OCTOBER 2021

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2022 PRODUCT RESOURCE GUIDE

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FCC Enrolls 4 Million in Emergency Broadband Benefit Program

The U.S. Federal Communications Commission (FCC) has announced that more than four million U.S. households have enrolled in its emergency relief program aimed at providing temporary discounts on internet bills during the COVID-19 pandemic.

Under an Order issued by the FCC, the Emergency Broadband Benefit Program provides qualified consumers discounts of up to $50 per month on their broadband services, as well as a one-time $100 discount on the purchase of a laptop, desktop, or tablet computer from participating providers. The program is being funded by a $3.2 billion allocation initiated by the U.S. Congress earlier this year.

The FCC has engaged in an extensive outreach program to increase awareness about the Program, enlisting over 25,000 community groups and local partners to host localized events to discuss the Program specifics and its benefits.

FCC Warns of Emergency Broadband Program Imposter Website

The U.S. Federal Communications Commission (FCC) is advising consumers of a fraudulent website set up to mimic the FCC's own enrollment site for its Emergency Broadband Benefit Program.

The website purportedly set up and run by "WiFi Freedom USA" falsely claims to administer the FCC's program, and that it can provide consumers with free devices and services under the program.

The FCC's Emergency Broadband Benefit Program (https://www.GetEmergencyBroadband.org) was established earlier this year to provide qualified consumers with discounts of up to $50 per month on their broadband services, as well as a one-time $100 discount on the purchase of a laptop, desktop, or tablet computer from participating providers.

The FCC is encouraging those who may have provided personal information through the WiFi Freedom USA website to visit https://www.IdentityTheft.gov.

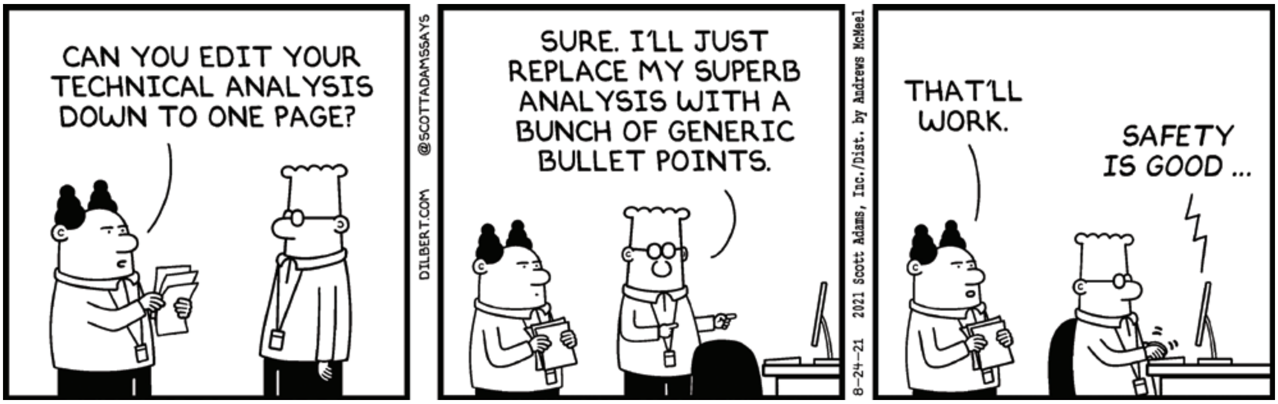
FCC Proposes Largest Robocall Fine Under TCPA

The U.S. Federal Communications Commission (FCC) has proposed a record-breaking fine in connection with what may be seen by many as a politically motivated robocall campaign.

In a Notice of Apparent Liability for Forfeiture, the FCC proposed a fine of $5,134,500 against John Burkman, Jacob Wohl, and J.M. Burkman & Associates LLC for allegedly making more than 1.1 million wireless phone calls without the prior consent of users. The U.S. Telephone Consumer Information Act (TCPA) prohibits making prerecorded voice calls to wireless phones without the express consent of those receiving the calls, regardless of the content of the calls.

According to the Notice, the calls were made between August 26 and September 14, 2020, and featured a prerecorded message telling potential voters that, if they voted by mail, their "personal information will be part of a public database that will be used by police departments to track down old warrants and be used by credit card companies to collect outstanding debts."

Burkman and Wohl, who are reportedly lobbyists and political consultants based in Arlington, VA, were identified by name in the prerecorded messages and Burkman's personal wireless phone number was listed as the calling party on the caller ID of recipients' phones. They also reportedly admitted their involvement in the creation and distribution of the robocalls under oath in a hearing in the U.S. District Court for the Southern District of New York.



A Single Atmospheric Nuclear Explosion Could Take Out Global Power Grids

Recent research provides a far more troubling prognosis of the damage that an EMP attack could cause.

Public awareness regarding the likely hazards associated with the detonation of an electromagnetic pulse (EMP) at high altitudes has been growing in recent years. But recent research provides a far more troubling prognosis of the potential damage that an EMP attack could cause on the global power infrastructure.

