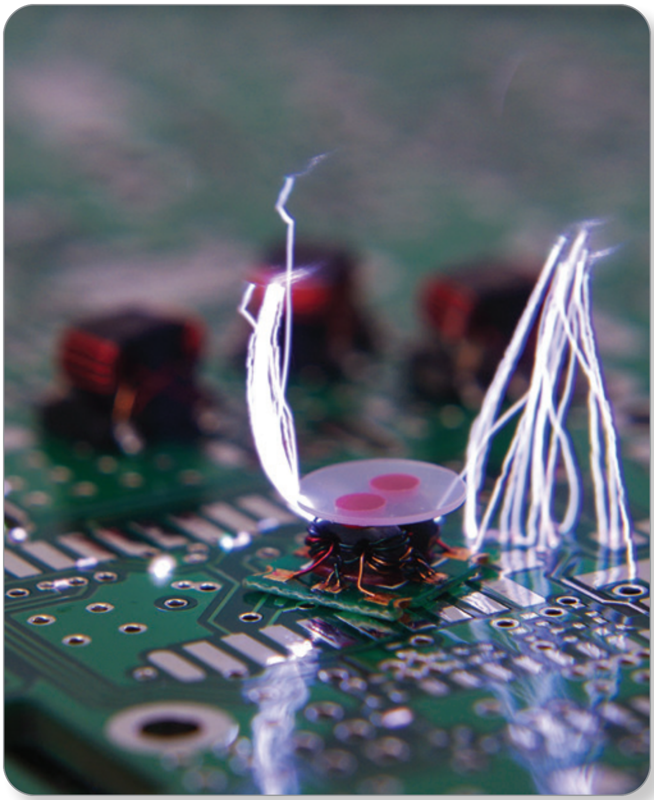
The integrity of radiated emissions measurements is all about the test site. It makes no difference how sophisticated or expensive your receiver/analyzer is. The real source of error or measurement uncertainty is the site. Even with a good site that is clear of reflecting surfaces but with a ground plane, errors of up to 18dB will be experienced if height scanning is not employed. In a screened room, the errors will be off the scale.

So focus your budget on the test site. A chamber or a test cell are the best solutions, if you can afford them. But, if the budgets are restricted (and they always are!), then create the best OATS that your facilities allow, and use an emissions reference source (ERS) to calibrate the site "as is." This will enable the characteristics of the site to be accurately measured and allow you to generate correction factors that can be applied to the results from your DUT. And the process can be entirely automated with advanced software solutions that are currently available. Another advantage of this technique is that the requirement for height scanning is avoided.

Ambient noise is the final issue to contend with. A problem with ambient noise is that it suffers significant short-term fluctuations which can mask DUT emissions. Again, software solutions can help stabilize ambient noise while the DUT is switched off, thereby permitting the measurement of DUT emissions on subsequent scans.

Device Failure from the Initial Current Step of a CDM Discharge

BY DAVID JOHNSSON, KRZYSZTOF DOMANSKI AND HARALD GOSSNER



Editor's Note: *The paper on which this article is based was originally presented at the 40th Annual EOS/ESD Symposium, where it was awarded the Symposium Outstanding Paper in 2019. It is reprinted here with the gracious permission of the EOS/ESD Association, Inc.*

INTRODUCTION

RF interfaces tend to get more sensitive as the gate oxide (GOX) thickness is continuously decreasing for every new technology node. At the same time, the high operating frequencies limit the capacitive budget for Electro Static Discharge (ESD) protection devices. This makes the ESD design challenging, especially for the Charged Device Model (CDM) pulse with its high current and fast rise time. In this work the CDM failures of a sensitive RF interface are investigated. By modifying a CDM tester it is proven that the failures are related to the fast current step that appears at the beginning of a CDM event. The analysis is supported by 3D electrical field simulation of a CDM tester, showing that the first current step can have a rise time in the order of 20 ps. It is shown that the failure can be reproduced by applying CC-TLP pulses with 20 ps rise time. By investigations of rise-time sensitive test structures on wafer, it is demonstrated how the wiring layout can strongly influence the failure level in this fast pulse regime.

INVESTIGATED DEVICE

The device in this study is a Low Noise Amplifier (LNA) manufactured in a 28-nm technology. The input stage consists of thin-GOX MOS transistors with a breakdown voltage around 5 V. Due to RF performance requirements, the gate is tied directly to the pad, which is critical from an ESD point of view. The chosen ESD protection scheme is a standard rail-based topology as shown in Figure 1. To meet the capacitance requirement of <180 fF, small diodes were used as ESD clamping devices. The diodes have no Shallow Trench Isolation (STI) between the anode and cathode diffusions, and thus exhibit a fast turn-on time [1]. All protection devices, including a large dedicated power clamp, were placed in a close vicinity to the LNA (max 100 µm) to avoid any inductive paths and to minimize the bus resistance. The LNA

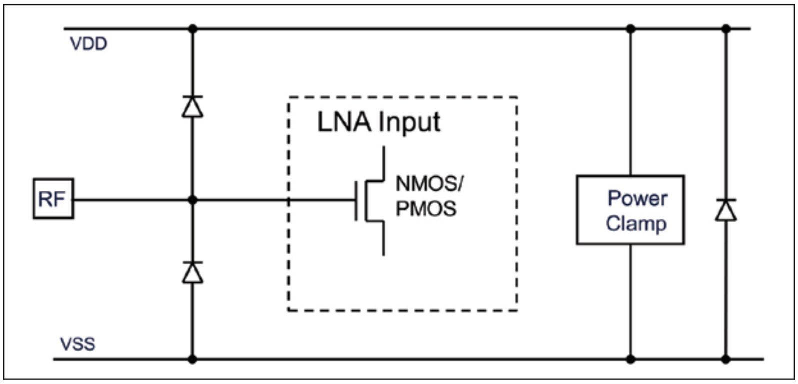


Figure 1: ESD Protection circuit for the LNA interface.

is located directly below the input ball of the package. Since the receiving gates of the LNA are connected directly to the pad, a GOX damage can be detected by DC leakage testing.

TEST RESULTS

VF-TLP Results

In an early design phase the LNA circuit was placed on a test chip, using a very similar topology as expected for the final LNA implementation. Testing was performed on wafer level using a VF-TLP test system with 1ns pulse width and 100 ps rise time. The result from VF-TLP testing is shown in Figure 2. The achieved robustness in the range of 5-6 A was considered sufficient to handle the minimum CDM requirement of 250 V. Identical values were obtained with 300 ps pulse rise time. TLP testing on the final packaged product showed identical results.

CDM Results

The packaged LNA interface was tested on an Orion 2 CDM tester with a JS-002 compliant test head. The results are presented in Table 1. Unexpectedly, the LNA failed at +250 V at a peak current of 2.7 A. This is only about half the current compared to the VF-TLP test results at negative polarity (corresponds to positive CDM stress). For the negative CDM stress polarity, the device failed at -400 V.

CC—TLP Results

The packaged LNA was tested with a CC-TLP setup [2] with a pulse source capable of rise times as low as 20 ps. Captured pulses into the device with 100 ps and 20 ps rise time are presented in Figure 3, and the CC- TLP test results in Table 2. At 100 ps rise time the currents resulting in failure are very similar to the VF- TLP results. However, at 20-ps rise time failures appear at a peak current as low as -2.4 A. Hence, it is evident that the failure is not caused by the peak current, but rather by the rise time of the pulse. This is consistent with [3], where it was shown how the current slew rate influences the fail level of a device in a CC-TLP setup. Note that in the case of 20 ps rise time the measured current through the device shows a fast rise time only up to 70% of the peak current, followed by a slower rise up to 100%. Tests performed on a short circuit (metal plane) showed identical waveforms, so the limited rise time seems to originate from a limited bandwidth of the CC-TLP probe.

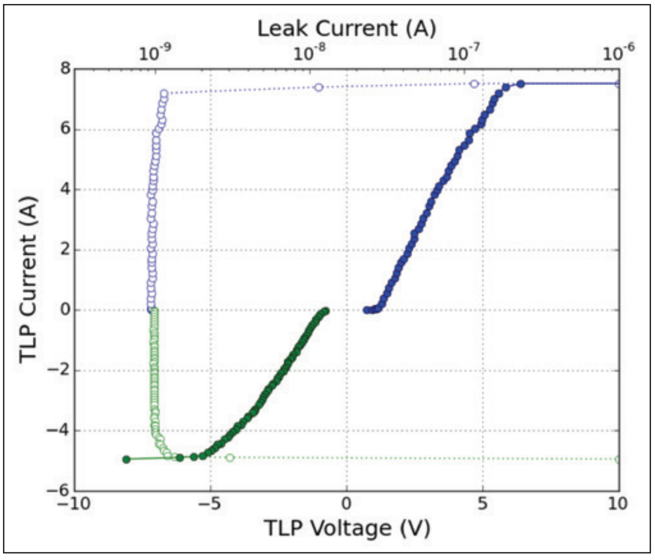


Figure 2: VF-TLP Results from an LNA test structure on wafer. The pulse width is 1 ns and the rise time is 100 ps.

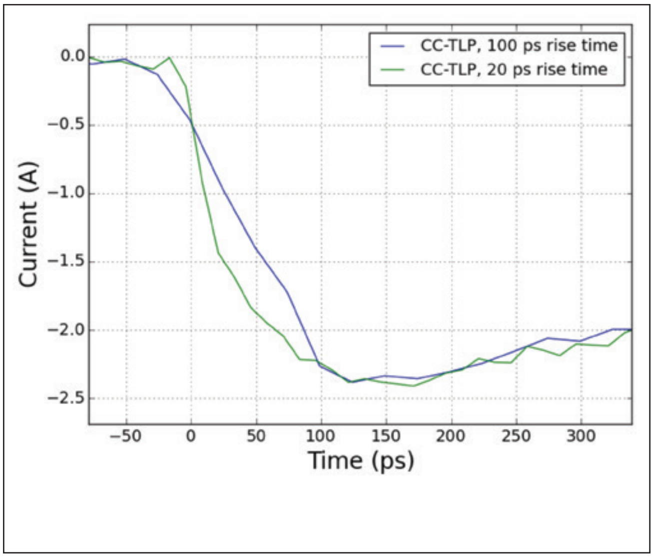


Figure 3: Measured pulse rise times of CC-TLP pulses at -2.4 A stress level (33 GHz measurement bandwidth)

Level	Peak Current	Pass/Fail
+200 V	2.4 A	Pass
+250 V	2.7 A	Fail
-350 V	-3.6 A	Pass
-400 V	-4.2 A	Fail

Table 1: CDM results for LNA interface.

CC-TLP Rise Time	Positive Fail	Negative Fail
100 ps	>+6 A	-7 A
20 ps	+3 A	-2.4 A

Table 2: Results from CC-TLP testing

CDM TESTER ANALYSIS

Series Resistance in the Pogo Pin

In this experiment, the pogo pin was cut, and a chip resistor of size 0604 was soldered in series, as shown in Figure 4. The resulting discharge currents are shown in Figure 5, and the results from LNA product testing in Table 3. As expected, the peak current decreases with increasing resistance. The most interesting results were obtained with the 1 M-Ω resistor: Although the captured current was practically zero, fails at +250 V were still observed. The failure mechanism seems to depend only on the CDM charge voltage, not on the measured current.

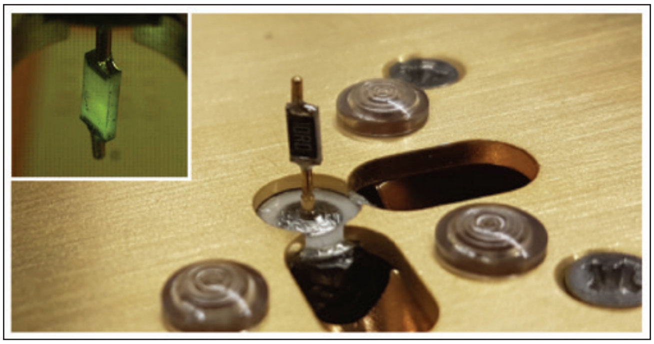


Figure 4: CDM discharge head with a size 0603 chip resistor soldered in series with the pogo pin

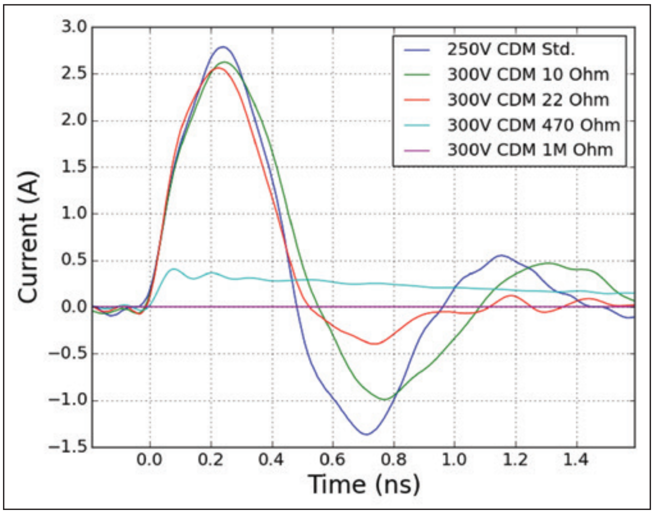


Figure 5: CDM discharge waveforms with different resistors inserted in the pogo pin

CDM Setup	Level Peak	Current	Pass/Fail
Standard Pogo	+250 V	2.7 A	Fail
22 Ω	+300 V	2.4 A	Fail
470 Ω	+300 V	0.4 A	Fail
1 MΩ	+200 V	~0 A	Pass
1 MΩ	+250 V	~0 A	Fail

Table 3: Results from CDM tests with resistor in the pogo pin

It should be pointed out that most CDM current probes have a limited bandwidth of only a few GHz [4]. Possibly, an important part of the waveform is not captured.

CDB Current into the Popo Pin

In simple LRC models, the pogo pin inductance defines the rise time of the CDM pulse. However, the simple model does not take into account the stray capacitance of the pogo pin. In the presented experiments with the 1-MΩ resistor in the pogo pin, the 2-mm-long tip has a certain capacitance to the surrounding (ground plane, charge plate, and to the device), as represented in Figure 6. Hence, a dipole charge is present at the pogo pin. When a device is discharged by the pogo pin, a current flows into the pogo-pin tip and charges its capacitance. Even though the pogo-pin capacitance is comparably small, the current can be considerable since there is only a small inductance in the path.

CDM Head S-Parameter Simulation

In [5] a method was demonstrated for measuring the S-parameters of a CDM head and simulating the resulting waveforms. In this work, we apply the same methodology but simulate the S-parameters with the 3D field solver HFSS from Ansys. Figure 7 shows the models used for

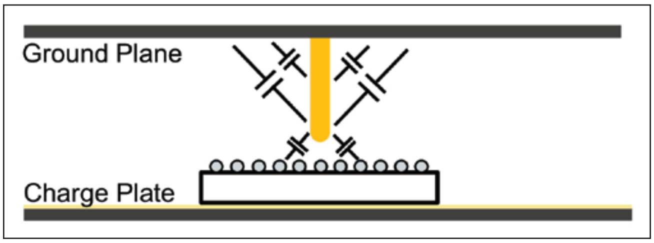


Figure 6: Capacitance contributions of the pogo pin

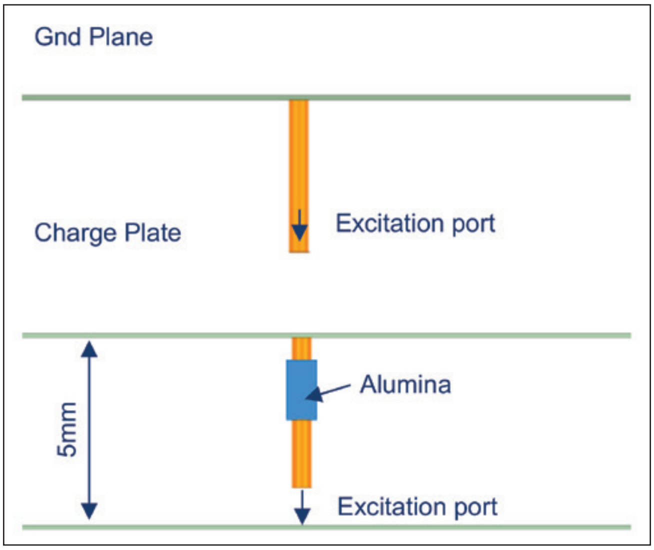


Figure 7: Side view of the 3D models used for simulation of a CDM head with standard pogo pin (top) and resistor in the pogo pin (bottom).

simulation of the CDM head with and without resistor. The S-parameters are simulated at the excitation port between the pogo pin tip and the charge plate. The 1-MΩ resistor is simplified as a block of alumina interrupting the pogo pin.

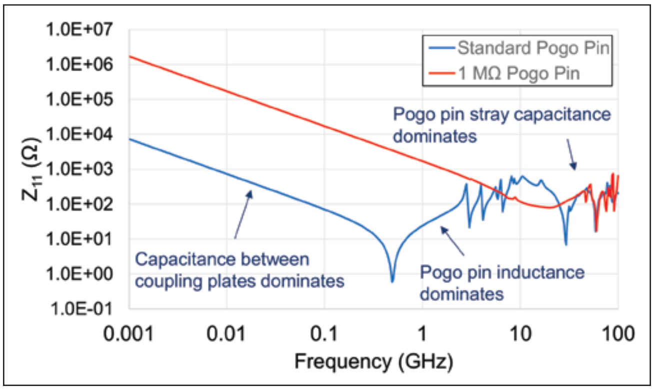


Figure 8: Simulated Z-parameters for a standard CDM head (blue), and a CDM head with 1-MΩ resistor in the pogo pin (red)

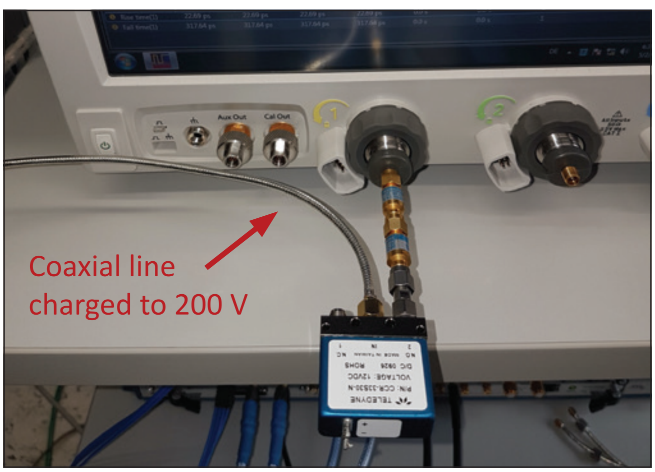


Figure 9: Measurement setup to characterize the pulse rise time from a coaxial switch

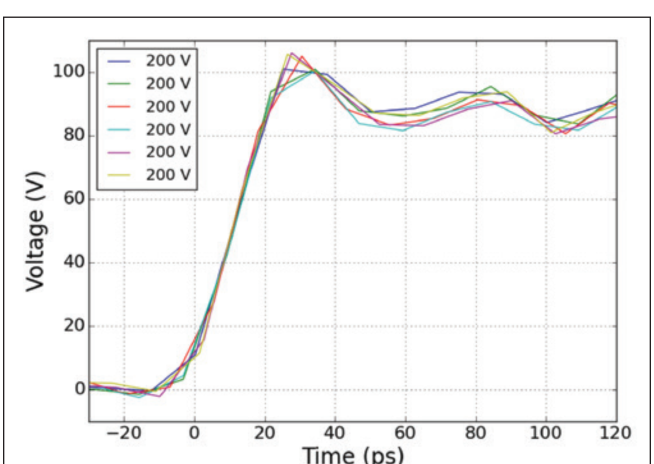


Figure 10: Discharge waveforms from a coaxial switch at 200V charge voltage

Figure 8 shows the simulated Z-parameters for the two configurations. Z-parameters are derived from the S-parameters and are easier to read since they represent the impedance seen into the pin tip. In the low frequency range the impedance decreases with increasing frequency as expected from a capacitance. For the standard CDM head the inductance of the pogo pin starts to dominate above 500 MHz and the impedance increases with the frequency. However, above 10 GHz the inductance loses its effect and the impedance remains in the order of 100 Ω up to 100 GHz. In this frequency range, the impedance with and without the resistor is similar. Thus, it is mainly the frequency spectrum of the discharge spark that determines the pulse shape in the upper frequency range, and it will be similar for the standard and the 1- MΩ pogo pin.

Rise Time of the CDM Spark

The most uncertain property of a CDM discharge event is the spark rise time and resistance. It varies strongly, depending on the applied voltage, air humidity, ball and pogo pin geometry and the speed of approach. In [6] it was shown that a CDM-like discharge between metal parts can have a rise time around 30 ps. To characterize an ideal metal-to-metal discharge a standard coaxial switch with 26 GHz bandwidth was used. The switch was connected in a TLP-like configuration with one port connected to a coaxial line that is charged up to 200 V. The other port of the switch was connected via attenuators directly to the input of an oscilloscope with 33 GHz bandwidth, shown in Figure 9. The coaxial switch is not an ideal TLP switch and shows strong pulse instability. Still, it was possible to capture several pulses with a rise time as low as 20 ps, as shown in Figure 10. Since the overall bandwidth of the setup is limited by the 18-GHz rated connectors and attenuators, the rise time might be even faster. In this publication, a spark rise time of 20 ps was chosen for the simulations.

CDM Current Simulation Results

Simulation of the CDM current was performed in ADS from Keysight. The simulation schematic is presented in Figure 11. Since the simulated CDM head S-parameters don't contain any package capacitance or spark resistance, the components C package and R spark have been added.

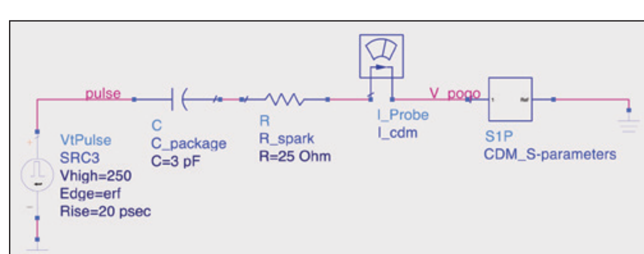


Figure 11: Schematic for CDM current simulation with S-parameters in ADS

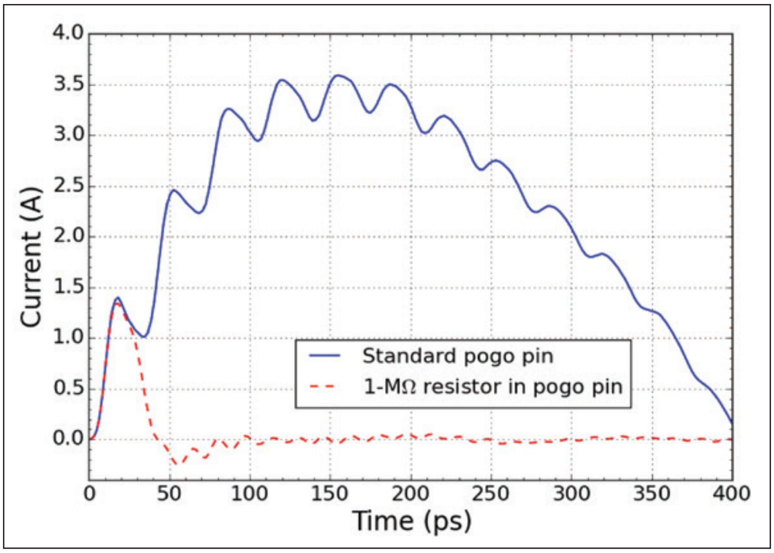


Figure 12: Simulated current entering the pogo pin with a standard pogo pin (blue) and a 1-MΩ resistor in the pogo pin (red)

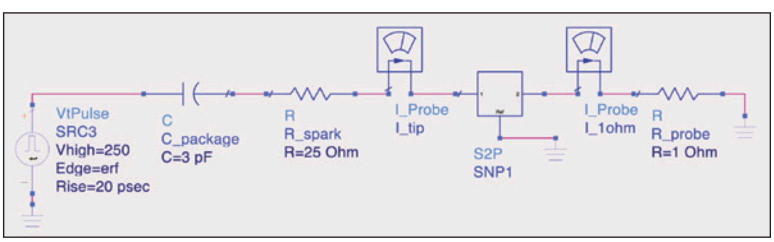


Figure 13: Schematic to simulate the current measured by an ideal 1-Ω CDM probe

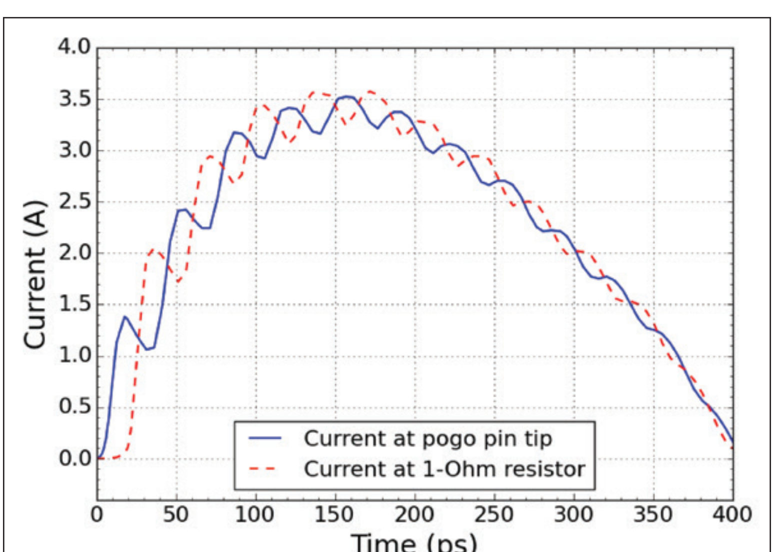


Figure 14: Simulated current of the current into the pogo pin tip (blue) and through the 1-Ω resistor of a CDM probe (red)

C package was chosen to 3 pF to fit the CDM pulse shape, and R spark to 25 Ohm. The simulation results are presented in Figure 12. The blue curve shows the discharge current from a standard CDM tester. Note that there is a first step in the waveform with about the 20-ps rise time of the pulse source. This corresponds to a current wave propagating along the pogo pin towards the ground plane, just like in a transmission line. When the wave reaches the ground plane, it gets reflected with a negative factor due to the low impedance of the ground plane. As a result, the amplitude is about doubled when the reflected wave reaches the pogo pin tip after about 50 ps. The current keeps increasing in steps until the peak amplitude is reached.

The first step also exists with the 1-MΩ resistor in the pogo pin, but the amplitude returns to zero after 40 ps since the resistor blocks the current flow. The comparison of both discharge waveforms and the fact that the damage occurs at the same CDM voltage level clearly demonstrates that the LNA is damaged by the current step at the onset of the CDM discharge.

According to the simulation, the first step has an amplitude of about 1.4 A at 250 V charge level. This appears to be in the same range as where the LNA failed in CC-TLP testing with 20 ps rise time, considering that the CC-TLP probe was only capable of delivering a fast rise time up to 1.5 A according to Figure 3.

With such fast current slew rates, wire inductance and ESD device turn-on time play an increasing role. Even short traces with an inductance in the order of 10 pH will create a voltage drop of several volts. For RF optimized designs with a short low-loss path from the ball to the sensitive gate, this poses a serious threat that needs to be addressed in the ESD design.

Can a CDM Tester Measure the Fast Rise Time?

CDM probe heads with a bandwidth of 20 GHz have been reported [7], but can a CDM probe head really measure the current at the pogo pin tip? This is investigated by performing a simulation with an additional excitation port between the pogo pin and the ground plane. The CDM waveform is simulated with an ideal 1-ohm resistor to ground at the second

It has been shown that a CDM probe head can principally measure the fast initial step, but the waveform will not be identical to the current entering the pogo pin.

port according to Figure 13. Hence, the current flowing through the 1-ohm resistor to the ground plane can be obtained, which is the current an ideal CDM probe would capture. The simulation result is presented in Figure 14. It is seen that an equally fast rising pulse arrives at the 1-Ω resistor with a time delay of about 20 ps. However, the current of the first step has a higher amplitude than the current entering the tip. This can be explained by the impedance mismatch that appears when terminating the pogo pin into a 1- ohm load. Theoretically, the current would double when terminating into close to a short circuit, but since the pogo pin is not a perfect transmission line, there will be losses.

It has been shown that a CDM probe head can principally measure the fast initial step, but the waveform will not be identical to the current entering the pogo pin.

TLP TESTS WITH 20-PS RISE TIME

Diode Performance

To assess the performance of the ESD protection a diode test structure on wafer was measured with the fast TLP source presented in section IV.B.2. The diode size was about twice as large as used in the ESD protection for the LNA. RF probes of type Cascade Infinity with a bandwidth of 40 GHz were used in TDT configuration. With a fast rise time of 20 ps the wiring inductance will cause a considerable inductive voltage drop. In order to eliminate this contribution, a de-embedding structure with the same metallization, but short-circuited in the lowest metal layer, was also measured. Hence, it is possible to assess the voltage contribution from the diode alone by subtracting the de-embedding waveform. In Figure 15 the voltage response of both the diode and the de-embedding structure at a current of -3 A are plotted. The voltage response after subtraction of the de-embedding waveform is presented in Figure 16.

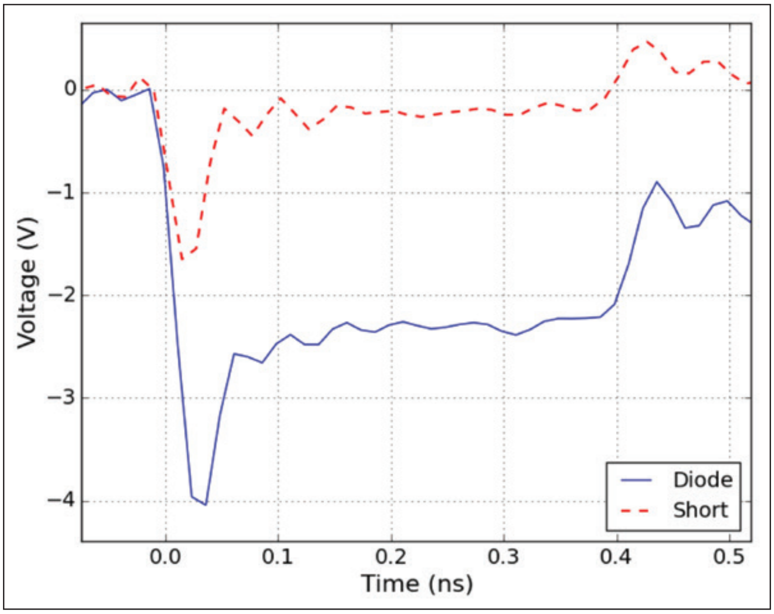


Figure 15: Voltage response of the ESD diode (blue), and the de-embedding structure (red) at -3 A TLP with 20 ps rise time

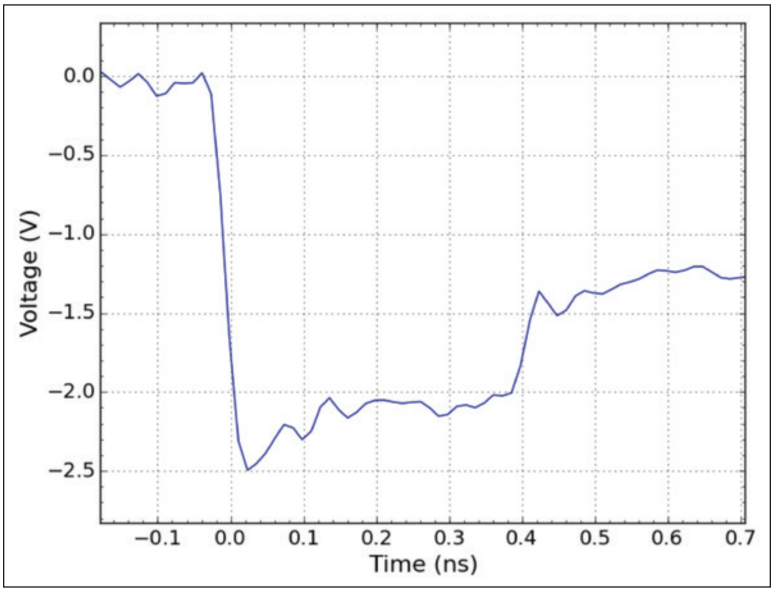


Figure 16: Voltage response of the ESD protection diode, de-embedded by subtracting the wiring contribution

The diode shows 2 V clamping voltage with an overshoot of 0.5 V. This should be considered a very fast diode with a turn on time of less than 50 ps. This can typically not be achieved with STI-bound diodes or SCR based devices.

LNA Test Structure TLP Results

To assess if these diodes can protect the LNA sufficiently, two different structures on wafer level were tested, as shown in Figure 17. Both structures use an LNA monitor device consisting of the transistors of a typical LNA. Test structure LNA1 has the VSS and VDD connections of the LNA monitor connected directly at the VSS/VDD nodes of the ESD diodes. LNA2 has the VSS of the LNA connected to the VSS rail with a 40-µm long trace. These test structures are only suitable for negative TLP testing, since the power clamp (not shown in the figure) is insufficiently connected with relatively large inductance. The results from TLP testing with 20-ps rise time are presented in Figure 18. LNA1 (with the short VSS connection) fails at -6 A current, which is about the same value as obtained from VF-TLP testing of the packaged LNA product with a rise time of 100 ps. This means that the fast rise time of 20 ps can be handled by the circuit. The small overshoot of the diodes is not harming the LNA gate oxide. LNA2, on the other hand, shows a much lower failure current of -3 A.

Analysis of the Failure of LNA2

The lower failure level of -3 A for LNA2 can be explained by the additional voltage drop appearing across the vertical connection down to the VSS rail. In Figure 19 the current path from the VSS pad to the RF pad has been drawn for LNA2. It is evident that the voltage drop across the vertical VSS trace between the diode and the VSS rail will be visible at the LNA monitor. It can be estimated that the 40-µm long trace will have about 40 pH of inductance. The resistance in the path is in the order of milliohms and can be neglected.

With a current slew rate of 3 A in 20 ps the voltage drop can be expressed as:

$$V = dI/dt * L = 3\ A / 20\ ps * 40\ pH = 6\ V$$

It seems plausible that an additional voltage drop of 6 V is enough to damage the gate oxide of the LNA monitor even for the very short stress time of 20 ps.

A similar VSS routing weakness could be identified in the LNA product. After redesign with improved routing, the product was able to meet the CDM requirements.

CONCLUSION AND OUTLOOK

It has been shown that the fast initial step of the CDM pulse damages the sensitive GOX of the investigated LNA. The exact rise time is not accessible, but it could be proven to be 20 ps or less. All test methodologies using 100 ps rise time failed to reproduce the CDM failure by a factor of two. This applies to VF-TLP and CC-TLP, but would also be the case for alternative CDM testing methods such as Contact CDM (C-CDM) or CDM2.

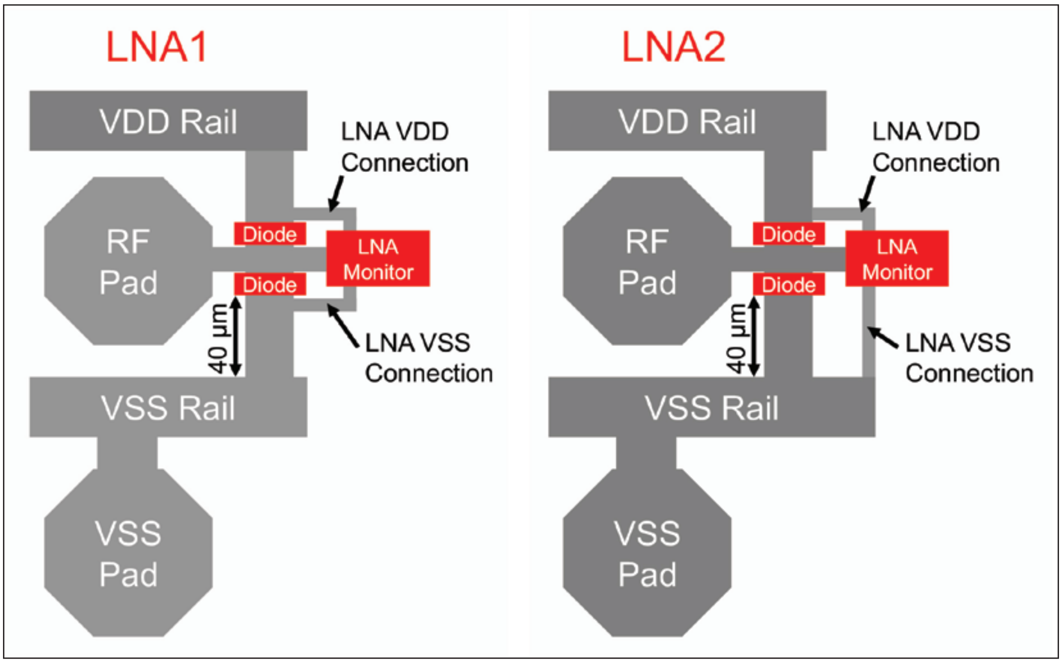


Figure 17: LNA test structures LNA1 with short VSS connection (left) and LNA2 with long VSS connection (right)

The failure mode from CDM testing could be reproduced by applying CC-TLP stress with a rise time of 20 ps. However, it is not straight forward to correlate the CC-TLP current slew rate with a certain CDM stress level. For the investigated LNA the CC- TLP fail level for positive and negative polarity only differed by 25% (+3 A / -2.4 A). However, in CDM testing the difference was as high as 60% (+250 V / -400V). This discrepancy is not yet understood, but it is believed that the polarity might have an impact on the spark rise time. These phenomena need to be fully understood before alternative CDM stress methods can be applied for qualification.

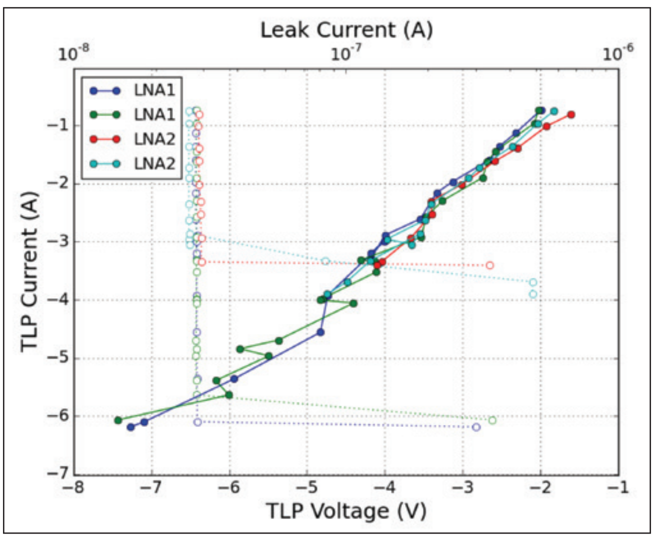


Figure 18: VF-TLP result for the LNA test structures measured with 20 ps rise time

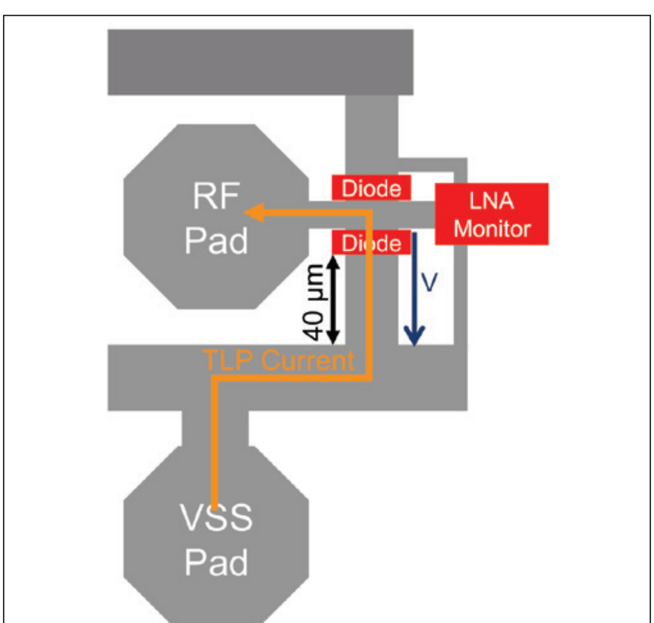


Figure 19: TLP current flow in test structure LNA2 for a negative pulse on the RF pad

Since the exact voltage level in a CDM tester varies in a wide range depending on the calibration, the level of the first step will depend on the calibration as well. This introduces an additional source of error.