According to a recent article in the *IEEE Spectrum*, researchers at the U.S. Geological Survey (USGS) and the University of Colorado are working to better understand the totality of effects that can be created by a high-altitude EMP. The researchers used data collected from sensors and voltmeters deployed in a small region of mid-America, along with USGS research on the impact of magnetic storm disturbances in various regions across the U.S. with either electrically resistive or electrically conductive rock.

The USGS/University of Colorado research yielded some important new information on the varying impacts from a high-altitude EMP event. High-frequency pulses categorized as E1 would likely disrupt consumer electronic products, an aspect that already garners most of the public attention. Separately, electrical systems which are most vulnerable to E2 pulses are a concern, but such systems are increasingly being hardened to withstand E2 effects.

The problem is the E3 waveform, the part of the EMP signal operating at the lowest amplitude. According to the research, E3 pulses last the longest, ranging from about 0.1 seconds to several hundred seconds. This factor, along with the conductivity of the surrounding Earth and the specific parameters of the local electrical grid infrastructure, could lead to catastrophic damage to the power grid in complex geological settings.

As a result of their findings, the USGS/University of Colorado researchers have called for more research to analyze surface impedance across regions like the eastern mid-continent, as well as the eastern U.S. where the impact from magnetic storms is significant.

FCC Published Interactive Mobile Broadband Map

As part of its effort to promote widespread access to mobile broadband capabilities in the U.S., the Federal Communications Commission (FCC) has published a first-of-its-kind interactive map showing mobile broadband coverage available from the country's largest wireless providers.

The FCC's new interactive mobile broadband map allows consumers to determine access to mobile broadband voice and data services in their immediate geographic area (down to individual street addresses!), and to identify providers providing mobile broadband services in that area. The map is based on data collected under standards set by the federal Broadband DATA Act, which mandated the FCC to adopt specific data collection, verification, and reporting protocols.

Currently, the mobile broadband map shows coverage for AT&T Mobility, T-Mobile, US Cellular, and Verizon, companies which voluntarily submitted their coverage data to the FCC. The FCC's Broadband Data Task Force is also encouraging other wireless carriers to share their standardized data for inclusion in the mobile broadband map.

FDA Offers Online Tracker for Premarket Submissions

The U.S. Food and Drug Administration (FDA) now has a secure web-based tracking system to help companies track the progress of the agency's review of their 510(k) submissions.

The FDA's Premarket Submission's Progress Tracker currently allows a medical device manufacturer to access up-to-date information on the status of traditional 510(k) submissions, which represent the most common type of device applications submitted to the FDA for review. Access to the Progress Tracker is limited to the "Official Correspondent" identified in the original submission, who will automatically receive an email with instructions on accessing the Tracker once the FDA has started its review of the submission.

ARRL Offers RF Exposure Calculators to Amateurs

The ARRL has developed an online calculator that will allow radio amateurs to evaluate the level of radiofrequency (RF) effects emanating from their equipment.

The ARRL's RF exposure calculator allows users to simply enter the transmit peak-envelope power (PEP) and operating mode of their radio systems and antennas, along with estimates about the maximum amount of transmission time. The exposure calculator then determines the minimum distances that people must maintain from this equipment to minimize their exposure to potentially harmful RF effects.

The ARRL says that its RF exposure calculator is intended to assist amateurs in the routine evaluations of RF exposure to help ensure that their systems and equipment comply with RF exposure rules mandated by the U.S. Federal Communications Commission (FCC).

FDA Releases Discussion Paper on Medical Device Cybersecurity Challenges

The U.S. Food and Drug Administration (FDA) has released a discussion paper on specific cybersecurity practices related to the servicing of medical devices.

The discussion paper, "Strengthening Cybersecurity Practices Associated with Servicing of Medical Devices: Challenges and Opportunities," considers cybersecurity issues that are unique to the repair or routine maintenance servicing of a finished medical device. Specific cybersecurity aspects addressed in the paper include 1) privileged access; 2) identification of cybersecurity vulnerabilities and incidents; 3) prevention and mitigation of cybersecurity vulnerabilities; and 4) product lifecycle challenges and opportunities.

The paper is part of the FDA's "total product lifecycle (TPLC)" approach to strengthening the overall cybersecurity of medical devices.

HENRY OTT 1936-2021

With deep sadness, we share news of the passing of a dear friend and honored colleague, Mr. Henry W. Ott, on May 20, 2021, in Livingston, NJ.

Henry was known by many as the nation's leading educator in Electromagnetic Compatibility design and engineering. You may have even had the good fortune to attend his class, where he got down to brass tacks and helped you develop a deep understanding of EMC engineering.

Henry earned his B.S. in electrical engineering from New Jersey Institute of Technology in 1957 and his M.S. in electrical engineering from New York University in 1963. He served three years in the U.S. Air Force, Air Research and Development Command, and served as a member of the technical staff of Bell Telephone Laboratories for 30 years. In 1970, he originated a continuing education course in noise reduction at Bell Laboratories. Henry established Henry Ott Consultants, his well-respected EMC/ESD training and consulting organization, and went on to train thousands of engineers throughout his career.