As perspective to real-world relevance, it should be mentioned that the first current step should not be considered as a tester artifact. The phenomenon takes place whenever a charged device is approached and touched by any metal object.

An improved high bandwidth TLP characterization method is needed to accurately assess the ESD design of sensitive RF interfaces.

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Automotive Product Certifications for the Indian Market: An Overview

BY JULIAN BUSCH

Over the past five years, India has made significant progress in boosting its domestic economy and in attracting investment from around the world. The government's "Made in India" campaign is focusing on 25 different industry sectors, including automobiles and automotive components, as part of its overall effort to improve India's infrastructure, increase worker salaries and strengthen consumer spending. These efforts hold promise for the future of India as a destination market for producers everywhere.

In order to sell products in India compliance with certain regulations must be shown. Consequently, manufacturers and importers have to ensure that public safety, automotive, wireless and telecommunication standards are met.

Throughout the last decades the Indian government developed and announced the following certification requirements:

- Automotive Industry Standard (AIS) for vehicles and automotive components
- Bureau of Indian Standards (BIS) certification for electrical equipment
- Wireless Planning and Coordination (WPC) certification for wireless products
- Telecommunication Engineering Center (TEC) certification for telecommunication and IT

Following is an overview of the four different certification systems.

AIS CERTIFICATION

The Automotive Industry Standard (AIS) describes the certification requirements for the automotive sector. Based on the UNECE norms, it is relevant for vehicles and automotive components.

The Ministry of Road Transport and Highways (MoRT&H) is the responsible governmental body for issues concerning transportation and traffic administration. In this function, it also ratifies the corresponding laws and regulations. In 1988 the Indian parliament ratified the Motor Vehicles Act which describes the general regulation requirements for vehicles. One year later in 1989, the Central Motor Vehicles Rules (CMVR) became effective and are responsible for the regulations of the Automotive Industry Standard (AIS).

There are different entities which are accredited and authorized to conduct product testing and certifications as described in the AIS:

- Automotive Research Association of India (ARAI)

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- Automotive Component Manufacturers Association of India (ACMA)
- International Centre for Automotive Technology (ICAT)

The actual implementation of the certification scheme occurs in several phases and will likely continue to be expanded in the future (see the table).

Similar to other product certifications, the AIS certification consists of five steps including the submission of application documents, a factory inspection, product tests, the issuance of the certificate and the marking of the product.

In a first step, the application documents must be prepared prior to submission to the respective authority. It is very important that all information on the documents is correctly filled out and complete.

In a second step the factory inspection can be scheduled. It is usually performed by one auditor from the subsequent Indian authority (e.g. ARAI) and will take one or two days. The purpose of the factory audit is to inspect the manufacturing plant's quality management system and confirm its compliance with the certification guidelines and regulations. The inspection is conducted with the use of checklists based on international quality management guidelines.

Furthermore, product tests as described in the appropriate standard must be conducted. Normally, testing is required to be performed at one of the accredited testing laboratories in India. In certain cases, it might be possible to have other test reports accepted. This, however, always requires an individual check.

As soon as the factory audit and the product testing have been completed successfully, the Type Approval certificate will be issued. From this point forward, the product may be marked with the manufacturer's name, a unique ID code and the Type Approval number. Based on the relevant standard, the application of a mark can be required. The location of the label is at discretion of the manufacturer.

In order to maintain the validity of this certification, a follow-up factory inspection is required every two years. In addition, product tests according to CoP lists must be conducted in India.

BIS CERTIFICATION

The BIS (Bureau of Indian Standards) certification is mandatory for certain products to prove the compliance of safety standards through standardization, certification and testing. It ensures the product quality and reliability by verifying safety requirements and minimizing health hazards to consumers. The BIS, formerly known as ISI (Indian Standards Institution), belongs to the Ministry of Consumer Affairs, Food and Public Distribution of the Indian government. Established by the Bureau of Indian Standards Act, it came into effect on December 23, 1986.

Forming India's largest certification scheme, the BIS certification is mainly mandatory for electronic and IT products such as laptops, printers, mobile phones, but also products such as cement and steel. The list of products required to be registered is subject to constant changes and extensions. Most recently on July 22, 2019 the Indian Ministry of Steel announced extensions of the certification scheme for steel products, most becoming effective immediately. Therefore, it is important to stay informed about the current announcements.

Phase 1 – Beginning April 2009:	
• Safety Glass	Technical Standard IS 2553
• Brake Hose	Technical Standard IS 7079
• Horn	Technical Standard IS 1884
• Tire	Technical Standard IS 13154
• CNG Regulator	Technical Standard ISO 15500
• LPG Vaporizer & Regulator	Technical Standard ECE R 67
Phase 2 – Beginning October 2009:	
• Bulb	Technical Standard AIS 034
• Speed Limiting Devices	Technical Standard AIS 001
• Seat Belt	Technical Standard IS 15142
• Wheels (M/N Category)	Technical Standard IS 9436/IS 9438
• Luminaires (M/N Category)	Technical Standard AIS 012
• Retro Reflectors (M/N Category)	Technical Standard AIS 057
• Warning Triangle	Technical Standard AIS 022
Phase 3 – Beginning April 2010:	
• Signaling Devices (L Category)	Technical Standard AIS 010
• Retro Reflectors (L Category)	Technical Standard AIS 057
• Retro Reflectors (Tractors & CEVs)	Technical Standard AIS 057A
• Luminaires (Tractors & CEVs)	Technical Standard AIS 030
• Door Locks/Retention Components	Technical Standard IS 14225
• Fuel Tanks	Technical Standard IS 12056/IS 15547
• Reflective Tapes	Technical Standard AIS 090
New Vehicle Components Added Recently:	
• Rear Warning Triangles	Technical Standard AIS 088
• LED Light Bulbs (replaceable)	Technical Standard AIS 130
• Wheels (L Category)	Technical Standard AIS 073
• Rear Marking Plate	Technical Standard AIS 089
• Wiper Blades	Technical Standard IS 15802/IS 15804
• Battery (Lead Acid)	Technical Standard AIS 048

The certification procedure includes three basic steps: Application, sample testing in India, submission and approval of marking.

The consistency of information on application documents is crucial. It is also very important that all application documents be complete and filled out correctly.

Several test laboratories in India are accredited to carry out the product testing. CB reports are normally not accepted. After successful completion of the testing the test reports must be submitted to the responsible authority within 90 days by an authorized Indian representative.

There are two different markings for the BIS certification: The Standard Mark and the ISI Mark. Depending on the product to be certified, the manufacturer has to use either one or the other. The latter also applies for certain voluntary certifications.

At the current time, there is no factory inspection required, but this could change in the near future. The BIS certification usually covers all products manufactured by a factory and can be renewed after two years if there haven't been any changes. The Ministry of Electronics and Information Technology (MeitY) may ask for random sample tests, which must be tested at a randomly assigned test lab. Within 15 business days the tests must be arranged and the reports submitted to MeitY when completed.

It is also possible that the BIS certification will be required for certain components of products (for example, batteries). In such a case, the component certification needs to be completed before the process of the actual product certification can be started.

FURTHER CERTIFICATIONS

Established in 1952, the Wireless Planning & Coordination of India (WPC) is the responsible authority for the establishment, maintenance and operation of wireless stations in India by managing the licensing processes. Administratively, it belongs to the Ministry of Communications and Information Technology.

All wireless devices, such as WIFI, ZigBee or Bluetooth require a WPC certification. For products that already have a WPC approved wireless module, no additional testing of the final product is required. All other products will have to be fully tested, unless there are test reports from ILAC accredited laboratories outside of India available and the devices do not use any restricted frequency ranges.

The certification process consists of the submission of application documents, evaluation and product testing. After completion and acceptance of the WPC certificate, a certification number will be issued. According to the status quo, no factory inspection is demanded and as long as there are no changes on the hardware, the certificate does not expire.

Besides the WPC certification the Telecommunication Engineering Center (TEC) certification for telecommunication equipment, such as mobile phones, telephone systems or modems, plays an important role in the field of certifications for the Indian market.

TEC certification was established in the early 1990s and up until recently had been a voluntary process. However, in their announcement No. 10-1/2017-IT/TEC/ER, the TEC shifted the process to an obligatory certification process with the roll-out of the Mandatory Testing Certification of Telecommunication Equipment (MTCTE).The implementation will take place in several steps, starting with the first phase rolling out October 1, 2019. The following phases will most likely cover products like routers, network security systems and servers.

Up until recently the products that are included in the certification scheme had to meet the requirements of electromagnetic compatibility (EMC/EMI). It is still under consideration if safety tests will be added. It is expected that the TEC certification will have a validity of five years and cover up to ten product models per certificate. The marking will consist of an individual factory ID number and has to be applied to the product.

Currently, reports of international accredited test laboratories (ILAC) are still accepted. After March 31, 2020 testing will have to be completed in India.

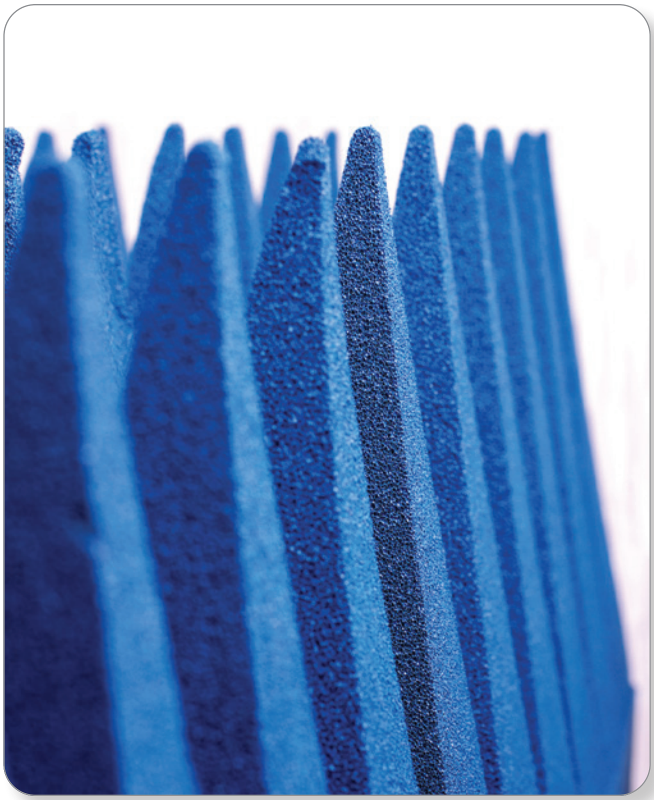
CONCLUSION

When dealing with the different certifications for the Indian market its schemes and processes, it becomes clear that due to ongoing development and changes it is important to stay aware of the current situation. While a product might be imported to the Indian market without any obstacle today, it may need a valid proof of certification tomorrow. As shown by the example of the steel products, these changes may happen very unexpectedly and become effective immediately.

Therefore, it is key to success to be informed on the development and keep an eye on the latest trends in the Indian market to stay in compliance with the most current rules and regulations. As stated in the beginning of this article, the Indian market shows interesting and growing tendencies and may offer great potential if PM Modi's promises will fully put into practice.

Basic Parameters of the Normalized Site Attenuation (NSA) Method for Open Area Test Sites (OATS) and Semi Anechoic Chambers (SAC) in CISPR 16-1-4

BY LOUIS A. FEUDI



This article is intended to provide an understanding of the requirements for qualification of either an open area test site (OATS), semi anechoic chamber, or fully anechoic room for use in the measurement of radiated disturbances in the frequency range of 30 MHz to 1 GHz. This is referred to as normalized site attenuation (NSA) testing, as described in CISPR 16-1-4. Qualification of these compliance test sites in the frequency range from 1-18 GHz, commonly referred to as site voltage standing wave ratio (sVSWR) testing, will be covered in a future article.

WHAT IS CISPR?

In order to provide the technical parameters for verification of these compliance test sites, let's review a few of the fundamentals of the EMC standard process.

CISPR is the abbreviation for the Comité International Spécial des Perturbations Radioélectriques (English translation: International Special Committee on Radio Interference), which is a part of the International Electrotechnical Commission (IEC). As most of us in the EMC industry know, the IEC is an international organization, of which the U.S. is a member, with committees and subcommittees that focus on the research and development of standards that cover areas like Product Safety, EMC and mechanical hazards. These standards are often adopted by the European Union in the form of EN (the abbreviation for the French words "Norme European," or European Standard), as well as in other jurisdictions around the world.

CISPR concentrates on drafting standards for controlling electromagnetic interference in electrical and electronic devices that can interfere with broadcasting frequency bands. These bands are regulated worldwide and include TV, AM and FM radio, as well as ISM, Wi-Fi, Bluetooth and other transmission bands.

IEC and CISPR standards are often divided into two categories, "Guideline" and "Product Specific." Product Specific standards are used to evaluate and confirm that a product from a given product category is compliant with a specific set of requirements. Guideline standards are intended for use by a product committee as a basic framework to establish the requirements for Product Specific standards.

WHAT IS CISPR 16-1-4?

CISPR 16, entitled "Specification for radio disturbance and immunity measuring apparatus and methods," is divided into multiple parts. Part 2-3 describes methods

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of measurement of electromagnetic disturbances, Part 3 provides radio disturbance information, and Part 4 covers uncertainties, statistics and limit modeling.

CISPR 16-1-4:2019 is the most recently published iteration of the standard. It is entitled "Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements" and is "a basic EMC publication for use by product committees of the IEC." It is intended to be used by product standard committees to determine the applicability of the EMC standard to their products of interest and in drafting their requirements.

As described in the Scope of the standard, CISPR 16-1-4 "specifies the characteristics and performance of equipment for the measurement of radiated disturbances in the frequency range 9 kHz to 18 GHz." Specifically, it focuses on antennas and test sites. CISPR 16-1-4 is referenced almost exclusively in EMC product standards for the qualification of test sites and antenna characteristics used in the measurement of those products.

For the purposes of this article, we will review the requirements for test sites in the range from 30 MHz to 1 GHz, and the qualifying requirements and verification methods that allow the use of these sites for electromagnetic disturbance measurement.

WHAT IS A COMPLIANCE TEST SITE?

A compliance test site is a testing environment that assures valid, reproduceable measurement results of the radio frequency (RF) disturbance field strengths generated by the device being tested. Many of our readers are probably familiar with an OATS, a semi anechoic chamber (SAC) and a fully anechoic room (FAR). Each of these test sites is defined in CISPR 16-1-4 and the standard provides both mechanical descriptions of the sites and the verification process used to ensure that these sites provide reproduceable, valid results from RF disturbance measurements.

The most basic and fundamental requirement of any of these sites is the establishment of a "quiet zone" or "equipment under test (EUT) volume" on the OATS, or within a test chamber that will contain an EUT and that will produce results that closely align with a theoretical "ideal open area test site." An ideal OATS is one having a perfectly flat, perfectly conducting ground plane of infinite area, with no reflecting objects except the ground plane. Since it is impossible in reality to produce this ideal OATS, CISPR 16-1-4 provides a method to evaluate OATS, SAC and FAR sites so that they approximate it in the area that encompasses the EUT as closely as possible. This quiet zone or EUT volume is characterized as a "cylinder defined by the EUT boundary diameter and height, encompassing the EUT, cable racks, and 1.6m of cable length" for measurement in the frequency range from 30 MHz-1 GHz.

Since the verification procedure is similar between an OATS and SAC, we will take a moment to describe each.

WHAT IS AN OATS?

As stated in CISPR 16-1-4, an OATS is "an area characterized by cleared level terrain and with the presence of a conducting ground plane." An OATS should be free of obstructions, including buildings, electric lines, fences and trees, and should have no underground pipes or cables except those necessary to power the site. If the site is used year-round, weather protection should be used to protect the EUT and the field strength measuring antenna. This protection often takes the form of materials that are RF transparent (tents, wooden enclosures, etc.).

An obstruction-free area is required around the EUT and field-strength measuring antenna. The antenna is mounted on an antenna mast that is also constructed of RF transparent material and tall enough to allow the antenna to reach a height of 4 meters.

Since it is impractical to judge the magnitude of reflectivity and scattering of RF fields from surrounding objects, the standard provides minimum dimensions for the construction of the site. The size and shape of the obstruction free area is dependent on:

1. Measurement distance: d
2. The presence of a turntable

The EUT can emit directional fields of RF disturbance, so the only way to effectively measure the disturbance level is to rotate the unit 360 degrees. In addition, the reflectivity of the ground plane will reflect downward directional disturbances, allowing the antenna to measure the reflected field strength. Since the angle of reflection as well as the direct emission of the directional focused RF disturbance vertically can vary, the ability to adjust the height of the antenna up to 4m in height helps to ensure that the maximized emission emanating from the EUT can be captured.

In the absence of a turntable, an OATS would be round in shape, requiring the antenna to be rotated around the EUT at a specified measurement distance. Figure 1 shows a diagram of an obstruction-free area with a stationary EUT. Note that the minimum distance of the area boundary is 1.5 times the measurement distance d (often 3, 5, or 10m).

As an alternative to OATS, many manufacturers have installed SACs and FARs to allow for year-round testing in areas with high RF ambient noise.

With the addition of the turntable, the EUT can be rotated, allowing for an obstruction-free area in the shape of an ellipse. In this case, the length of the ellipse is 2 times the measuring distance d, with ½ d between both the test sample/antenna and the boundary behind them. Figure 2 shows an obstruction-free area of a test site with a turntable.

The ambient RF levels of an OATS must be sufficiently low relative to the levels of the disturbance measurements to be performed. OATS sites are classified for the quality of ambient noise in the following manner:

A. The ambient emissions are 6 dB or more below the measurement levels;

B. Some ambient emissions are within 6 db of the measurement levels;

C. Some ambient emissions are above measurement levels but are either spaced long in time between transmission to allow for a measurement to be made (aperiodic) or are continuous only on limited identifiable frequencies (i.e., FM bands);

D. The ambient levels are above the measurement levels over a large portion of the measurement frequency range continually transmitting.

Quality classification d is unacceptable. With the increasing use of cellular towers, Wi-Fi hotspots, and other transmission sources, most OATS need to be located in remote areas.

OTHER GROUND-PLANE TEST SITES

As an alternative to OATS, many manufacturers have installed SACs and FARs to allow for year-round testing in areas with high RF ambient noise.

A shielded enclosure is often constructed of steel, and includes a door, honeycombed ventilation openings, electrical power filters, and pipe penetrations/bulkhead panels that contain any RF generated signals inside the enclosure and that block any external ambient RF noise. Most shielded enclosures have an attenuation

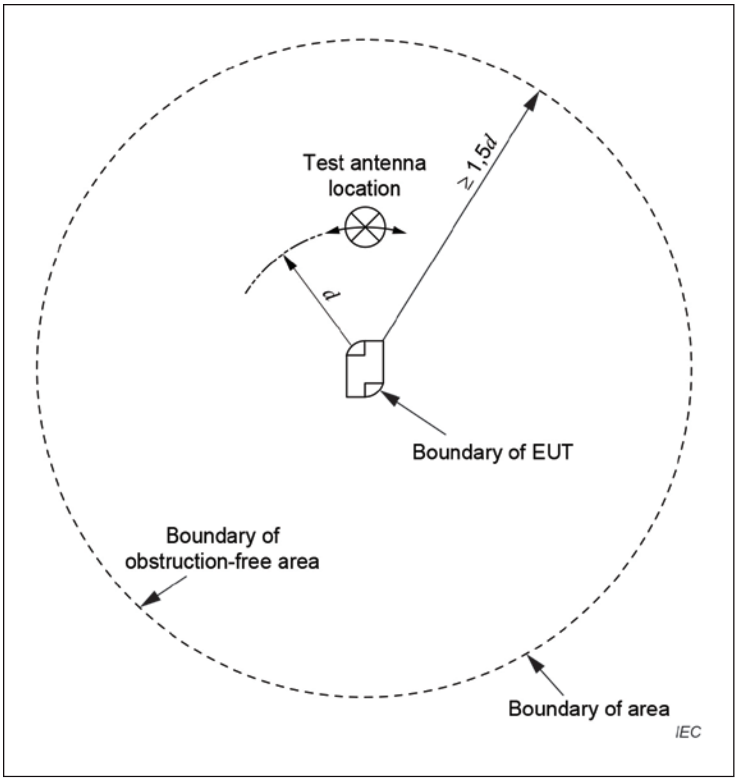

Figure 1: Obstruction-free area with stationary EUT

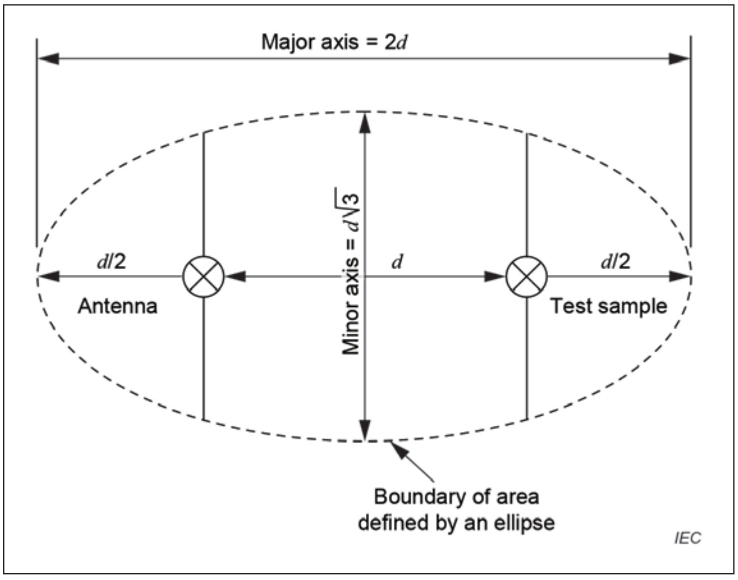

Figure 2: Obstruction-free area of a test site with turntable

value between the inside and outside of the enclosure of 90-110 dB across a range of 15 kHz to 18 GHz. The bulkhead panels allow for connection of RF cables to antennas within the enclosure, vents allow for air flow, and pipe penetrations allow for cabling required to support equipment or fiber lines, and water or other substances for fire suppression.

The RF shielded enclosure is usually indoors, thereby protected from the weather while also eliminating concerns about ambient RF emissions.

A SAC is simply a shielded enclosure with walls and ceilings lined with ferrite tile, as well as absorber cones made of polyurethane, polystyrene or polypropylene material doped with a combination of fire retardant and RF absorptive materials. The floor is left bare to provide the reflective ground plane for NSA measurements and RF disturbance measurements in the range of 30 MHz to 1 GHz. For measurements over 1GHz, ferrite tile and absorber cones are placed on the floor between the EUT and the measuring antenna in a pattern to maximize RF disturbance measurements. These SACs can be constructed to allow for measurement distances of 3m, 5m or 10m as required by the product standard. As the size of the chamber grows, so does the cost of construction.

A FAR is a shielded enclosure with absorber on the ceiling, the floor and all walls. It is intended to simulate a free space environment so that only the direct ray waves transmitted intentionally or unintentionally from the EUT reach the receiving antenna. All indirect and reflected ray waves are reduced by the absorber on the walls, ceiling and floor. In a FAR, the equipment is elevated to place the product and its associated quiet zone in the center of the absorber lined walls, floor and ceiling.

TEST SITE VALIDATION USING THE NSA METHOD

Test site validation is determined using the NSA method. Site attenuation is defined in paragraph 3.1.26 as the "minimum site insertion loss measured between two polarization-matched antennas located at a test site when one antenna is moved vertically over a specified height range and the other is set at a fixed height."

The fixed height antenna is located in the center of an unprotected OATS and the variable height antenna is located at the specified measurement distance (3m for example) from the turntable center on an antenna mast, adjustable up to a height of 4m.

Table 1 shows the site validation methods applicable for OATS-based, SAC and FAR site types.

Used with broadband antennas, the NSA method is the most common method of site validation. In fact, the NSA method with tuned dipoles is not specifically described in section 6.4 of the standard, "Test Site Validations," but can be used for the purposes of the document. (The standard also refers to other documents for NSA tables for tuned dipoles that are not discussed in this article.)

The site validation methods listed in Table 1 that show "Yes" indications are interchangeable vertically, so no one method is required and any one method is acceptable. These measures "provide a measure of uniformity of the validated test volume" (quiet zone) by comparing the ideal or theoretical site attenuation between the transmit and receive antenna with the actual measured site attenuation across the frequency range.

The procedure is simple, and is performed using two co-polarized antennas, or both antennas oriented in the vertical then horizontal position. Site attenuation (SA) is obtained by measuring the difference between the source voltage level V_i, which is applied to the transmit antenna located at a fixed height above the turn table, and the maximum received voltage V_R as measured on the terminals of the receive antenna during the variation of antenna height between 1 and 4 meters.

The voltage measurements are performed in a 50 ohm system. To reduce impedance mismatch at either the output of the signal source or the input of the measuring receiver (which could result in errors in measurement accuracy), it is recommended that a 10 dB attenuator be placed at the transmit and receive antenna during both direct and site voltage measurements (essentially, the entire verification procedure).

Once these values are obtained, they are compared to the site attenuation characteristics obtained at an ideal OATS or that measured for site validations. The result of the

Test site type	Applicability of site validation methods		
	Tuned dipoles NSA	Broadband antennas NSA	Broadband antennas RSM
OATS	Yes	Yes	Yes
OATS with weather protection	No	Yes	Yes
SAC	No	Yes	Yes
FAR	No	Yes	Yes

Table 1: Site validation methods applicable for OATS, OATS-based, SAC and FAR site types

comparison is the site attenuation deviation, or ΔA_S in dB. See Equation 1 below:

$$\Delta A_S = V_{DIRECT} - V_{SITE} - F_{aT} - F_{aR} - A_N$$

Where:

--ΔA_S is the SA deviation

--F_{aT} is the transmit antenna factor

--F_{aR} is the receive antenna factor

--A_N is the theoretical NSA (as provided in table 2 of the standard)

--V_{DIRECT} is a direct measurement of the voltage value at the terminal of the transmit antenna

--V_{SITE} is the measurement of the voltage on the terminal of the receive antenna

V_{DIRECT} can also be visualized as the output of the signal generator measured by the receiver. So the procedure is simple. You link the output of the signal generator to the input of the receiver by connecting the two cables with a low loss connector, and measure the direct voltage generated.

You then repeat the measurement with the cables connected to the broadband antennas separated from each other at the test distance, varying the height of the receive antenna from 1m to 4m to maximize the measured voltage and to compensate for the antenna factors of both antennas. The cable losses are nullified since they are used in both measurements.

The spacing of log periodic antennas is measured from the projection on the ground plane of the mid-point of the longitudinal axis of each antenna. The spacing of the biconical antennas is measured from the element centerline axis at the feedpoint. Figure 3 shows a representation of the fixed and variable height antennas. Consideration should be given to provide sufficient separation between the antenna and the mast body to prevent undue influence on the performance of the receiving antenna.

The calculated site attenuation deviation ΔA_S shall not be more than ±4 dB. The standard outlines the procedure for both discrete frequency selection (paragraph 6.7.1) and swept frequency testing (paragraph 6.7.2). However, the sequence of testing of V_{Direct} and V_{site} are the same. For both methods, it should be noted that NSA values for frequencies between those listed in Table 1 can be obtained using linear extrapolation between the tabulated values.

Due to size constraints the theoretical normalized site attenuation table called out as Table 2 in CISPR 16-1-4:2019 is not shown here.

VALIDATION OF A WEATHER-PROTECTION-ENCLOSED OATS OR A SAC

As previously noted, an OATS without weather protection or an enclosing structure is simply tested with the transmit antenna located at height h_1 (usually 1m) in the center of the turntable. However, within paragraph 6.3.1, the standard states:

> *"Whenever construction material encloses a ground-plane test site, it is possible that the results of a validation measurement at a single location, as specified on 6.7, are not adequate to show acceptability of such an alternative site."*

The standard further explains in paragraph 6.8 that the single point measurement is insufficient to pick up possible reflections from the construction material surrounding an OATS turntable, or the walls and ceiling of a SAC, even when lined with absorbing ferrite tile and cones. For this reason, a "test volume" is defined as the volume traced out by the largest EUT or system as it is rotated 360 degrees on the turntable. To evaluate horizontal and vertical positions, a maximum of 20 SA measurements may be required.

These 20 measurement positions would include the center of the turntable, the forward, left, right and rear edges of the turntable (5 transmit antenna locations), with horizontal and vertical polarizations (2 polarizations) and 2 heights of the transmit antenna (1 and 1.5m for horizontal polarization and 1m and 2m for vertical polarization) for each transmit antenna location.

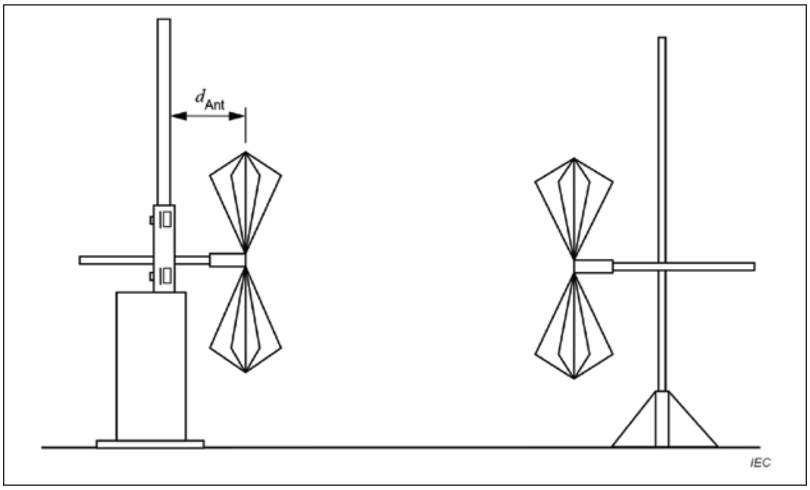

Figure 3: Illustration of vertically co-polarized antennas

Figure 4 shows the antenna positions for vertical polarization validation measurements. Figure 5 shows antenna positions for horizontal validation measurements.

As mentioned previously, broadband antennas are used for this testing, and measurement distances are calculated with respect to the centers of the antennas. So, as the transmit antenna is moved forward, the receive antenna is moved as well to maintain the measurement distance specified. For SACs, when testing the periphery of the "test volume," a minimum of 25cm spacing should be maintained between the antenna tip and the closest absorber cone tip, or at least 1m between the antenna midpoint and the closest absorber tip. In addition, for vertical polarization testing, the lower tip of the antenna should be greater than 25cm from the floor to prevent coupling to the ground plane, even if this means the center of the antenna is slightly higher than the specified 1m height.

For weather enclosed sites, the edges of the turntable are usually selected as the "test volume" diameter, and an arbitrary height is assigned based on the projected EUT sizes. This selection is necessary prior to SAC design to ensure proper separation between the turntable and the absorber tips, and to properly model the chamber for size and absorber placement location to ensure a "test volume" that will meet the maximum deviation of ± 4 dB. The selected test volume also guarantees that, if the EUT fits within the turntable diameter and is of a height less than that projected, it is entirely enclosed within the test volume and repeatable data can be recorded during testing. Therefore, the turntable size is also critical and needs to be selected prior to SAC design, usually during the procurement quotation process. Figure 6 shows an illustration of the test volume.

The standard allows for a smaller amount of measurements if certain conditions are met. For example, the rear position measurements for vertical and horizontal polarization can be omitted if the closest construction or absorbing materials are more than 1m away from the rear boundary of the test volume.

Other allowances can be made for height restricted EUTs and smaller test volumes. The standard also specifies the transmit antenna height variance during validation testing if the height of the EUT exceeds 2m.

At the same time, the standard specifies that, if the EUT does not exceed a volume of 1m depth, 1.5m width, and 1.5m height, and the periphery of the test volume is greater than 1m from the closest material that may cause undesirable reflection, then transmit antennas can be placed at a reduced distance from the center (see Figure 7 on page 149 and Figure 8 on page 150 for illustrations of vertical and horizontal polarization respectively).

POSSIBLE CAUSES FOR EXCEEDING SITE ACCEPTABILITY LIMITS

CISPR 16-1-4 recommends that the following items be rechecked if the site deviation ΔA_S exceeds the ± 4 dB requirement:

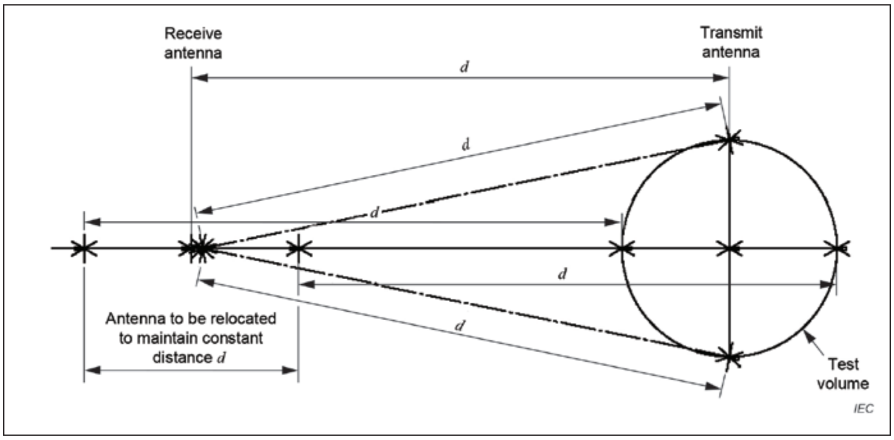

Figure 4: Typical antenna positions for a weather-protected OATS or SAC-vertical polarization validation measurements

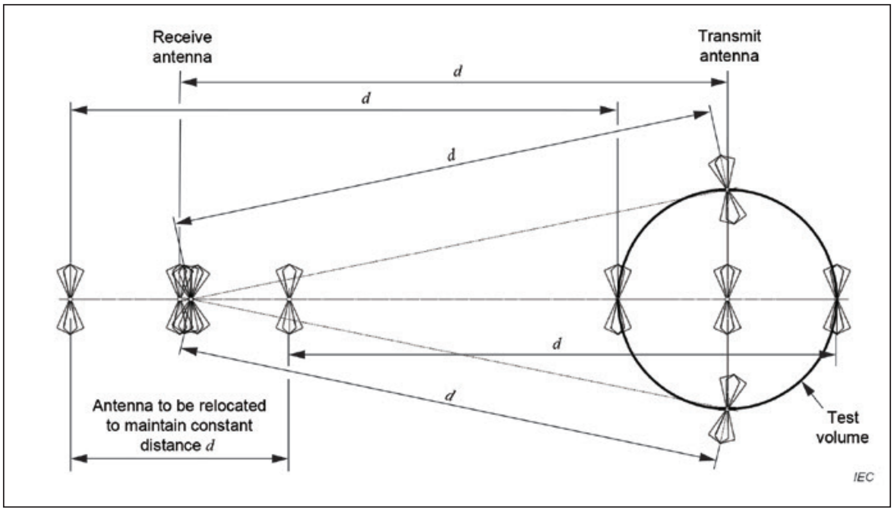

Figure 5: Typical antenna positions for a weather-protected OATS or SAC-horizontal polarization validation measurements

- Measurement procedure;
- Antenna factors accuracy;
- Drift in the signal source;
- Accuracy of the receiver or spectrum analyzer input attenuator; and
- Measurement device readings.

Annex F of the standard describes errors that can occur in NSA measurement. If no errors are found, it is likely that the site is at fault and should be investigated. Key items recommended by the standard include:

a. Ground plane construction inadequacies;
b. Undesired reflections from the perimeter of the site or from all-weather cover;
c. Poor or no continuity between the turntable and the surrounding ground plane when the turntable is flush mounted and conductive;
d. Thickness of any dielectric ground plane covers; and
e. Openings in the ground plane like trap door seams.

ONE FINAL IMPORTANT NOTE

Although we have not covered FAR site verification testing, there has been a change to the recent 2019 version of the standard that will impact FAR construction and is worth mentioning here.

As described earlier in this article, SAC test volume is that volume traced out by the EUT rotated in a 360-degree arc.