Henry was a member of the IEEE, IEEE Communications Society, and the IEEE Electromagnetic Compatibility Society. He was a distinguished lecturer and published numerous technical articles, authored two well-known textbooks, "Electromagnetic Compatibility Engineering" (Wiley, 2009) and the iconic "Noise Reduction Techniques in Electronic Systems" (Wiley 1976 and 1988), of which together have sold over 65,000 copies. Henry also held two patents with the USPTO. Henry was always willing to take the time to discuss technical matters and to share his knowledge and experience of this highly specialized profession with other engineers.

Henry's devotion to learning from and educating engineers will always be a shared point of connection between us. In fact, it served as the cornerstone of our partnership. In 2011, the In Compliance team proudly had the honor to begin working with Henry to bring his teachings to the public with bi-annual seminars across the country. For the next six years, we worked

closely together as we prepared for, traveled to, and co-hosted one of the most sought-after engineering courses. Henry's ability to convey the most complex principles in the simplest form and the opportunity for other engineering professionals to have access to his wealth of knowledge earned him a packed house with a waiting list almost every year.

We watched Henry impart his wisdom and serve as a mentor to hundreds of engineers facing uniquely common EMC challenges. His contributions to the engineering community are so well regarded that he was indeed considered an EMC celebrity. Although he would, most likely, modestly tell you he just happened to be in the right place at the right time, we served witness to many students and tradeshow attendees seeking out his signature.

Henry was a kind, intelligent, bright star in the EMC community, and we were made better for having known him.

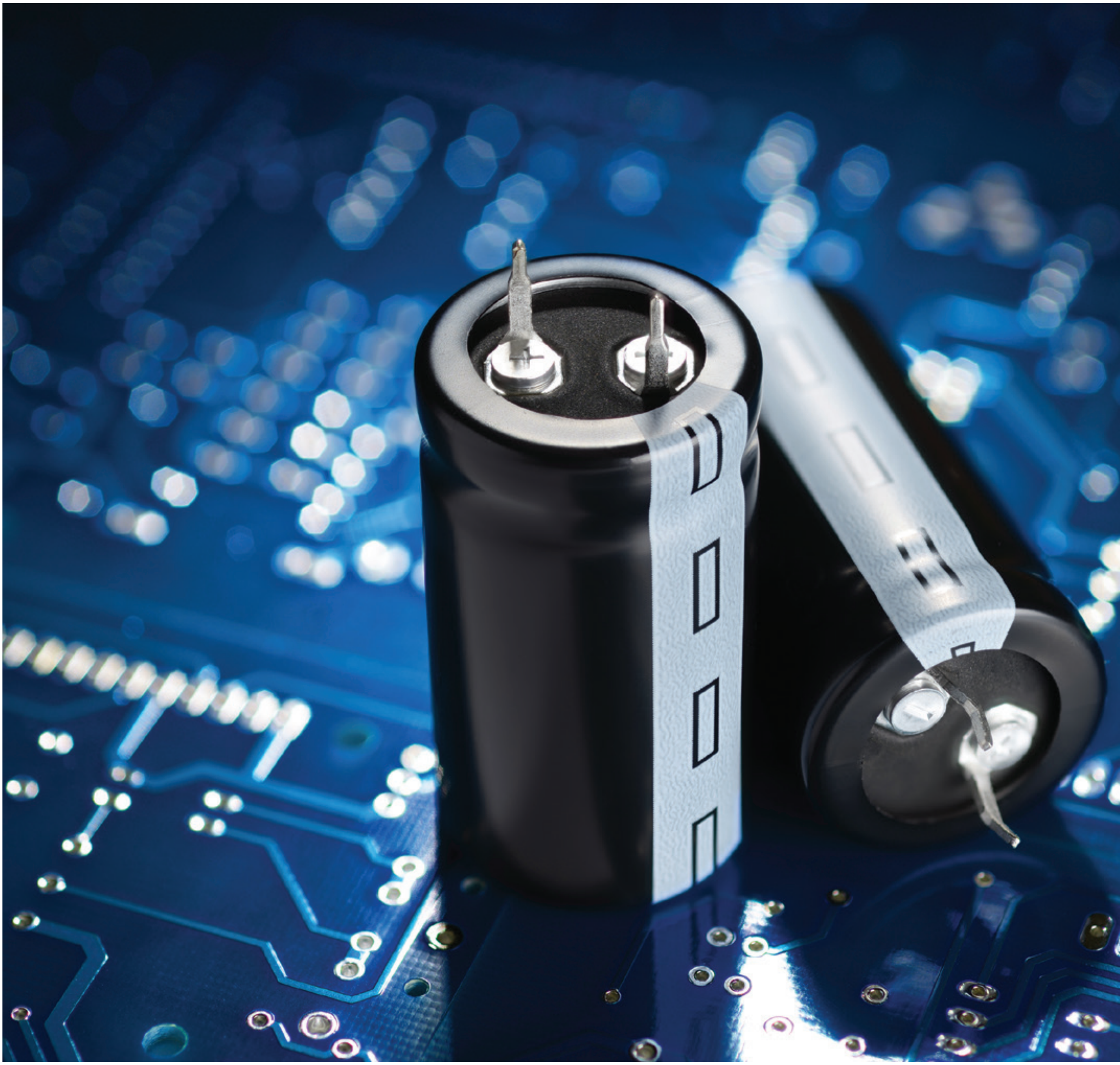
Cheers, Henry, to another successful chapter well done.

Until we meet again,

Lorie, Sharon, Erin, Ashleigh, and Alexis

CAPACITORS: THEORY AND APPLICATION

Capacitor Design Techniques for EMC



Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd, a UK-based engineering firm that specializes in EMC consulting, troubleshooting, and training. His in-depth knowledge in power electronics, digital electronics, electric machines, and product design has been benefitting companies worldwide. Zhang can be reached at info@mach1desgin.co.uk.

By Min Zhang

Capacitors are among the most commonly used components on a circuit board. With the ever-increasing number of electronics devices (from mobile phones to cars), there has been a growing demand for capacitors. Covid 19 pandemic has disrupted the global supply chain of components from semiconductors to passive components, and capacitors have been in short supply[1].

A discussion on the subject of capacitors could easily become a book or a dictionary. To start with, there are different types of capacitors such as electrolytic, film, ceramic capacitors, and so on. Then, within the same type, there are different dielectric materials. There are also different classes. As for physical construction, there are two-terminal and three-terminal capacitor types. There's also an X2Y type capacitor which essentially is a pair of Y-capacitors packaged in one[2]. What about supercapacitors? The fact is, if you sit down and start reading the capacitor selection guide of major manufacturers, you could easily spend a day!

Since this article is about fundamentals, I will use a different approach as I would normally do. As mentioned before, a capacitors selection guide can be easily found with supplier websites[3,4] and field engineers can often answer most of the questions about capacitors. In this article, rather than repeating what you can find on the internet, I will use practical examples to demonstrate how to select and use capacitors. Some lesser-known aspects of capacitor selection, such as capacitance degradation, will also be covered. After reading this article, you should have a good sense of using capacitors.

But first, let's answer the most fundamental question, what is a capacitor?

A CAPACITOR FROM THE FIELD THEORY POINT OF VIEW

Years ago, when I was working for a company making electronics devices, we had an interview question for power electronics engineers. On the schematics of an existing product, we would ask the potential candidates "What is the function of the DC link electrolytic capacitor?" and "What is the function of a ceramic capacitor that is located next to a chip?" We would expect the correct answer to be that the DC link capacitor is used for energy storage and the ceramic capacitor is used for filtering.

The "correct" answers we were seeking actually showed that everyone in the design team viewed a capacitor from the simple circuit point of view, not from the field theory. There's nothing wrong with the circuit theory viewpoint. At low frequency (from a few kHz to a few MHz), circuit theory often explains things very well. This is because, at lower frequencies, signals are predominantly in differential mode. Using circuit theory, we can view a capacitor as that shown in Figure 1 on page 12, with an equivalent series resistor (ESR) and an equivalent series inductor (ESL) causing the impedance of the capacitor to change with frequency.

This model explains the circuit performance adequately when the circuit switches slowly. However, as frequency goes up, things are becoming much more complex. At some point, components start showing nonlinearities. A simple L-C-R model has its limits when frequency increases.

Today, if I were asked the same interview questions, I would put my field theory viewing glasses on and say both capacitor types are energy storage devices. The difference is that an electrolytic capacitor can store much more energy than a ceramic capacitor. But when