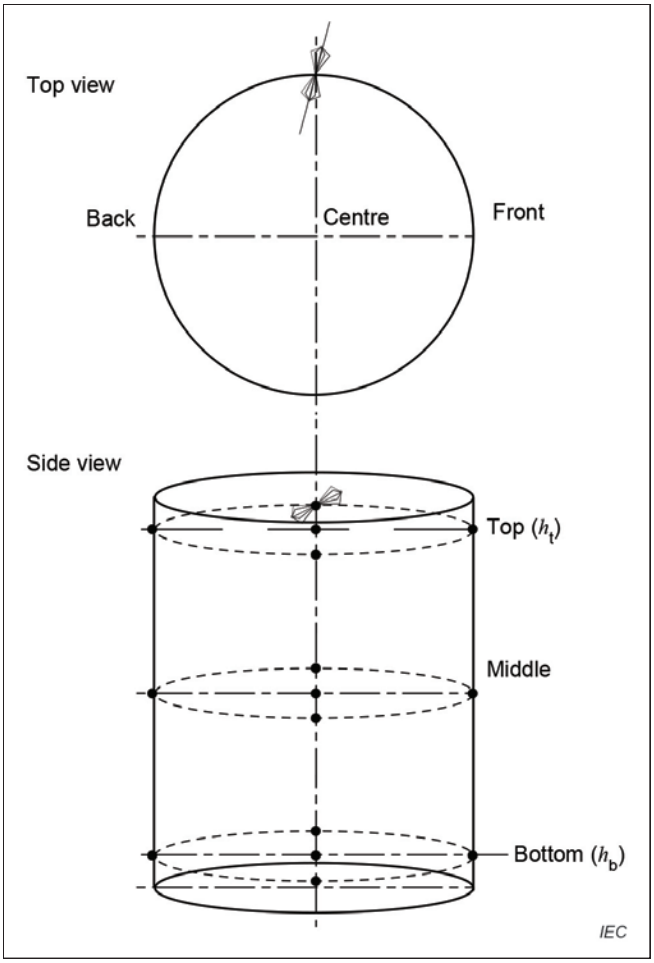

Figure 6: Test volume cylinder

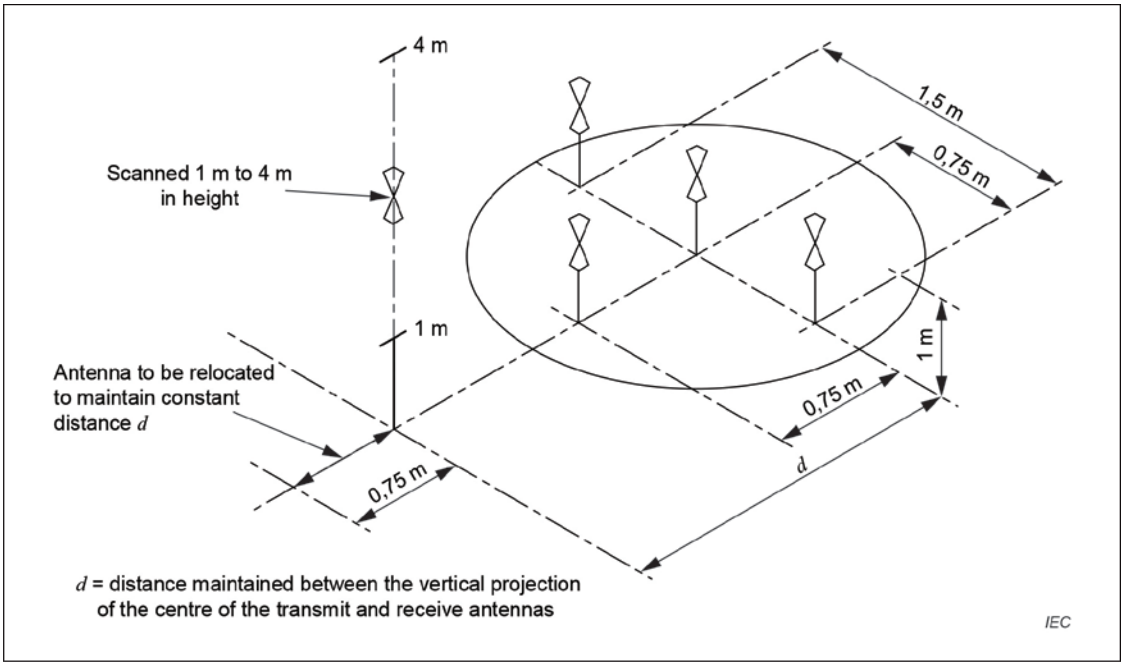

Figure 7: Typical antenna positions for a weather-protected OATS or SAC-vertical polarization validation measurements for a smaller EUT

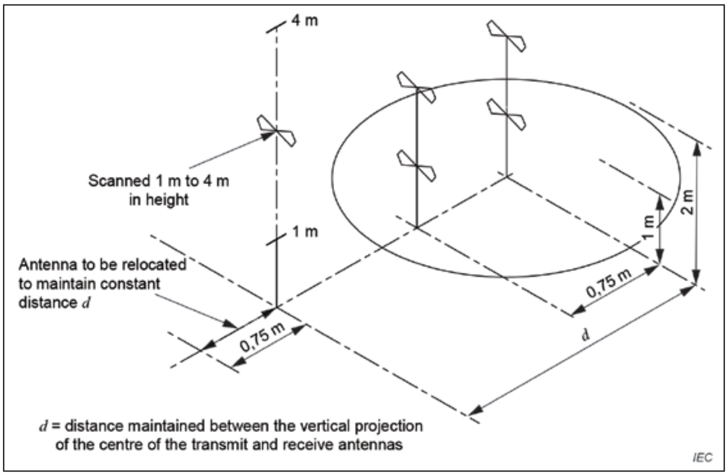

Figure 8: Typical antenna positions for a weather-protected OATS or SAC-horizontal polarization validation measurements for a smaller EUT

So there is no limitation to the size of the test volume based upon measurement distance, and the test volume is acceptable if the SA deviation is within the ± 4 dB criteria.

However, the 2019 version of the standard includes new requirements for FAR site validation, as shown in Table 2.

Maximum diameter d_{max} and height h_{max} of the test volume m	Test distance $d_{nominal}$ m
1,5	3,0
2,5	5,0
5,0	10,0

Table 2: Maximum dimensions of test volume versus test distance

This table limits the size of the test volume diameter and height dependent on the test measurement distance. This limitation did not exist in the previous standard publication and we will delve into this further in future articles. In the meantime, if you wish to have a test volume of greater than 1.5m diameter, for example, then you must construct a 5m chamber, as a 3m chamber will not meet this criteria. Again, this is only for FAR chambers and does not impact SAC and OATS requirements.

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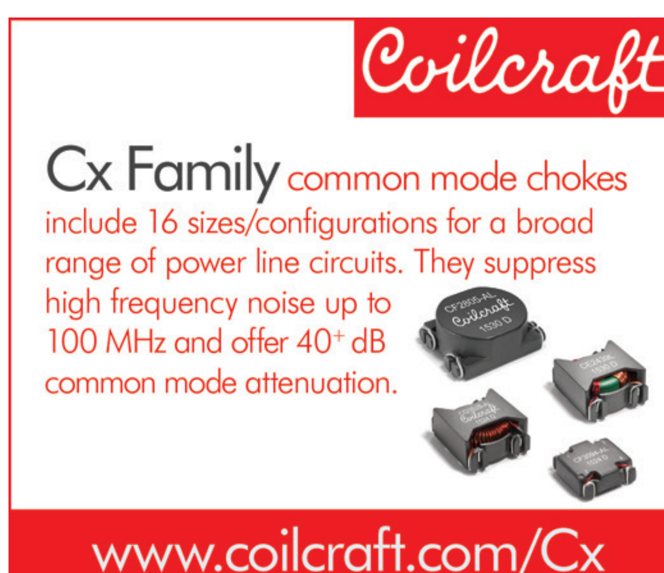

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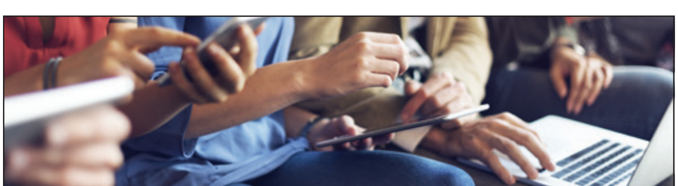

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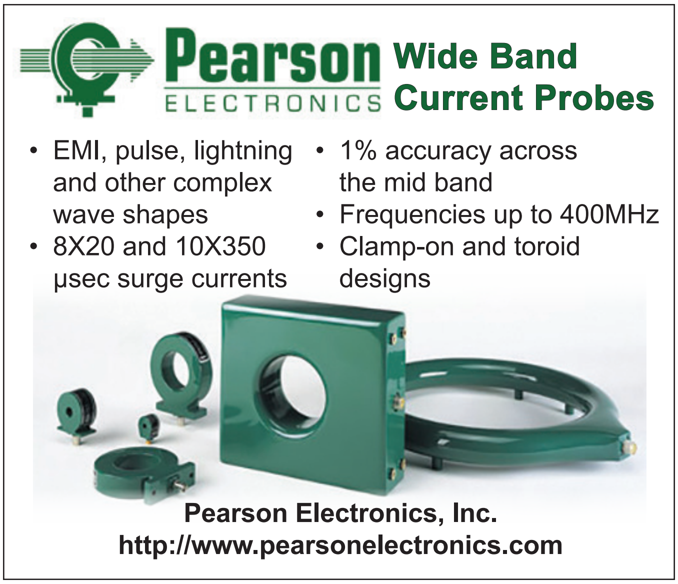

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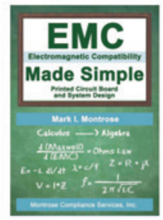
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StaticStop manufactures a full line of ESD/Static Control Flooring, including an adhesive-free interlocking flooring that can be used over bad subfloors and installed directly on top of existing floors without any disruption to operations. We offer the most comprehensive line of ESD flooring solutions available, including installation and maintenance options to provide the right product at the best price for any application.

StaticWorx, Inc.
Waterbury Center, VT 05677 USA http://www.staticworx.com

SunAR RF Motion
Dublin, CA 94568 USA http://www.sunarrfmotion.com

Suzhou 3ctest Electronic Co. Ltd.

99 Emeishan Rd, SND, Suzhou
Jiangsu, 215153, China
tel: 86 512 6807 7192
http://www.3c-test.com

3CTEST, established in 2004 in Suzhou, China, is dedicated to scientific research and technological progress in the field of Electromagnetic Compatibility (EMC) and Complicated Electromagnetic Environment (CEE), and has been a leading enterprise integrating design, manufacture, sales and service of corresponding testing equipment. 3CTEST's R&D team is rich with experience, having participated in the drafting and reviewing of more than 40 national EMC standards in China, also published two EMC-related books. Having set up offices in Beijing, Shenzhen, Chengdu, Xi'an and partnered with overseas distributors in Asia, North America and Europe, 3CTEST is committed to supreme product quality and professional customer service.

SW Safety Solutions
Union City, CA 94587 USA http://www.swsafety.com

Swift Textile Metalizing LLC
Bloomfield, CT 06002 USA http://www.swift-textile.com

TDK Electronics
Iselin, NJ 08830 USA http://www.epcos.com

TDK RF Solutions

1101 Cypress Creek Road
Cedar Park, TX 78613 USA
tel: 512-258-9478
http://www.tdkrfsolutions.com

TDK RF Solutions is a world leader in the design, development & manufacture of technical solutions for the EMC testing and Antenna measurement industries. We offer a complete range of solutions including automated test systems, anechoic chambers, RF absorber, antennas, software, RF filters, and a wide range of test products & accessories. We call it Total System Technology®, and it means TDK RF Solutions is your best choice of partner for proven solutions & services. If you are in the market for a complete turnkey solution or looking to expand your test capabilities with a new antenna, contact us to see what TDK can do for you.

TECH WEAR, INC.
Mesa, AZ 85215 USA http://www.techwear.com

Tech-Etch
Plymouth, MA 02360 USA http://www.tech-etch.com

Techmaster Electronics
Vista, CA 92081 USA https://techmaster.us

Technical Safety Services
Berkeley, CA 94710 USA http://techsafety.com/services/test-certification/cleanroom-testing

Teledyne LeCroy
Chestnut Ridge, NY 10977 USA http://teledynelecroy.com

TESEO SpA
Druento, Terni 10040 Italy http://www.teseo.net

Test Site Services Inc
Milford, MA 01757 USA http://www.testsiteservices.com

Testing Partners
Boardman, OH 44512 USA https://testingpartners.com

TestWorld Inc
Rocklin, CA 95765 USA http://www.testworldinc.com

Thermo Fisher Scientific
Tewksbury, MA 01876 USA http://www.thermoscientific.com

Thermotron
Holland, MI 49423 USA http://www.thermotron.com

Thermtest
Fredericton, New Brunswick E3A 6W1 Canada https://thermtest.com

Timco Engineering, Inc.
Newberry, FL 32669 USA http://www.timcoengr.com

Times Microwave Systems
Wallingford, CT 06492 USA https://www.timesmicrowave.com

TJS Technical Services Inc.
Airdrie, AB T4B 3C3 Canada http://tjstechnical.com

TMD Technologies
Hayes, Middlesex UB3 1DQ Great Britain http://www.tmd.co.uk

TOYO Corporation
Fremont, CA 94538 USA https://toyotechus.com

Transient Specialists, Inc.
Burr Ridge, IL 60527 USA http://transientspecialists.com

Transtector
Hayden, ID 83835 USA https://www.transtector.com

TREK, INC.
Lockport, NY 14094 USA http://www.trekinc.com

Trescal
Hartland, MI 48363-0559 USA http://www.trescal.com

TTE Filters, LLC
Los Angeles, CA 90064 USA http://www.tte.com

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Littleton, MA 01460 USA
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https://www.tuv.com

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UL Knowledge Solutions
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UL LLC
Northbrook, IL 60062 USA http://www.UL.com

United Static Control Products Inc.
Bradenton, FL 34205 USA http://ultrastatinc.com

Universal Shielding Corp.

20 West Jefryn Boulevard
Deer Park, NY 11729 USA
tel: (631) 667-7900
info@universalshielding.com
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Universal Shielding Corp. was established in 1972 and is a pioneer in providing pre-fabricated shielded enclosures for the military, commercial, and medical industries. USC has the capabilities to provide a shielded enclosure of any size; from the smallest prefabricated unit for an R & D lab to the largest and most complex installations for a computer or communications center. USC offers a full range of RF Shielded Enclosures, RF Shielded Doors, RF Shielded Cabinets, Exterior Doors and RF Shielding Accessories.

University of Oxford Continuing Professional Development - Technology Programme

Oxford, Oxfordshire OX1 2JA
Great Britain
http://www.conted.ox.ac.uk/about/continuing-professional-development

US Microwave Laboratories

Summerfield, NC 27358 USA
http://www.usmicrolabs.com

V Technical Textiles, Inc.

Palmyra, NY 14522 USA
https://www.vtechtextiles.com

VDE Americas

Burlington, MA 01803 USA
http://vdeamericas.com

Vectawave Technology Limited

Newport, Isle of Wight PO30 5XW
Great Britain
http://vectawave.co.uk

VEROCH - Testing Equipment USA

Sunrise, FL 33351 USA
http://www.veroch.com

Versus Technology (Versus Global LLC)

Wilmington, DE 19806 USA
http://www.versusglobal.com

VIAVI Solutions

Wichita, KS 67215 USA
https://www.viavisolutions.com/en-us

Videon Central, Inc.

State College, PA 16803 USA
http://videon-central.com

Vitrek Corporation

Poway, CA 92064 USA
http://www.vitrek.com

VPI Laboratories, Inc.

Draper, UT 84020 USA
http://www.vpilaboratories.com

VTI Vacuum Technologies, Inc.

Reedsburg, WI 53959 USA
http://www.vactecinc.com

W. L. Gore & Associates, Inc.

Landenberg, PA 19350 USA
http://www.gore.com

Washington Laboratories

Frederick, MD 21703 USA
http://www.wll.com

Wave Computation Technologies, Inc.

Durham, NC 27707 USA
http://www.wavenology.com

Wave Scientific Ltd

Henfield, West Sussex BN5 9DZ
Great Britain
http://www.wave-scientific.com

WAVECONTROL INC.

Roseland, NJ 07068 USA
https://www.wavecontrol.com

WECO Electrical Connectors

Kirkland, QC H9J4A1 Canada
http://www.wecoconnectors.com

WEMS Electronics

Hawthorne, CA 90250 USA
http://www.wems.com

Wewontech

NDongcheng, Hong Kong 523119
China
http://www.wewontech.com

Willrich Precision Instrument Company, Inc

Cresskill, NJ 07626 USA
http://willrich.com

WorkHub

Calgary, AB T1Y 7H8 Canada
https://www.workhub.com

Würth Elektronik

Waldenburg, Baden-Württemberg
74638 Germany
https://www.we-online.com

Wyatt Technical Services LLC

Woodland Park, CO 80863 USA
http://www.emc-seminars.com

XGR Technologies

Newark, DE 19702 USA
http://www.xgrtec.com

Yazaki Testing Laboratory

Canton, MI 48187 USA
http://www.yazakiemc.com

THE Solutions Directory

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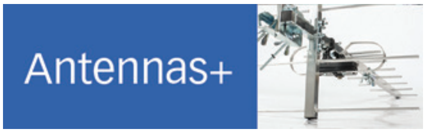

Antenna Couplers

AP Americas Inc.
AVX Corporation
dB Instruments Co.
Mag Daddy, LLC

Antenna Masts

Absolute EMC
AP Americas Inc.
AR RF/Microwave Instrumentation
C-Wave, Inc.
Com-Power
dB Instruments Co.
Electronic Instrument Associates
ETS-Lindgren
Frankonia GmbH
HV TECHNOLOGIES, Inc.
Innco Systems GmbH
Mag Daddy, LLC
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions

Biconical Antennas

A.H. Systems, Inc.
Aaronia USA
C-Wave, Inc.
Clark Testing
Com-Power
dB Instruments Co.
ETS-Lindgren
Frankonia GmbH
Mag Daddy, LLC
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions
Techmaster Electronics

Broadband Antennas

A.H. Systems, Inc.
Aaronia USA
AR RF/Microwave Instrumentation
Barth Electronics, Inc.
C-Wave, Inc.
Com-Power
dB Instruments Co.
EMC Test Design, LLC
ETS-Lindgren
Eurofins York
Frankonia GmbH
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Mag Daddy, LLC
Micom Labs
Microwave Vision Group
NSI-MI Technologies
Reality Consulting Yemen
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions

EMI Test Antennas

A.H. Systems, Inc.
Aaronia USA
Absolute EMC
AP Americas Inc.
Applied EM Technology
Applied Physical Electronics, L.C. (APELC)
AR RF/Microwave Instrumentation
Barth Electronics, Inc.
C-Wave, Inc.
Clark Testing
Com-Power
dB Instruments Co.
Electronic Instrument Associates
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Eurofins York
Frankonia GmbH
Lionheart Northwest
Mag Daddy, LLC
Micom Labs
Narda STS, USA
QAI Laboratories
Reliant EMC LLC

Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG
Siglent Technologies North America
Solar Electronics Co.
SunAR RF Motion
TDK RF Solutions
TOYO Corporation

Horn Antennas

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C-Wave, Inc.
Com-Power
dB Instruments Co.
ETS-Lindgren
Mag Daddy, LLC
Micom Labs
Microwave Vision Group
NSI-MI Technologies
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions
Techmaster Electronics

Log Periodic Antennas

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C-Wave, Inc.
Com-Power
dB Instruments Co.
ETS-Lindgren
Mag Daddy, LLC
NSI-MI Technologies
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions

Loop Antennas

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AFJ INSTRUMENTS Srl
C-Wave, Inc.
Com-Power
dB Instruments Co.
ETS-Lindgren
General Test Systems LLC
Mag Daddy, LLC
NSI-MI Technologies
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
TDK RF Solutions

Non-ionizing Radiation Hazard Antennas

dB Instruments Co.
EMC Test Design, LLC
Mag Daddy, LLC
Narda STS, USA
WAVECONTROL INC.

Rod Antennas

A.H. Systems, Inc.
C-Wave, Inc.
Com-Power
dB Instruments Co.
ETS-Lindgren
Fair-Rite Products Corp.
Mag Daddy, LLC
Narda STS, USA
NSI-MI Technologies
Schwarzbeck Mess-Elektronik OHG

Tunable Dipole

A.H. Systems, Inc.
Applied Physical Electronics, L.C. (APELC)
C-Wave, Inc.
Com-Power
ETS-Lindgren
General Test Systems LLC

Whip Antennas

Com-Power

Absorbers

EMC Absorbers

AP Americas Inc.
AR RF/Microwave Instrumentation
ARC Technologies, Inc
Comtest Engineering BV
Dutch Microwave Absorber Solutions
Electronic Instrument Associates
ETS-Lindgren
Frankonia GmbH
General Test Systems LLC
Leader Tech Inc.
Lionheart Northwest
MAJR Products
Marktek Inc.
MH&W International Corporation
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
TDK RF Solutions

Honeycomb RF

AP Americas Inc.
ARC Technologies, Inc
Leader Tech Inc.
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
TDK RF Solutions

Low Frequency Absorber

AP Americas Inc.
ARC Technologies, Inc
Leader Tech Inc.
Magnetic Shield Corporation
Microwave Vision Group
The MuShield Company, Inc.
PPG Aerospace Cuming-Lehman Chambers
TDK RF Solutions

Microwave Absorber

AP Americas Inc.
ARC Technologies, Inc
Comtest Engineering BV
Dutch Microwave Absorber Solutions
Eeonyx Corporation
ETS-Lindgren
Frankonia GmbH
Leader Tech Inc.
MAJR Products
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Seal Science, Inc.
TDK RF Solutions

Anechoic Materials

AP Americas Inc.
ARC Technologies, Inc
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Frankonia GmbH
General Test Systems LLC
HV TECHNOLOGIES, Inc.
Langer EMV-Technik GmbH
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
TDK RF Solutions
TESEO SpA

Cells

GTEM Cells

ETS-Lindgren
Laplace Instruments Ltd

Cells

TEM & Strip Line

ARC Technical Resources, Inc.
ESDEMC Technology LLC
ETS-Lindgren
Fischer Custom Communications, Inc.
TDK RF Solutions

Test Chambers

Anechoic Chambers

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AR RF/Microwave Instrumentation
Clark Testing
Comtest Engineering BV
Dutch Microwave Absorber Solutions
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Enerdoor
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General Test Systems LLC
Lionheart Northwest
Magnetic Shield Corporation
Micom Labs
Microwave Vision Group
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QAI Laboratories
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Reliant EMC LLC
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TESEO SpA

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Wave Scientific Ltd

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QAI Laboratories
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Lionheart Northwest
Microwave Vision Group
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Tempe, AZ
QAI Laboratories
Raymond EMC Enclosures Ltd.
V Technical Textiles, Inc.