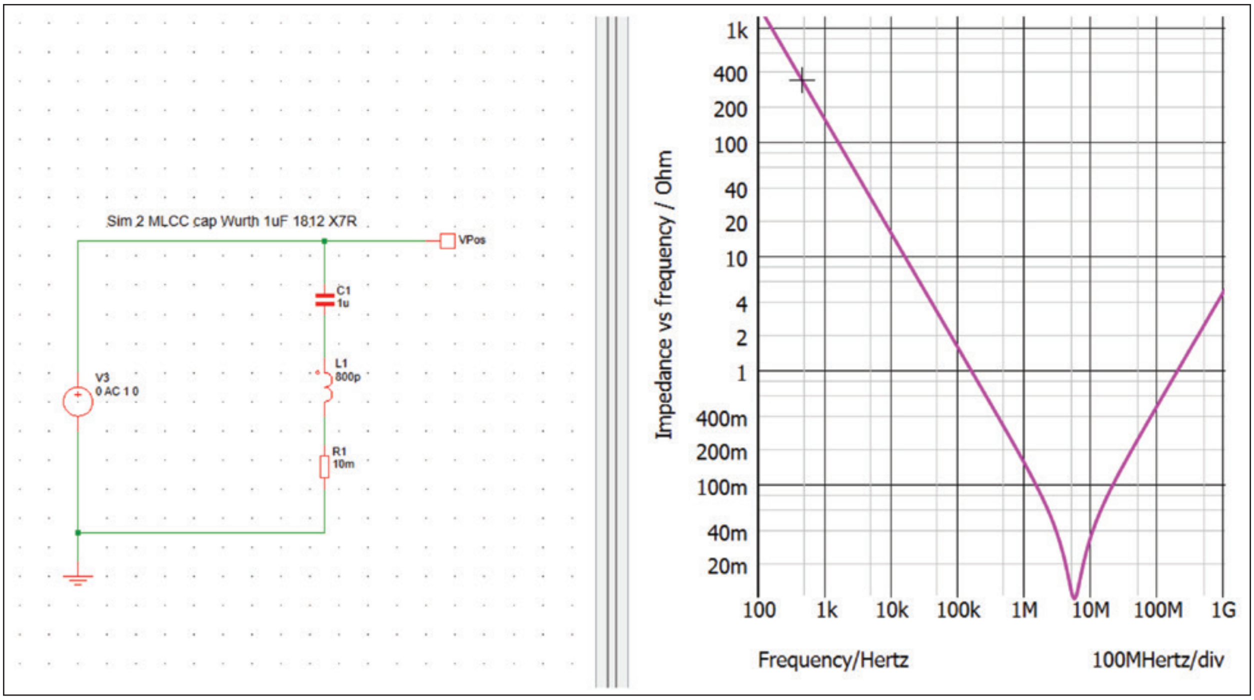


Figure 1: Spice model of an equivalent circuit of a ceramic capacitor and its impedance curve

it comes to energy delivery, a ceramic capacitor can deliver the energy much more quickly. This explains why ceramic capacitors need to be located next to the chip because a chip has a much higher switching frequency and switching speed compared to the main power circuit.

From this viewpoint, we can simply define two performance criteria for a capacitor. One is how much energy a capacitor can store, the other is how quickly can this energy be delivered. Both depend on how a capacitor is made, the dielectric materials, the connection to the capacitor, and more.

When a switch is closed in a circuit (see Figure 2), it indicates that the load demands energy from the source. How fast this switch closes determines the urgency of the energy demand. As energy travels at the speed of light (half of this speed in an FR4 material), it takes time for the energy to be delivered. Besides, there's an impedance mismatch between the source and the transmission line, and with the load as well. This means energy is never delivered in one trip but over many round trips[5] and this is why, when a switch is switched fast, we see delay and ringing in the switching waveform.

The fact that energy delivery takes time and many round trips tells us we need to locate the energy source as close as we can to the load, and we need to find

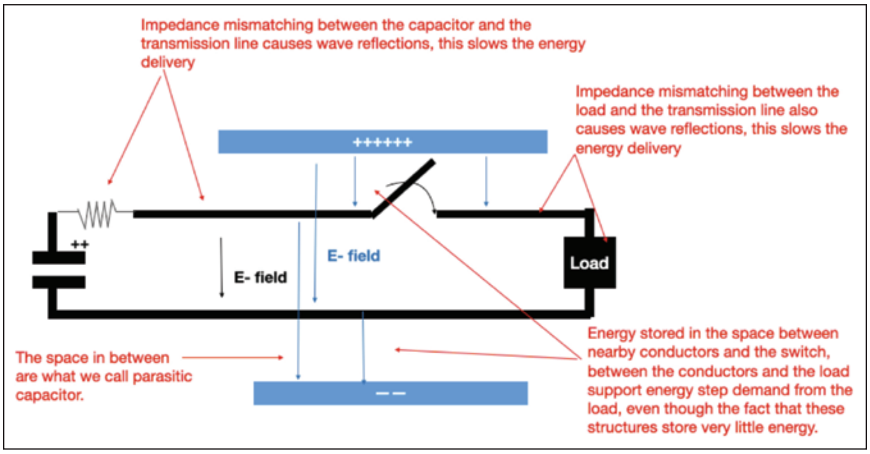


Figure 2: Energy travels in space and it takes time; impedance mismatch causes multiple round trips of energy delivery.

ways of delivering it fast. The first is often achieved by reducing the physical distance between the load, the switch, and the capacitor. The latter is achieved by clustering a group of capacitors with minimum impedance.

The field theory also explains what causes the common-mode noise. Simply put, the common-mode noise is created when a load's demand for energy is not satisfied at the instance when the switch is switched. As a result, energy stored in the space between the load and nearby conductors will be supplied to support the step demand. The space between the load and nearby conductors is what we call a parasitic/mutual capacitor (see Figure 2).

We use the following examples to demonstrate how to use electrolytic capacitors, multi-layer ceramic capacitors (MLCCs), and film capacitors. Both circuit and field theories are used to explain the performance of the selected capacitors.