Turntables

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ETS-Lindgren
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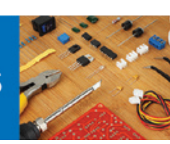
HV TECHNOLOGIES, Inc.
Innco Systems GmbH
NSI-MI Technologies
PPG Aerospace Cuming-Lehman Chambers
Raymond RF Measurement Corporation
SunAR RF Motion
VEROCH - Testing Equipment USA

Components



Attenuators

Barth Electronics, Inc.
ES Components
Pearson Electronics, Inc
Solar Electronics Co.

Bluetooth Modules

TDK Electronics

Cabinets & Enclosures

Deltron Enclosures
Elma Electronic Inc.
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Times Microwave Systems
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Backshells

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Gemini Electronic Components, Inc.
Isodyne Inc.
MegaPhase, LLC
Nolato Jabar LLC
Quell Corporation
Tech-Etch

Terminal Blocks

Americor Electronics Ltd.
APITech
Cinch Connectivity Solutions
CONEC Corporation
Curtis Industries/Tri-Mag, LLC
METZ CONNECT USA
SCHURTER, Inc.
WECO Electrical Connectors

Displays

Digital LED Display

DELO Adhesives

Touch Screen Display

DELO Adhesives
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Videon Central, Inc.

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Magnetic Shield Corporation
Megger

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Würth Elektronik

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Lightning Protection Systems

Captor Corporation
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Seal Science, Inc.

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Globe Composite Solutions
Omni Controls
Ross Engineering Corp.

Solid State Relays

Applied Physical Electronics, L.C. (APELC)

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Pickering Interfaces
Ross Engineering Corp.
SCHURTER, Inc.
Würth Elektronik

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Absorptive Filters

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Air Filters

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Metal Textiles Corporation

Antenna Filters

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Curtis Industries/Tri-Mag, LLC
EMC Instrument & Solution
EMI Filter Company
EMI Solutions, Inc.
Enerdoor
Gemini Electronic Components, Inc.
KGS America
Knowles (UK) Ltd

Filters

EMC & RFI Filters *(continued)*

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Okaya Electric America, Inc.
OnFILTER
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Quell Corporation
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Roxburgh EMC
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TDK RF Solutions
Tech-Etch
TTE Filters, LLC
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Coilcraft Critical Products & Services
Curtis Industries/Tri-Mag, LLC

Filter Pins

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Frequency Converters

VEROCH - Testing Equipment USA

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Micom Labs

Passive & Discrete

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Oak-Mitsui Technologies
Okaya Electric America, Inc.
Würth Elektronik

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EMI Solutions, Inc.
Oak-Mitsui Technologies

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KGS America
KOA Speer Electronics
Leader Tech Inc.
MAJR Products
MH&W International Corporation
TDK Electronics

Inductors/Chokes

Data & Signal Line Chokes

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TDK Electronics
WEMS Electronics

EMI/RFI Inductors

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Captor Corporation
Coilcraft Critical Products & Services

Coilcraft, Inc.
Gowanda Electronics
NRD LLC
WEMS Electronics

Power Line Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
MH&W International Corporation
SCHURTER, Inc.
WEMS Electronics

Reactors for Frequency Converters

Coilcraft Critical Products & Services
Gowanda Electronics
NRD LLC
OnFILTER

RF Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
MH&W International Corporation
NRD LLC
The Schaffner Group

Surface Mount Inductors

AVX Corporation
Coilcraft Critical Products & Services
Gowanda Electronics

Switchmode Inductors

Coilcraft Critical Products & Services
Gowanda Electronics

VHF Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
NRD LLC

Mains (X & Y)

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Electronic Loads

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Bourns, Inc.

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KOA Speer Electronics

Power Supply & Conditioning

Adapters

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DANA Power Supplies
Oak-Mitsui Technologies
Siglent Technologies North America

Converters

Curtis Industries/Tri-Mag, LLC
Equipnet
Oak-Mitsui Technologies

Interruptions, AC Power

DANA Power Supplies
Hilo-Test

Isolators, Power/Signal Line

OnFILTER

Line Conditioning Equipment

DANA Power Supplies
Merus Power
MH&W International Corporation
Okaya Electric America, Inc.

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Empower RF Systems
Giga-tronics Incorporated

Power Cords

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SCHURTER, Inc.

Power Generators

DANA Power Supplies
Preen AC Power Corp.

Power Rectifier

DANA Power Supplies

Power Strips

DANA Power Supplies
SCHURTER, Inc.

Power Supply & Conditioning

Power Supplies

Americor Electronics Ltd.
AMETEK Programmable Power Supplies
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
EaglePicher Technologies
Equipnet
Foster Transformer Company
Hilo-Test
Kikusui America Inc
Langer EMV-Technik GmbH
MH&W International Corporation
Preen AC Power Corp.
Rigol Technologies
Siglent Technologies North America

Switching Power Supplies

Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Kikusui America Inc
MH&W International Corporation
Würth Elektronik

Voltage Regulators

DANA Power Supplies
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Printed Circuit Boards

Americor Electronics Ltd.
AVX Corporation
Candor Industries Inc
Captor Corporation
Curtis Industries/Tri-Mag, LLC
Elma Electronic Inc.
MegaPhase, LLC
Oak-Mitsui Technologies
Polyonics
SCHURTER, Inc.

Resonators

ES Components

Semiconductors

Diodes

Cree, Inc.
Gemini Electronic Components, Inc.

Transistors

Cree, Inc.
ES Components

Surge Suppressors

Captor Corporation
CITEL, Inc.
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
ES Components
Fischer Custom Communications, Inc.
Gemini Electronic Components, Inc.
NexTek, Inc.
Okaya Electric America, Inc.
OnFILTER
TDK Electronics
Transtector

Materials

Absorbing Materials

3Gmetalworx Inc.
AR RF/Microwave Instrumentation
ARC Technologies, Inc
Dutch Microwave Absorber Solutions
Frankonia GmbH
Globe Composite Solutions
KGS America
Leader Tech Inc.
Marktek Inc.
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Seal Science, Inc.
TDK RF Solutions
V Technical Textiles, Inc.

Additives

Fonon Technologies
Marktek Inc.

Adhesives

Alpha Assembly Solutions
ARC Technologies, Inc
DELO Adhesives
Fonon Technologies
Master Bond
Metal Textiles Corporation
Polyonics
Seal Science, Inc.

Coatings and Sealants

Enviro Tech International
Oak-Mitsui Technologies
Seal Science, Inc.

Conductive Materials

Globe Composite Solutions
Leader Tech Inc.
Marktek Inc.
MFG Tray Company (Molded Fiber Glass Tray Co.)
Nolato Jabar LLC
Parker Chomerics
Quell Corporation
Polyonics
Seal Science, Inc.
Tech-Etch
Thermtest
V Technical Textiles, Inc.

Foams & Insulation

Enertech UPS Pvt Ltd

Metals and Alloys

3Gmetalworx Inc.
Alpha Assembly Solutions
Ferrotec-Nord
Fonon Technologies
Globe Composite Solutions
Johnson Bros Metal Forming Co
Leader Tech Inc.
Magnetic Shield Corporation
The MuShield Company, Inc.
PPG Engineered Materials - MicroGrid® EM
Testing Partners

Plastics

Resins & Compounds

ARC Technologies, Inc
Bicerano & Associates Consulting
DELO Adhesives
Fonon Technologies
Globe Composite Solutions
Jordi Labs
Lubrizol Engineered Polymers
Seal Science, Inc.

Thermoplastics & Thermoplastic Materials

ARC Technologies, Inc
Bicerano & Associates Consulting
Conductive Containers Inc
Crystal Rubber Ltd
Fonon Technologies
Globe Composite Solutions
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)
Parker Chomerics

Resources

Associations

A2LA
Saf-T-Gard International, Inc.

Education

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Andre Consulting, Inc.
Archambeault EMI/EMC Enterprises
BestESD Technical Services
Cherry Clough Consultants Ltd
Compliance inSight Consulting Inc.
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Military
D.L.S. - Wireless
Eisner Safety Consultants
Equipment Reliability Institute (ERI)
ESD Association
Go Global Compliance Inc.
Hoolihan EMC Consulting
In Compliance Magazine
Jastech EMC Consulting LLC
Keysight Technologies Inc.
Kimmel Gerke Associates Ltd.
LearnEMC
Lewis Bass International Engineering Services
Micom Labs
Montrose Compliance Services, Inc.
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
SILENT Solutions LLC
UL Knowledge Solutions
WorkHub
Wyatt Technical Services LLC

Training Courses

A2LA
Analysis and Measurement Services Corporation
Andre Consulting, Inc.
ARC Technical Resources, Inc.
Cherry Clough Consultants Ltd
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Military
DEKRA
DG Technologies
Eisner Safety Consultants
Electronic Instrument Associates
EMC FastPass
Equipment Reliability Institute (ERI)
Eurofins York
Hoolihan EMC Consulting
iNARTE
Jastech EMC Consulting LLC
Kimmel Gerke Associates Ltd.
LearnEMC
Lewis Bass International Engineering Services
Lion Technology, Inc.
Montrose Compliance Services, Inc.
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Pittsfield, MA
NTS - Plano, TX
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
SILENT Solutions LLC
UL Knowledge Solutions
University of Oxford Continuing Professional Development - Technology Programme
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

University

Purdue Engineering Professional Education
WorkHub

Videos

ARC Technical Resources, Inc.
ESD Association
Keysight Technologies Inc.
Purdue Engineering Professional Education
Washington Laboratories
WorkHub

Webinars

Cherry Clough Consultants Ltd
Compliance inSight Consulting Inc.
D.L.S. - Military
Eisner Safety Consultants
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
ESD Association
LearnEMC
Micom Labs
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
WorkHub

Publications

Books

EMI/EMC Books

Andre Consulting, Inc.
Cherry Clough Consultants Ltd
D.L.S. - Military
Montrose Compliance Services, Inc.

Product Safety Books

Lewis Bass International Engineering Services

Publications

Magazines

In Compliance Magazine

Standards Resellers

ESD Association

Safety+

Eyes, Face, and Head

Elimstat.com
HEMCO Corporation
Saf-T-Gard International, Inc.
WorkHub

Hand and Foot Protection

Elimstat.com
Saf-T-Gard International, Inc.
SW Safety Solutions
WorkHub

Safety & Warning Labels

Abstraction Engineering Inc
Clarion Safety Systems
Coast Label
Enerdoor
HM Cragg
InfoSight Corporation
Lewis Bass International Engineering Services
Micom Labs
Polyonics
Saf-T-Gard International, Inc.
WorkHub

Safety Clothing

Elimstat.com
Saf-T-Gard International, Inc.
SW Safety Solutions
TECH WEAR, INC.
WorkHub

Services

Calibration & Repair

A.com Electronic Measurement Technology
A.H. Systems, Inc.
Alltest Instruments
ARC Technical Resources, Inc.
Avalon Equipment Corporation Rentals
Barth Electronics, Inc.
Electronic Instrument Associates
Enertech UPS Pvt Ltd
ETS-Lindgren
Excalibur Engineering Inc.
Fischer Custom Communications, Inc.
Haefely AG
Keysight Technologies Inc.
Lightning EMC
MPB Measuring Instruments
NRD LLC
NSI-MI Technologies
Omni Controls
Pearson Electronics, Inc
Ross Engineering Corp.
Sanwood Environmental Chambers Co., Ltd
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
TDK RF Solutions
Techmaster Electronics
Technical Safety Services
TESEO SpA
Trescal
VEROCH - Testing Equipment USA
Wave Scientific Ltd
Willrich Precision Instrument Company, Inc

Codes, Standards & Regulations

A2LA
American Certification Body
American National Standards Institute
Analysis and Measurement Services Corporation
Clarion Safety Systems
CSA Group
DEKRA
DG Technologies
Eisner Safety Consultants
EMCE Engineering
Enerdoor
Enertech UPS Pvt Ltd
Go Global Compliance Inc.
GreenSoft Technology, Inc.
Grund Technical Solutions, Inc.
H.B. Compliance Solutions
iNARTE
InfoSight Corporation
Micom Laboratories Inc
Omni Controls
The Photonics Group
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.
UL Knowledge Solutions

Consulting

Cleanroom/Static Control

Advanced ESD Services +
BestESD Technical Services
Bystat International Inc
Elimstat.com
Estion Technologies GmbH
OnFILTER
Protective Industrial Polymers

EMC Consulting

Analysis and Measurement Services Corporation
Andre Consulting, Inc.
Atlas Compliance & Engineering
BestESD Technical Services
Cherry Clough Consultants Ltd
CKC Laboratories, Inc.
Compliance inSight Consulting Inc.
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DG Technologies
DNB Engineering, Inc.
Electro Magnetic Applications, Inc (EMA)

EMC Instrument & Solution
Enerdoor
ESDEMC Technology LLC
ETS-Lindgren
Eurofins York
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
Grund Technical Solutions, Inc.
Heavyside Corporation
Hoolihan EMC Consulting
International Certification Services, Inc.
Jastech EMC Consulting LLC
JBRC Consulting LLC
JDM LABS LLC
Kimmel Gerke Associates Ltd.
Laird Connectivity
LearnEMC
Machinery Safety & Compliance Services
Montrose Compliance Services, Inc.
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
NTS - Tinton Falls, NJ
OnFILTER
Pulver Laboratories
R&B Laboratory
Remcom
RM Regulatory & Export Compliance, LLC
SILENT Solutions LLC
Southwest Research Institute
Spectrum EMC, LLC
Test Site Services Inc
TJS Technical Services Inc.
Wave Scientific Ltd
WEMS Electronics
Wyatt Technical Services LLC

ESD Consulting

BestESD Technical Services
Conductive Containers Inc
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Military
Electro-Tech Systems
ESDEMC Technology LLC
Estion Technologies GmbH
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
JBRC Consulting LLC
Laird Connectivity
Montrose Compliance Services, Inc.
OnFILTER
SILENT Solutions LLC

Government Regulations

BSMI Regulatory Consulting

Atlas Compliance & Engineering
D.L.S. - EMC
D.L.S. - Wireless
Go Global Compliance Inc.
NTS - Silicon Valley Fremont & Newark, CA
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.

EU (Europe) Regulatory Consulting

ACEMA
Andre Consulting, Inc.
Atlas Compliance & Engineering
CKC Laboratories, Inc.
Compliance inSight Consulting Inc.
Compliance Specialty International Associates
Compliance Worldwide, Inc.
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Product Safety
D.L.S. - Wireless
Eisner Safety Consultants
Elite Electronic Engineering Inc.
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
GreenSoft Technology, Inc.
International Certification Services, Inc.
JBRC Consulting LLC
Kimmel Gerke Associates Ltd.
Laird Connectivity
Montrose Compliance Services, Inc.
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
RM Regulatory & Export Compliance, LLC
The Compliance Map
TJS Technical Services Inc.
VPI Laboratories, Inc.
Wyatt Technical Services LLC

FCC (U.S) Regulatory Consulting

Andre Consulting, Inc.
Atlas Compliance & Engineering
CKC Laboratories, Inc.
Compliance Specialty International Associates
Compliance Worldwide, Inc.
D.L.S. - EMC
D.L.S. - Product Safety
D.L.S. - Wireless
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
International Certification Services, Inc.
JBRC Consulting LLC
Kimmel Gerke Associates Ltd.
Laird Connectivity
Montrose Compliance Services, Inc.
NTS - Silicon Valley Fremont & Newark, CA
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.
TÜV Rheinland of North America
VPI Laboratories, Inc.

Government Regulations

GOST (Russia) Regulatory Consulting

Go Global Compliance Inc.
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Silicon Valley Fremont & Newark, CA
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.

VCCI Consulting

Atlas Compliance & Engineering
CKC Laboratories, Inc.
D.L.S. - EMC
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.

Lightning Protection

Andre Consulting, Inc.
D. C. Smith Consultants
D.L.S. - Military
Electro Magnetic Applications, Inc (EMA)
NexTek, Inc.
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Pittsfield, MA
NTS - Plano, TX
NTS - Silicon Valley Fremont & Newark, CA
UL Knowledge Solutions

Medical Device

Andre Consulting, Inc.
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Product Safety
D.L.S. - Wireless
Darryl Ray EMC Consultants LLC
Eisner Safety Consultants
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Kimmel Gerke Associates Ltd.
Laird Connectivity
MedicalRegs.com
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Silicon Valley Fremont & Newark, CA
Orbis Compliance LLC
The Photonics Group
Product Safety Consulting
Pulver Laboratories
Test Site Services Inc
TJS Technical Services Inc.
UL Knowledge Solutions

Product Safety Consulting

360 Compliance Partners
Applied Research Laboratories , LLC
Clarion Safety Systems
Compliance inSight Consulting Inc.
D.L.S. - Environmental
D.L.S. - Product Safety
Eisner Safety Consultants
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
InfoSight Corporation
Intertek
JBRC Consulting LLC
Lewis Bass International Engineering Services
M.C. Global Access LLC
Machinery Safety & Compliance Services
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Silicon Valley Fremont & Newark, CA
Orbis Compliance LLC
PC Squared Consultants
The Photonics Group
Product EHS Consulting LLC
Product Safety Consulting
RM Regulatory & Export Compliance, LLC
Test Site Services Inc
UL Knowledge Solutions
VDE Americas
VEROCH - Testing Equipment USA

Quality

DEKRA
Eisner Safety Consultants
Estion Technologies GmbH
Globe Composite Solutions
GreenSoft Technology, Inc.
InfoSight Corporation
RM Regulatory & Export Compliance, LLC
Spectrum EMC, LLC
UL Knowledge Solutions

Telecom

Agent In Mada
Compliance Specialty International Associates
CV. DIMULTI
D. C. Smith Consultants
D.L.S. - Wireless
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
NTS - Boxborough, MA
NTS - Fullerton, CA
NTS - Plano, TX
NTS - Silicon Valley Fremont & Newark, CA
Orbis Compliance LLC
UL Knowledge Solutions

Tempest

Dayton T. Brown, Inc.

Transient

Andre Consulting, Inc.
BestESD Technical Services
D. C. Smith Consultants
D.L.S. - EMC
F2 Labs - Middlefield, OH
Grund Technical Solutions, Inc.
JBRC Consulting LLC
NexTek, Inc.
SILENT Solutions LLC

Design

Andre Consulting, Inc.
BestESD Technical Services
Captor Corporation
Clarion Safety Systems
Conductive Containers Inc

DG Technologies
Elimstat.com
EMCE Engineering
EMS-PLUS
Enertech UPS Pvt Ltd
Fonon Technologies
Globe Composite Solutions
Jastech EMC Consulting LLC
JBRC Consulting LLC
Machinery Safety & Compliance Services
NTS - Baltimore, MD
NTS - Boxborough, MA
NTS - Chicago, IL
NTS - Detroit, MI
NTS - Europe
NTS - Fullerton, CA
NTS - Pittsfield, MA
NTS - Plano, TX
NTS - Rockford, IL
NTS - Santa Clarita, CA
NTS - Silicon Valley Fremont & Newark, CA
NTS - Tempe, AZ
Orbel Corporation
The Photonics Group
SILENT Solutions LLC
UL Knowledge Solutions
V Technical Textiles, Inc.
VEROCH - Testing Equipment USA
Videon Central, Inc.
WEMS Electronics
Wyatt Technical Services LLC

Other

Conductive Painting Services

VTI Vacuum Technologies, Inc.