ELECTROLYTIC CAPACITORS

Electrolytic capacitors are mostly used in a DC link as the prime energy source. The selection of electrolytic capacitors often depends on:

1. Capacitance value, as this often determines the very low-frequency ripple of the circuit;
2. ESR and ESL, as this determines the differential-mode noise ripple on the capacitor;
3. Temperature, as it can affect the ESR of the capacitor (in this case, the higher the temperature, the lower the ESR as the ESR is a result of the chemical reaction of the capacitor);
4. Aging is an important factor to consider since the capacitance value can be significantly reduced due to temperature, humidity, stress, etc.; and
5. Leakage current.

For EMC performance, the most important feature of a capacitor is the impedance versus frequency characteristics. Low frequency conducted emissions always depend on how good the DC link capacitor is.

The impedance of the DC link depends not only on the ESR and ESL of the capacitors but also on the hot loop area as illustrated in Figure 3. A larger hot loop area means energy delivery takes longer, hence the performance is compromised.

A step-down DC-DC converter was set up to demonstrate the point. A pre-compliance EMC test set-up shown in Figure 4 performs the conducted emission sweep between 150kHz and 108MHz.

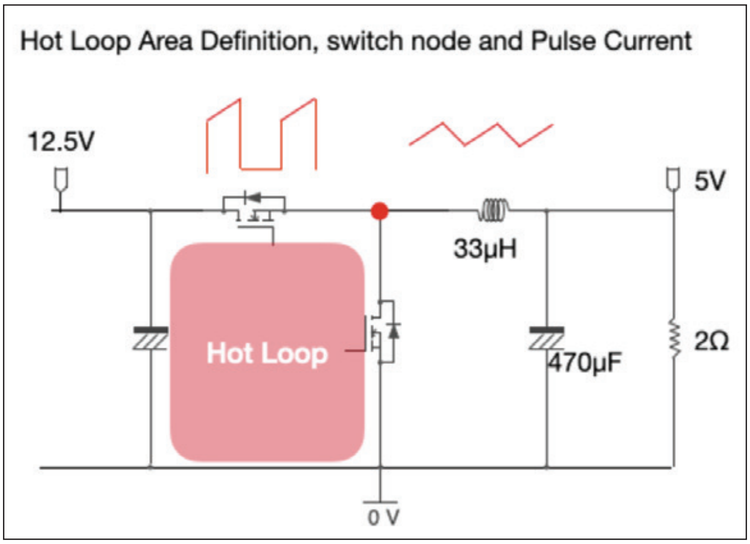


Figure 3: Hot loop area in a DC-DC converter

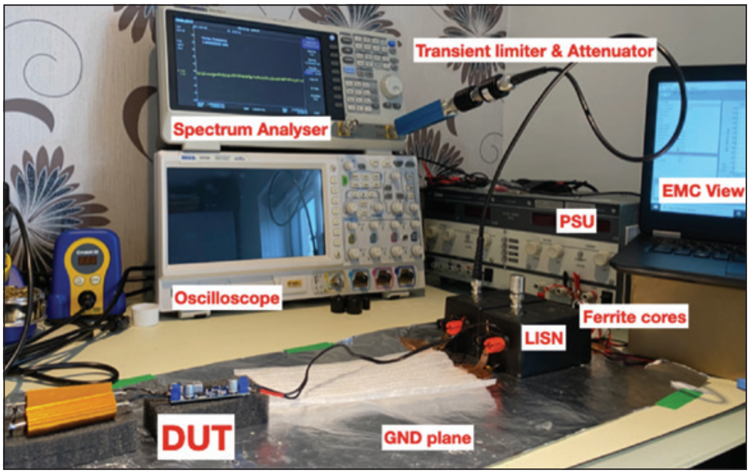


Figure 4: Bench pre-compliance conducted emission test set-up for the device under test

Three configurations for the input capacitors were tested:

1. One 680 µF surface mount electrolytic capacitor;
2. Two 330 µF surface mount electrolytic capacitors in parallel; and
3. Two 330 µF surface mount electrolytic capacitors in parallel, with one capacitor moved closer to the switch side.

It is important to make sure that the capacitors used in this case study were all from the same manufacturer to avoid impedance characteristics differences. When soldering the capacitor on the PCB, make sure there are no long leads as this will increase the ESL of the capacitor. Figure 5 shows the three configurations.

The conducted emission results of these three configurations are shown in Figure 6. As it can be seen, two 330 µF capacitors achieve 6 dB noise reduction performance across a wide frequency range compared with a single 680 µF capacitor.

From the circuit theory, one can say that, by having two capacitors in parallel, both ESL and ESR are halved. From the field theory, rather than having one energy source, two energy sources supplied to the same load effectively reduce the overall energy delivery time. However, at higher frequencies, the difference between two 330 µF capacitors and one 680 µF capacitor narrows. This is because high-frequency noise indicates an insufficient step energy response. When moving one 330 µF capacitor closer to the switch, we reduce the energy delivery time, this effectively increases the step response of the capacitor.

The results tell us a very important lesson. Increasing the capacitance of a single capacitor will not usually support the step demand for more energy. If possible, use a few smaller capacitance components. There are many good reasons for doing so. First is the cost. Generally speaking, the cost of capacitors increases exponentially with capacitance value for the same package size. Using one single capacitor is perhaps more expensive than using a few smaller capacitors. The second reason is the size. The limiting factor for a product design is often the height of a component. For capacitors with large capacitance, the height is often too big to be fit in the product design. The third reason is the EMC performance as we have seen in our case study.

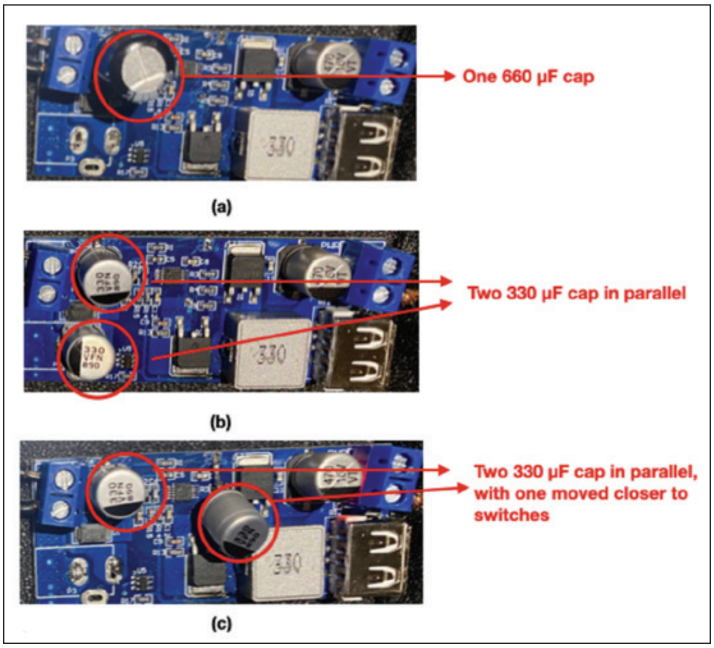


Figure 5: Three configurations for input capacitors

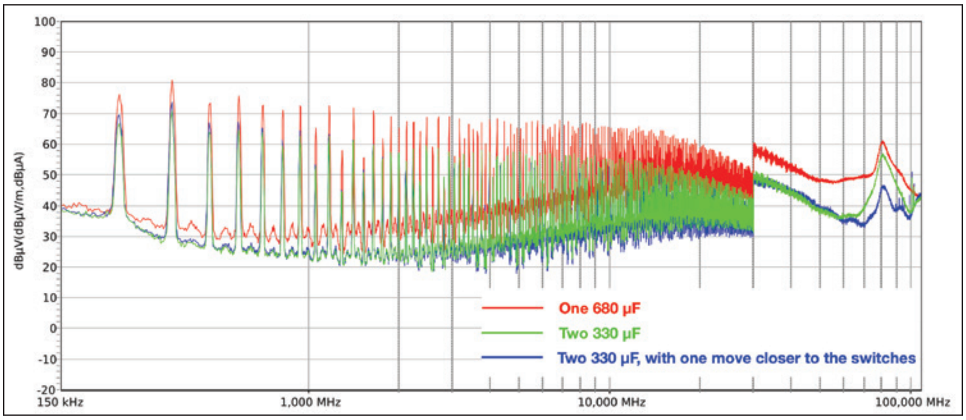


Figure 6: Conducted emission test results of three different capacitor configurations

Another factor to consider when using electrolytic capacitors is that balancing resistors will be needed when you put two capacitors in series to share voltage[6].

MULTI-LAYER CERAMIC CAPACITORS (MLCCS)

As explained before, ceramic capacitors are tiny devices that can deliver energy fast. I often get asked the question "How much capacitance do I need?". The answer to this question is that for ceramic capacitors, the capacitance value shouldn't matter that much. The important consideration here is to work out at which frequency the speed of the energy delivery would be sufficient for your application. If a conducted emission failed at 100 MHz, then a capacitor that has the least impedance at 100 MHz would be a good option.

Here's another misconception of MLCCs. I have seen engineers spend great effort selecting a ceramic capacitor with the least ESR and ESL, only to then connect the capacitor to the RF reference point via a long trace. It is worth knowing that the ESL of an MLCC is generally much lower than the connection inductances on the board. The connection inductance remains the single most important parameter affecting the high-frequency impedance of ceramic capacitors[7].

A bad example of this is shown in Figure 7 on page 16. The long trace (0.5 inch long) introduces at least 10nH inductance. Simulation results show that the impedance of the capacitor becomes a lot higher at the frequency point (50 MHz) than is intended.

One of the problems with MLCCs is that they tend to resonate with the inductive structures on the board. This can be seen in the example shown in Figure 8 on page 16, in which the use of a 10 µF MLCC introduces a resonance at about 300 kHz.