Shielded Enclosure Design

3Gmetalworx Inc.
Conductive Containers Inc
Elma Electronic Inc.
Leader Tech Inc.
VTI Vacuum Technologies, Inc.

Site Survey Services

BestESD Technical Services
Clarion Safety Systems
Dayton T. Brown, Inc.
Electronic Instrument Associates
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
NRD LLC
Spectrum EMC, LLC
Wave Scientific Ltd
WorkHub

Other Services

Jay Hoehl Inc. E-Scrap
Machinery Safety & Compliance Services
Technical Safety Services

Shielding

Architectural Shielding Products

ETS-Lindgren
Leader Tech Inc.
MAJR Products
Marktek Inc.
Metal Textiles Corporation

Fingerstock

3Gmetalworx Inc.
Leader Tech Inc.
Metal Textiles Corporation
Orbel Corporation
Parker Chomerics
Raymond EMC Enclosures Ltd.
Schlegel Electronic Materials
Tech-Etch

Shielded Air Filters

Leader Tech Inc.
MAJR Products
Nolato Jabar LLC
P & P Technology Ltd
Parker Chomerics
Spira Manufacturing Corporation
Tech-Etch
Universal Shielding Corp.

Shielded Cable Assemblies & Harnesses

CONEC Corporation
Leader Tech Inc.
MAJR Products

Shielded Coatings

A&A Coatings
ARC Technologies, Inc
Leader Tech Inc.
Marktek Inc.
Parker Chomerics
VTI Vacuum Technologies, Inc.

Shielded Compounds

Leader Tech Inc.
Marktek Inc.
Parker Chomerics

Shielded Conduit

Electri-Flex Company
Leader Tech Inc.
Magnetic Shield Corporation

Shielded Connectors

American Swiss
Amphenol Industrial Products Group
CONEC Corporation
Gemini Electronic Components, Inc.
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
METZ CONNECT USA
Quell Corporation
Spira Manufacturing Corporation
Tech-Etch
Würth Elektronik

Shielded Enclosures

3Gmetalworx Inc.
AR RF/Microwave Instrumentation
Comtest Engineering BV
Crenlo
Elma Electronic Inc.
ETS-Lindgren
Frankonia GmbH
Leader Tech Inc.

Shielded Enclosures *(continued)*

- Lionheart Northwest
- Magnetic Shield Corporation
- Marktek Inc.
- The MuShield Company, Inc.
- PPG Aerospace Cuming-Lehman Chambers
- **Raymond EMC Enclosures Ltd.**
- Select Fabricators, Inc.
- **Universal Shielding Corp.**
- V Technical Textiles, Inc.
- VTI Vacuum Technologies, Inc.

Shielded Tubing

- Electri-Flex Company
- **Leader Tech Inc.**
- Magnetic Shield Corporation
- Marktek Inc.

Shielded Wire & Cable

- CONEC Corporation
- Elimstat.com
- Isodyne Inc.
- **Leader Tech Inc.**
- Metal Textiles Corporation
- METZ CONNECT USA

Shielding Gaskets

- 3Gmetalworx Inc.
- KGS America
- **Leader Tech Inc.**
- MAJR Products
- Metal Textiles Corporation
- **Nolato Jabar LLC**
- Orbel Corporation
- P & P Technology Ltd
- Parker Chomerics
- Quell Corporation
- SAS Industries, Inc.
- Schlegel Electronic Materials
- **Spira Manufacturing Corporation**
- Tech-Etch
- VTI Vacuum Technologies, Inc.
- W. L. Gore & Associates, Inc.
- XGR Technologies

Shielding Materials

EMI/RFI Shielding Materials

- A&A Coatings
- Aaronia USA
- **AR RF/Microwave Instrumentation**
- Bal Seal Engineering
- Fabritech, Inc.
- **Fair-Rite Products Corp.**
- Isodyne Inc.
- KGS America
- **Leader Tech Inc.**
- MAJR Products
- Metal Textiles Corporation
- MH&W International Corporation
- **Nolato Jabar LLC**
- Orbel Corporation
- P & P Technology Ltd
- Polyonics
- PPG Aerospace Cuming-Lehman Chambers
- Schlegel Electronic Materials
- **Spira Manufacturing Corporation**
- Swift Textile Metalizing LLC
- **Universal Shielding Corp.**
- V Technical Textiles, Inc.
- VTI Vacuum Technologies, Inc.
- W. L. Gore & Associates, Inc.
- **Würth Elektronik**
- XGR Technologies

Magnetic Field Shielding Materials

- 3Gmetalworx Inc.
- KGS America
- **Leader Tech Inc.**
- Magnetic Shield Corporation
- MAJR Products
- The MuShield Company, Inc.
- PPG Aerospace Cuming-Lehman Chambers

Shielding, Board-Level

- 3Gmetalworx Inc.
- Conductive Containers Inc
- Elma Electronic Inc.
- Faspro Technologies
- KGS America
- **Leader Tech Inc.**
- MAJR Products
- Orbel Corporation
- XGR Technologies

Software

Compliance Management Software

- WorkHub

EMC Simulation Software

- **AE Techron, Inc.**
- Altair Engineering Inc.
- ANSYS Inc.
- Electro Magnetic Applications, Inc (EMA)
- EMS-PLUS
- Heavyside Corporation
- Hilo-Test
- Remcom
- TESEO SpA
- TOYO Corporation
- Wave Computation Technologies, Inc.

ESD/Static Control Software

- **ACL Staticide Inc.**
- Antistat Inc
- Desco Industries Inc.
- Estion Technologies GmbH
- Langer EMV-Technik GmbH
- Monroe Electronics

Lab Control Software

- **AR RF/Microwave Instrumentation**
- **ETS-Lindgren**
- Lionheart Northwest
- TESEO SpA
- TOYO Corporation

Product Safety Software

- GreenSoft Technology, Inc.
- Heavyside Corporation
- **OnRule**
- The Photonics Group

Signal Integrity & EMC Analysis Software

AFJ INSTRUMENTS Srl
Altair Engineering Inc.
EMZER Technological Solutions
Heavyside Corporation
Remcom
TDK RF Solutions
TOYO Corporation

Wireless Propagation Software

Altair Engineering Inc.
Heavyside Corporation
Remcom

Air Ionizers

Bystat International Inc
Desco Industries Inc.
Elimstat.com
Estatec
NRD LLC
Simco-Ion

Clothing & Accessories

ESD Garments

Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
TECH WEAR, INC.
United Static Control Products Inc.

Footwear

Amstat Industries, Inc.
Estatec
Lubrizol Engineered Polymers
Saf-T-Gard International, Inc.

Wrist Straps

Amstat Industries, Inc.
Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
Static Solutions, Inc.
United Static Control Products Inc.

Containers

Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)

ESD Tape

Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Leader Tech Inc.
Polyonics
United Static Control Products Inc.

Flooring

Carpet

Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
StaticStop ESD Flooring
StaticWorx, Inc.

Floor Coatings

ACL Staticide Inc.

Correct Products, Inc.
Estatec
Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
Static Solutions, Inc.
StaticStop ESD Flooring
StaticWorx, Inc.
United Static Control Products Inc.

Mats

Bystat International Inc
Correct Products, Inc.
Estatec
Static Solutions, Inc.
StaticStop ESD Flooring

Flooring

Tiles

Bystat International Inc
Ground Zero
Julie Industries, Inc.
StaticStop ESD Flooring

StaticWorx, Inc.

Packaging

Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
EaglePicher Technologies
Estatec
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)

Simulators

EMP Simulators

Fischer Custom Communications, Inc.
Grund Technical Solutions, Inc.

ESD Simulators

Electro-Tech Systems
ESDEMC Technology LLC
Hilo-Test
Kikusui America Inc

Transient Detectors & Suppressors

CITEL, Inc.
EMI Solutions, Inc.
EMZER Technological Solutions
Fischer Custom Communications, Inc.
NexTek, Inc.

Workstations

ACL Staticide Inc.
Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
HEMCO Corporation
Langer EMV-Technik GmbH
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)
NRD LLC
United Static Control Products Inc.

Test and Measure

Accelerometers

Clark Testing
Essco Calibration Laboratory
PCE Instruments
Techmaster Electronics

Amplifiers

Amplifier Modules

AR RF/Microwave Instrumentation
Empower RF Systems
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana
TREK, INC.
Vectawave Technology Limited

Low Power Amplifiers

A.H. Systems, Inc.
AR RF/Microwave Instrumentation
ETS-Lindgren
Exodus Advanced Communications
Siglent Technologies North America
TREK, INC.
Vectawave Technology Limited

Microwave Amplifiers

AMETEK CTS
Applied Systems Engineering, Inc.
AR RF/Microwave Instrumentation
Axiom Test Equipment Rentals
Empower RF Systems
ETS-Lindgren
Exodus Advanced Communications
Giga-tronics Incorporated
HV TECHNOLOGIES, Inc.
OPHIR RF/Ophir EMC
Prana
TMD Technologies
Wave Scientific Ltd

Power Amplifiers

Advanced Test Equipment Rentals
AE Techron, Inc.

AMETEK CTS
AR RF/Microwave Instrumentation
CPI, Inc.
Empower RF Systems
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
OPHIR RF/Ophir EMC
Prana

Rohde & Schwarz
TESEO SpA
TMD Technologies
TOYO Corporation
TREK, INC.
Vectawave Technology Limited

RF Amplifiers

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AMETEK CTS
AR RF/Microwave Instrumentation
Avalon Equipment Corporation Rentals
Axiom Test Equipment Rentals
CPI, Inc.
Empower RF Systems
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
OPHIR RF/Ophir EMC
Prana
Reliant EMC LLC
Rohde & Schwarz
US Microwave Laboratories
Wave Scientific Ltd

Solid State Amplifiers

AMETEK CTS
AR RF/Microwave Instrumentation
CPI, Inc.
Empower RF Systems
ETS-Lindgren
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana
TREK, INC.
Vectawave Technology Limited

Traveling Wave Tube Amplifiers

AMETEK CTS
AR RF/Microwave Instrumentation
Avalon Equipment Corporation Rentals
CPI, Inc.
Hilo-Test
OPHIR RF/Ophir EMC
TMD Technologies

Analyzers

EMI/EMC, Spectrum Analyzers

Aaronia USA
Advanced Test Equipment Rentals
AFJ INSTRUMENTS Srl
Agile Calibration
Alltest Instruments
Anritsu Company
Axiom Test Equipment Rentals
Electro Rent Corporation
Electronic Instrument Associates
EMC Instrument & Solution
EMZER Technological Solutions
Excalibur Engineering Inc.
GAUSS INSTRUMENTS
Keysight Technologies Inc.
Laplace Instruments Ltd
MPB Measuring Instruments
Reliant EMC LLC
Rigol Technologies
Rohde & Schwarz
Siglent Technologies North America
Signal Hound
TOYO Corporation
VIAVI Solutions

Flicker Analyzers

Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc

Harmonics Analyzers

Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc
Laplace Instruments Ltd

Network Analyzers

AFJ INSTRUMENTS Srl
Agile Calibration
Axiom Test Equipment Rentals
Copper Mountain Technologies
Electro Rent Corporation
Excalibur Engineering Inc.
Keysight Technologies Inc.
PCE Instruments
Rohde & Schwarz
Siglent Technologies North America
TOYO Corporation
VIAVI Solutions

Power Quality Analyzers

Advanced Test Equipment Rentals
Electro Rent Corporation
Excalibur Engineering Inc.
Lionheart Northwest

Telecom Analyzers

MPB Measuring Instruments

Audio & Video

Audio Systems

Audivo GmbH
Videon Central, Inc.

CCTV

Audivo GmbH
TDK RF Solutions
TESEO SpA
Videon Central, Inc.

Automatic Test Sets

AFJ INSTRUMENTS Srl
ARC Technical Resources, Inc.
Detectus AB
Essco Calibration Laboratory
General Test Systems LLC
Omni Controls
Preen AC Power Corp.
TOYO Corporation
United Static Control Products Inc.

Avionics Test Equipment

AE Techron, Inc.
Alltest Instruments
Cincinnati Sub Zero, LLC
The EMC Shop
Essco Calibration Laboratory
HV TECHNOLOGIES, Inc.
NTS - Huntsville, AL
Omni Controls
Pickering Interfaces
Preen AC Power Corp.
TMD Technologies
VIAVI Solutions
Vitrek Corporation

Burn-in Test Equipment

Essco Calibration Laboratory
General Test Systems LLC
inTEST Thermal Solutions
Mechanical Devices
OPHIR RF/Ophir EMC
Preen AC Power Corp.
Sanwood Environmental Chambers Co., Ltd

Data Acquisition Monitoring Systems

Analysis and Measurement Services Corporation
Axiom Test Equipment Rentals
Degree Controls, Inc.
Desco Industries Inc.
DG Technologies
Essco Calibration Laboratory
NSI-MI Technologies

Fiber-Optic Systems

Absolute EMC
DG Technologies
Essco Calibration Laboratory
Excalibur Engineering Inc.
Ferrotec-Nord
HV TECHNOLOGIES, Inc.
Michigan Scientific Corp.
Ross Engineering Corp.
TESEO SpA

Flow Meters

Essco Calibration Laboratory
Omni Controls
PCE Instruments
VEROCH - Testing Equipment USA

Generators

Arbitrary Waveform Generators

AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Axiom Test Equipment Rentals
Eurofins York
Hilo-Test
Keysight Technologies Inc.
Rigol Technologies
Siglent Technologies North America
Suzhou 3ctest Electronic Co., Ltd.

EMP Generator

HV TECHNOLOGIES, Inc.
Suzhou 3ctest Electronic Co., Ltd.

ESD Generators

Absolute EMC
Advanced Test Equipment Rentals
AMETEK CTS
ARC Technical Resources, Inc.
Axiom Test Equipment Rentals
The EMC Shop
Grund Technical Solutions, Inc.
Haefely AG
HV TECHNOLOGIES, Inc.
Lightning EMC
Reliant EMC LLC
Suzhou 3ctest Electronic Co., Ltd.

Fast/Transient Burst Generators

Absolute EMC
ARC Technical Resources, Inc.
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Reliant EMC LLC
Suzhou 3ctest Electronic Co., Ltd.

Impulse Generators

Absolute EMC
AFJ INSTRUMENTS Srl
AMETEK CTS
Applied EM Technology
Applied Physical Electronics, L.C. (APELC)
Grund Technical Solutions, Inc.
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Interference Generators

Absolute EMC
Suzhou 3ctest Electronic Co., Ltd.

Lightning Generators

Absolute EMC
Advanced Test Equipment Rentals
ARC Technical Resources, Inc.
Avalon Equipment Corporation Rentals
The EMC Shop
Haefely AG
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Signal Generators

Aaronia USA
AFJ INSTRUMENTS Srl
Alltest Instruments
Applied EM Technology
Axiom Test Equipment Rentals
Electro Rent Corporation
Eurofins York
Excalibur Engineering Inc.
Giga-tronics Incorporated
Keysight Technologies Inc.
Kikusui America Inc
Laplace Instruments Ltd
Reliant EMC LLC
Rohde & Schwarz
Signal Hound
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
TOYO Corporation
VIAVI Solutions

Surge Transient Generators

Absolute EMC
Advanced Test Equipment Rentals
AMETEK CTS
ARC Technical Resources, Inc.
Avalon Equipment Corporation Rentals
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
Thermo Fisher Scientific

Meters

Field Strength Meters

AR RF/Microwave Instrumentation
Desco Industries Inc.
Monroe Electronics
Narda STS, USA
TREK, INC.
United Static Control Products Inc.
WAVECONTROL INC.

Gaussmeters

Omni Controls
PCE Instruments
WAVECONTROL INC.

Magnetic Field Meters

AR RF/Microwave Instrumentation
MPB Measuring Instruments
PCE Instruments
WAVECONTROL INC.

Megohmmeters

ACL Staticide Inc.
Amstat Industries, Inc.
Chroma Systems Solutions, Inc
Megger
Monroe Electronics
PCE Instruments
Ross Engineering Corp.
Static Solutions, Inc.
United Static Control Products Inc.

Radiation Hazard Meters

AR RF/Microwave Instrumentation
EMC Test Design, LLC
WAVECONTROL INC.

RF Power Meters

Alltest Instruments
Anritsu Company
AR RF/Microwave Instrumentation
Electro Rent Corporation
Giga-tronics Incorporated
Keysight Technologies Inc.
OPHIR RF/Ophir EMC
VIAVI Solutions

Static Charge Meters

ACL Staticide Inc.
Electro-Tech Systems
Estion Technologies GmbH
Monroe Electronics
TREK, INC.

Static Decay Meters

Electro-Tech Systems
Monroe Electronics
TREK, INC.

Monitors

Current Monitors

Grund Technical Solutions, Inc.
PCE Instruments
Pearson Electronics, Inc

EMI Test Monitors

Absolute EMC
DG Technologies
OnFILTER

ESD Monitors

Bystat International Inc
Estion Technologies GmbH
Monroe Electronics
Static Solutions, Inc.

Ionizer Balance Monitors

Monroe Electronics
TREK, INC.

Static Voltage Monitors

Desco Industries Inc.
Michigan Scientific Corp.
TREK, INC.

Oscilloscopes & Transient Recorders

Agile Calibration
Alltest Instruments
Avalon Equipment Corporation Rentals
Electro Rent Corporation
Essco Calibration Laboratory
Keysight Technologies Inc.
PCE Instruments
Rigol Technologies
Rohde & Schwarz
Siglent Technologies North America
Techmaster Electronics
Teledyne LeCroy

Pressure Measurement

Gauges

Willrich Precision Instrument Company, Inc

Probes

Current/Magnetic Field Probes

A.H. Systems, Inc.
AEMC Instruments
Alltest Instruments
Fischer Custom Communications, Inc.
General Test Systems LLC
Langer EMV-Technik GmbH
MPB Measuring Instruments
Pearson Electronics, Inc
Prana
Rigol Technologies
Siglent Technologies North America
Solar Electronics Co.

Electric Field Probes

AR RF/Microwave Instrumentation
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Langer EMV-Technik GmbH
MPB Measuring Instruments
Narda STS, USA
Siglent Technologies North America
TREK, INC.
WAVECONTROL INC.

Voltage Probes

Fischer Custom Communications, Inc.
Hilo-Test
Langer EMV-Technik GmbH
Laplace Instruments Ltd
OnFILTER
Ross Engineering Corp.
Solar Electronics Co.

Receivers

EMI/EMC Receivers

AFJ INSTRUMENTS Srl
AR RF/Microwave Instrumentation
EMZER Technological Solutions

Excalibur Engineering Inc.
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG

RF Receivers

AFJ INSTRUMENTS Srl
EMZER Technological Solutions
Narda STS, USA
NSI-MI Technologies
Rigol Technologies
Rohde & Schwarz

TEMPEST Receivers

Rohde & Schwarz

RF Leak Detectors

AR RF/Microwave Instrumentation
MPB Measuring Instruments
NRD LLC

Safety Test Equipment

AE Techron, Inc.
AEMC Instruments
Chroma Systems Solutions, Inc
Cincinnati Sub Zero, LLC
ED&D
EMC Test Design, LLC
Kikusui America Inc
Micom Laboratories Inc
MPB Measuring Instruments
Packaging Compliance Labs
Preen AC Power Corp.
Product Safety Consulting
Pulver Laboratories
Saf-T-Gard International, Inc.
Sanwood Environmental Chambers Co., Ltd
United Static Control Products Inc.
VEROCH - Testing Equipment USA
Vitrek Corporation

SAR Testing Equipment

ART-MAN

Shock & Vibration Testing Shakers

Cincinnati Sub Zero, LLC
Globe Composite Solutions
Micom Laboratories Inc
Sanwood Environmental Chambers Co., Ltd
Thermotron
Wewontech

Susceptibility Test Instruments

ARC Technical Resources, Inc.
Detectus AB
DG Technologies
EMC Test Design, LLC
ESDEMC Technology LLC
Grund Technical Solutions, Inc.
Laplace Instruments Ltd
TDK RF Solutions

Telecom Test Equipment

AE Techron, Inc.
Agent In Mada
Anritsu Company
Avalon Equipment Corporation Rentals
Cincinnati Sub Zero, LLC
Electro Rent Corporation
Fischer Custom Communications, Inc.
Haefely AG
Megger
Pickering Interfaces
VIAVI Solutions

Test Equipment Rentals

Advanced Test Equipment Rentals
Alltest Instruments
AR RF/Microwave Instrumentation
Avalon Equipment Corporation Rentals
Axiom Test Equipment Rentals
Barth Electronics, Inc.
Electro Rent Corporation
Electro-Tech Systems
The EMC Shop
ESDEMC Technology LLC
Excalibur Engineering Inc.
GAUSS INSTRUMENTS
Grund Technical Solutions, Inc.
Lionheart Northwest
Megger
Michigan Scientific Corp.

MPB Measuring Instruments
Techmaster Electronics
TestWorld Inc
Transient Specialists, Inc.
United Static Control Products Inc.
VEROCH - Testing Equipment USA

Testers

Common Mode Transient Immunity (CMTI)

Barth Electronics, Inc.

Current Leakage Testers

Associated Research, Inc
Chroma Systems Solutions, Inc
ESDEMC Technology LLC
Kikusui America Inc
Megger
Ross Engineering Corp.
SCI

Dielectric Strength Testers

Associated Research, Inc
Chroma Systems Solutions, Inc
Megger
Ross Engineering Corp.
SCI

Electrical Safety Testers

Associated Power Technologies
Associated Research, Inc
Chroma Systems Solutions, Inc
Kikusui America Inc
Megger
Saf-T-Gard International, Inc.
SCI

EMC Testers

AMETEK CTS
Detectus AB
DG Technologies
EMC PARTNER AG
EMC Technologies
EMC Test Design, LLC
EMZER Technological Solutions
ESDEMC Technology LLC
Grund Technical Solutions, Inc.
Langer EMV-Technik GmbH
OPHIR RF/Ophir EMC

ESD Testers

CDM (Charged Device Model)

Barth Electronics, Inc.
Electro-Tech Systems
Thermo Fisher Scientific

HBM (Human Body Model)

Electro-Tech Systems
Thermo Fisher Scientific

TLP (Transmission Line Pulser)

Barth Electronics, Inc.
Thermo Fisher Scientific

Ground Bond Testers

Associated Power Technologies

Ground Resistance Testers

AEMC Instruments
Associated Research, Inc
Megger
SCI

Hipot Testers

Applied Physical Electronics, L.C. (APELC)
Associated Power Technologies
Associated Research, Inc
Chroma Systems Solutions, Inc
Electro Rent Corporation
GW INSTEK
Kikusui America Inc
Ross Engineering Corp.
SCI

Thermocouples

Applied Physical Electronics, L.C. (APELC)
Pickering Interfaces
VEROCH - Testing Equipment USA

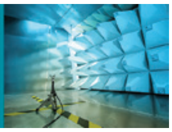
Used & Refurbished Test Equipment

Alltest Instruments
AR RF/Microwave Instrumentation
Avalon Equipment Corporation Rentals
Electro Rent Corporation
Techmaster Electronics

Vibration Controllers

Cincinnati Sub Zero, LLC
Excalibur Engineering Inc.
Globe Composite Solutions
Micom Laboratories Inc
Thermotron

Testing



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Green Mountain Electromagnetics, Inc.
Nemko USA, Inc.
QAI Laboratories

Calibration Testing

Agile Calibration
Essco Calibration Laboratory
GAUSS INSTRUMENTS
Haefely AG
ITC India

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UL LLC

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Micom Labs
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Nemko Norway
Nemko USA, East Coast
Nemko USA, Inc.
Pulver Laboratories
QAI Laboratories
TESEO SpA
Test Site Services Inc

Environmental Testing & Analysis Services

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ITC India
Micom Laboratories Inc
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NTS - Boxborough, MA
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QAI Laboratories
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
Test Site Services Inc
TÜV SÜD America Inc.
UL LLC
Washington Laboratories

Homologation Services

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Element Materials Technology - Washington, Columbia, Oakland Mills
Go Global Compliance Inc.
Lewis Bass International Engineering Services
Nemko USA, East Coast
Orbis Compliance LLC
Versus Technology (Versus Global LLC)

Pre-Assessments

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Clark Testing
Compatible Electronics, Inc.
Curtis Industries/Tri-Mag, LLC
CVG Strategy
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D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
DEKRA
Eisner Safety Consultants
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
International Certification Services, Inc.
Jastech EMC Consulting LLC
Lewis Bass International Engineering Services
Nemko Canada Inc. - Cambridge, ON
Nemko USA, East Coast
Product Safety Consulting
Quanta Laboratories
SILENT Solutions LLC
Spectrum EMC, LLC
Testing Partners
VPI Laboratories, Inc.
Washington Laboratories
Wyatt Technical Services LLC

Product & Component Testing Services

Agent In Mada
Agile Calibration
Analysis and Measurement Services Corporation
ART-MAN
Bureau Veritas Consumer Products Services Inc.
The Compliance Management Group
Compliance Specialty International Associates
Compliance Testing, LLC
CVG Strategy
D.L.S. - EMC
D.L.S. - Environmental

D.L.S. - Military

D.L.S. - Product Safety

D.L.S. - Wireless

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DEKRA

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Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

Elite Electronic Engineering Inc.

Energy Assurance LLC

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

Ferrotec-Nord

Green Mountain Electromagnetics, Inc.

International Certification Services, Inc.

ITC India

Micom Laboratories Inc

Nemko Canada Inc. - Cambridge, ON

Nemko USA, East Coast

Nemko USA, Inc.

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NTS - Baltimore, MD

NTS - Boxborough, MA

NTS - Chicago, IL

NTS - Fullerton, CA

NTS - Huntsville, AL

NTS - Longmont, CO

NTS - Montreal, Canada

NTS - Orlando, FL

NTS - Plano, TX

NTS - Santa Clarita, CA

NTS - Silicon Valley Fremont & Newark, CA

NTS - Tempe, AZ

NTS - Tinton Falls, NJ

The Photonics Group

Product Safety Consulting

Pulver Laboratories

R&B Laboratory

Retlif Testing Laboratories

RF Solutions, LLC.

RM Regulatory & Export Compliance, LLC

Sanwood Environmental Chambers Co., Ltd

Southwest Research Institute

Testing Partners

TÜV SÜD America Inc.

UL LLC

VPI Laboratories, Inc.

Washington Laboratories

Testing Laboratories

Accelerated Stress Testing

Core Compliance Testing Services

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D.L.S. - Wireless

Dayton T. Brown, Inc.

Elite Electronic Engineering Inc.

Intertek

NTS - Anaheim, CA

NTS - Baltimore, MD

NTS - Boxborough, MA

NTS - Chicago, IL

NTS - Fullerton, CA

NTS - Huntsville, AL

NTS - Longmont, CO

NTS - Orlando, FL

NTS - Plano, TX

NTS - Santa Clarita, CA

NTS - Tempe, AZ

NTS - Tinton Falls, NJ

Product Safety Consulting

Professional Testing (EMI), Inc.

Quanta Laboratories

Radiometrics Midwest Corporation

Videon Central, Inc.

Acoustical Testing

A2LA

Clark Testing

The Compliance Management Group

Core Compliance Testing Services

D.L.S. - Environmental

D.L.S. - Product Safety

Dayton T. Brown, Inc.

DNB Engineering, Inc.

Electronic Instrument Associates

ETS-Lindgren

Intertek

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NTS - Chicago, IL

NTS - Europe

NTS - Fullerton, CA

NTS - Huntsville, AL

NTS - Plano, TX

NTS - Rockford, IL

NTS - Santa Clarita, CA

NTS - Tinton Falls, NJ

Quanta Laboratories

Retlif Testing Laboratories

BSMI Compliant Certification Testing

Atlas Compliance & Engineering

Compliance Worldwide, Inc.

Core Compliance Testing Services

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D.L.S. - Wireless

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

Nemko Canada Inc. - Cambridge, ON

Nemko Canada Inc. - Ottawa, ON

Nemko Norway

Nemko USA, East Coast

Nemko USA, Inc.

NTS - Baltimore, MD

NTS - Boxborough, MA

NTS - Chicago, IL

NTS - Fullerton, CA

NTS - Plano, TX

NTS - Silicon Valley Fremont & Newark, CA

CB Test Report

CSA Group

D.L.S. - Product Safety

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Testing Laboratories

CB Test Report *(continued)*

Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Energy Assurance LLC
Eurofins MET Labs
Intertek
Nemko Canada Inc. - Cambridge, ON
Nemko Canada Inc. - Ottawa, ON
Nemko Norway
Nemko USA, East Coast
Nemko USA, Inc.
NTS - Baltimore, MD
NTS - Chicago, IL
NTS - Longmont, CO
Professional Testing (EMI), Inc.
TÜV Rheinland of North America

CE Marking

Abstraction Engineering Inc
Atlas Compliance & Engineering
CertifiGroup Inc
CKC Laboratories, Inc.
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
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D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
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DNB Engineering, Inc.
Element Materials Technology - Brooklyn Park, MN
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Element Materials Technology - Washington, Columbia, Oakland Mills
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Energy Assurance LLC
Eurofins MET Labs
F2 Labs - Middlefield, OH
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Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
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Intertek
Laird Connectivity
Lewis Bass International Engineering Services
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Professional Testing (EMI), Inc.
Pulver Laboratories
Retlif Testing Laboratories
TESEO SpA
Test Site Services Inc
TÜV Rheinland of North America
VPI Laboratories, Inc.

China Compulsory Certification

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Electrical Safety Testing

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Coilcraft Critical Products & Services
CSA Group
CVG Strategy
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Energy Assurance LLC
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TÜV Rheinland of North America
TÜV SÜD America Inc.
UL LLC

EMC Testing

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AHD
Analysis and Measurement Services Corporation
APREL Inc.
ART-MAN
Atlas Compliance & Engineering
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
CSA Group
CVG Strategy
D.L.S. - EMC

D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
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Electronics Test Centre
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Element Materials Technology - Washington, Columbia, Oakland Mills
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EMC Bayswater Pty Ltd
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Global Testing Laboratories
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International Certification Services, Inc.
Intertek
ITC India
Jastech EMC Consulting LLC
Laird Connectivity
Montrose Compliance Services, Inc.
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NTS - Plano, TX
NTS - Rockford, IL
NTS - Silicon Valley Fremont & Newark, CA
NTS - Tempe, AZ
NTS - Tinton Falls, NJ
Parker Chomerics
Professional Testing (EMI), Inc.
Pulver Laboratories
R&B Laboratory
Radiometrics Midwest Corporation
Retlif Testing Laboratories
Southwest Research Institute
Spes Development Co
Test Site Services Inc
Timco Engineering, Inc.
TÜV Rheinland of North America
TÜV SÜD America Inc.
UL LLC
VPI Laboratories, Inc.
Washington Laboratories
Wave Scientific Ltd
WEMS Electronics
Wyatt Technical Services LLC
Yazaki Testing Laboratory

Energy Efficiency Testing

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NTS - Chicago, IL
NTS - Fullerton, CA
NTS - Plano, TX
TÜV SÜD America Inc.
UL LLC

Solutions Directory

Testing Laboratories

Environmental Simulation Testing

CertifiGroup Inc

Coilcraft Critical Products & Services

The Compliance Management Group

Core Compliance Testing Services

CVG Strategy

D.L.S. - Environmental

D.L.S. - Military

DNB Engineering, Inc.

Energy Assurance LLC

H.B. Compliance Solutions

NTS - Anaheim, CA

NTS - Baltimore, MD

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NTS - Chicago, IL

NTS - Detroit, MI

NTS - Europe

NTS - Fullerton, CA

NTS - Huntsville, AL

NTS - Longmont, CO

NTS - Montreal, Canada

NTS - Orlando, FL

NTS - Pittsfield, MA

NTS - Plano, TX

NTS - Rockford, IL

NTS - Santa Clarita, CA

NTS - Silicon Valley Fremont & Newark, CA

NTS - Tempe, AZ

NTS - Tinton Falls, NJ

Professional Testing (EMI), Inc.

Quanta Laboratories

Retlif Testing Laboratories

Sanwood Environmental Chambers Co., Ltd

TÜV SÜD America Inc.

ESD Testing

Barth Electronics, Inc.

The Compliance Management Group

Compliance Worldwide, Inc.

CVG Strategy

D.L.S. - EMC

D.L.S. - Military

DNB Engineering, Inc.

Electro-Tech Systems

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

ESDEMC Technology LLC

Estion Technologies GmbH

F2 Labs - Middlefield, OH

H.B. Compliance Solutions

Laird Connectivity

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Nemko Norway

Nemko USA, East Coast

Nemko USA, Inc.

NTS - Baltimore, MD

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NTS - Huntsville, AL

NTS - Longmont, CO

NTS - Orlando, FL

NTS - Pittsfield, MA

NTS - Plano, TX

NTS - Tempe, AZ

Pulver Laboratories

VPI Laboratories, Inc.

EuP Directive Compliance

Nemko Norway

NTS - Baltimore, MD

NTS - Chicago, IL

NTS - Silicon Valley Fremont & Newark, CA

GOST R Certification

G&M Compliance, Inc.

Nemko Canada Inc. - Ottawa, ON

Nemko Norway

Nemko USA, East Coast

Nemko USA, Inc.

NTS - Baltimore, MD

NTS - Chicago, IL

NTS - Silicon Valley Fremont & Newark, CA

Green Energy Compliance

CertifiGroup Inc

NTS - Baltimore, MD

NTS - Chicago, IL

GS Mark Certification

Nemko Canada Inc. - Ottawa, ON

Nemko Norway

Nemko USA, East Coast

Nemko USA, Inc.

NTS - Baltimore, MD

NTS - Chicago, IL

NTS - Silicon Valley Fremont & Newark, CA

TÜV Rheinland of North America

Halogen Testing

NTS - Baltimore, MD

NTS - Chicago, IL

Lithium-Ion Battery Testing

CSA Group

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Element Materials Technology - Portland Hillsboro, OR

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Energy Assurance LLC

F2 Labs - Middlefield, OH

ITC India

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NTS - Chicago, IL

NTS - Detroit, MI

NTS - Fullerton, CA

NTS - Plano, TX

Quanta Laboratories

TÜV SÜD America Inc.

Marine Electronics Testing

CertifiGroup Inc

Core Compliance Testing Services

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D.L.S. - Wireless

Green Mountain Electromagnetics, Inc.

Nemko Norway

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NTS - Chicago, IL

NTS - Fullerton, CA

NTS - Plano, TX

R&B Laboratory

Retlif Testing Laboratories

National Recognized Testing Laboratory (NRTL)

Applied Research Laboratories , LLC

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc

CSA Group

Eurofins MET Labs

Nemko Canada Inc. - Ottawa, ON

Nemko USA, Inc.

NTS - Baltimore, MD

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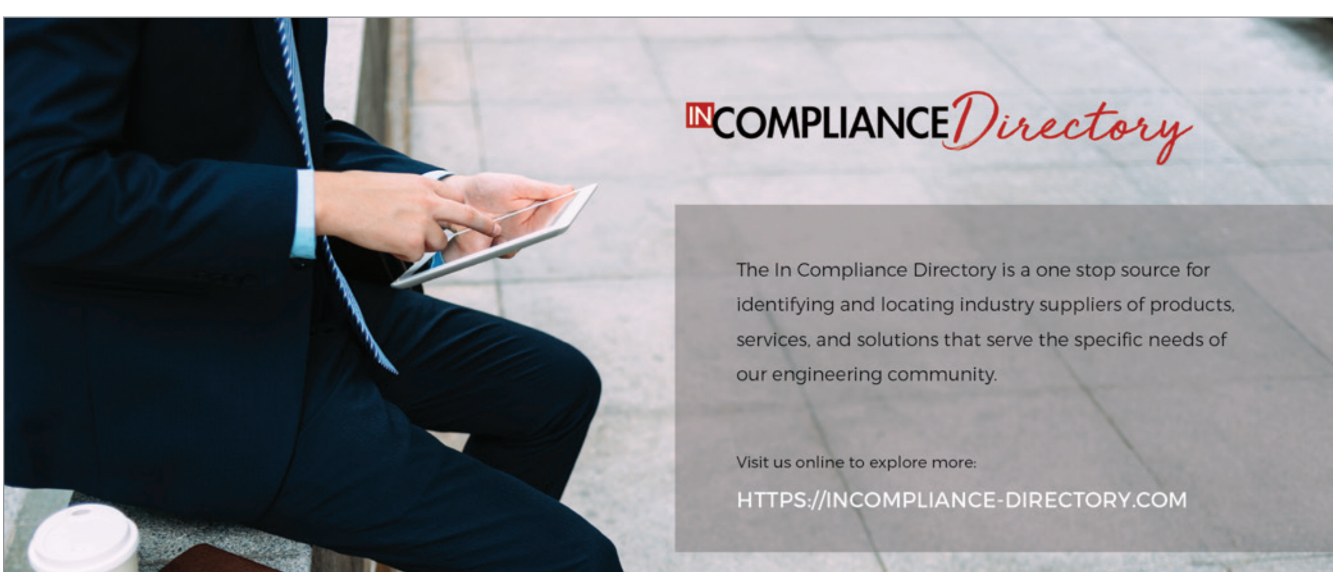


Events

March 1

Understanding ISO/IEC 17025:2017 for Testing & Calibration Laboratories

March 2-4

Fundamentals of Random Vibration and Shock Testing

March 16

Introduction to Measurement Uncertainty

March 22-26

EUCAP 2021 - The 15th European Conference on Antennas and Propagation

March 23-25

EMV 2021

March 31-April 1

R&F Microwave 2021

April 5-9

EMC Week

April 6

Understanding ISO/IEC 17025:2017 for Testing & Calibration Laboratories

April 12

Introduction to Measurement Uncertainty

April 13-14

Advanced Printed Circuit Board Design for EMC+SI

April 13-14

Mechanical Design for EMC

April 13-16

Applying Practical EMI Design & Troubleshooting Techniques

April 22-23

Principles of Electromagnetic Compatibility

May 11

Annual Chicago IEEE EMC MiniSymposium

May 11-14

Applying Practical EMI Design & Troubleshooting Techniques

May 13

EMC Fest 2021

May 17-20

IEEE International Instrumentation & Measurement Technology Conference

May 19-20

EMC & Compliance International 2021 Workshop

June 6-11

International Microwave Symposium (IMS)

June 15-18

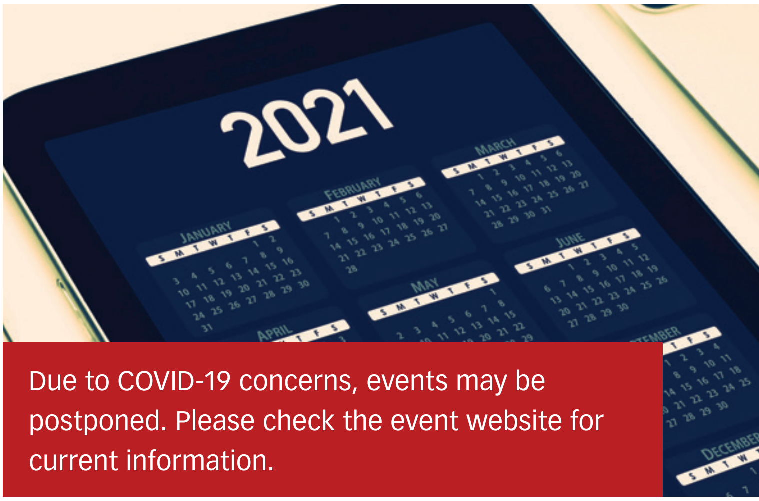
Applying Practical EMI Design & Troubleshooting Techniques

June 26

IEC International Sepcial Committee on Radio Interference (CISPR)

June 28-30

Sensors Expo & Conference



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