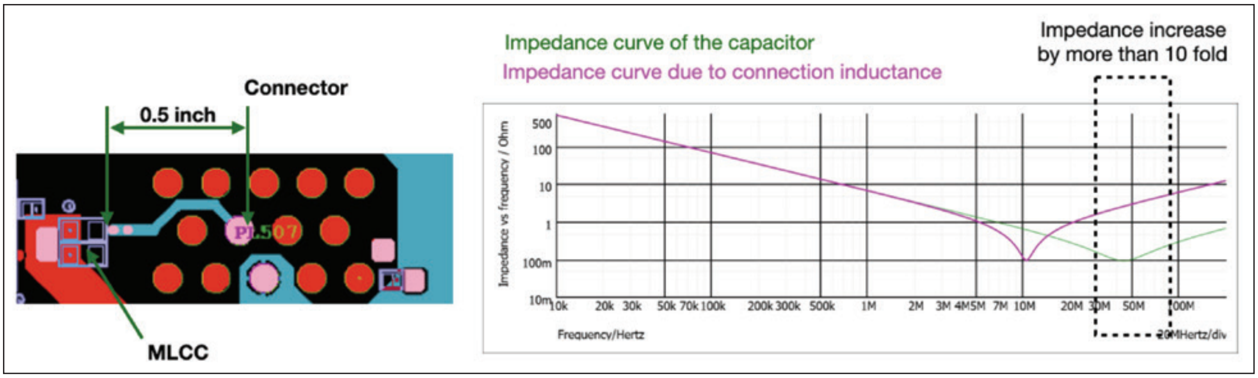


Figure 7: Long trace to the MLCC connection increases inductance

You can reduce the resonance by including select parts that have larger ESR, or by simply putting a small value resistor (like one ohm) in series with the capacitor. Such methods use lossy components to damp the system. Another way is to use another capacitance value to shift the resonance either to a lower or a higher resonance point.

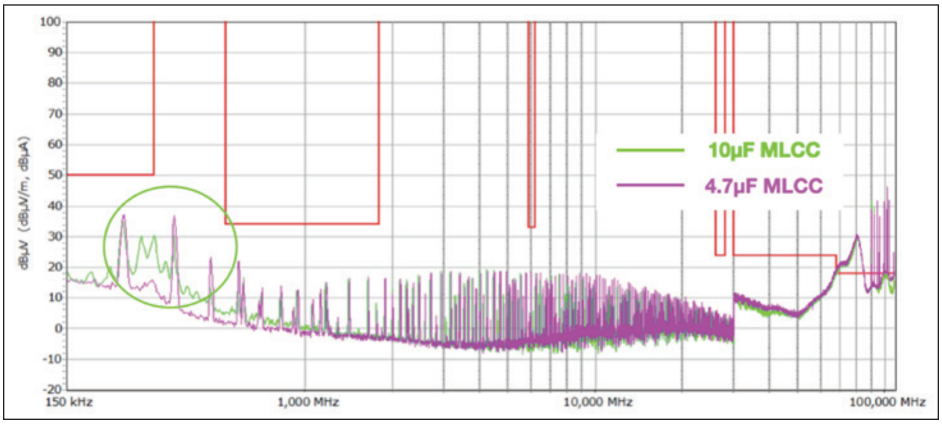


Figure 8: A 10 μF MLCC introduced a resonance at 300 kHz

FILM CAPACITORS

Film capacitors are used in many applications. They are the capacitors of choice for high-power DC-DC converters and are used as EMI suppression filters across the supply lines (both AC and DC), as well as in common-mode filtering configurations. We use an X capacitor as an example to demonstrate some of the key points of using film capacitors.

Generally, an X capacitor performs the following functions:

1. Attenuates the conducted noise directly from any switching events on the lines (for instance, a Triac device switching the mains AC line);
2. Together with an inductor, it forms a low pass filter for differential mode noise appearing on the lines; and
3. It helps limit the peak voltage stress on the lines if there is a surge event, so it is often used together with a transient voltage suppressor (TVS) or metal oxide varistor (MOV).

You probably already know all of these, but do you know the capacitance value of an X capacitor can be reduced significantly over years of service? This is particularly true if the capacitor is used in a humid environment. I have seen cases where an X capacitor's capacitance value dropped to only a few percentages of its rated value in a year or two, so the system initially designed with X capacitor effectively lost all the protections that a front-end capacitor could have.

So, what has been happening? Damp air can leak into the capacitor, up the wires, and between the box and the epoxy potting compound. The aluminium metallization can then oxidize. Aluminium oxide is a good electrical insulator, thereby reducing the capacitance. That's one problem all film capacitors can have. The problem I was talking about was the film thickness. Reputable capacitor brands use a thicker film, resulting in a larger capacitor than other brands. The thinner film makes the capacitor less robust to overload (voltage, current, or temperature) and less likely to self-heal as well.

If the X capacitor is not permanently connected to the supply, then you have less concern. For instance, for a product that has a hard switch between the mains and the capacitor, size is probably more important than lifetime and you can then choose a thinner capacitor. However, if the capacitor is permanently connected to the supply, then it must be highly reliable. Oxidation of capacitors is not inevitable. If the capacitor epoxy material is of good quality and the capacitor is not routinely exposed to temperature extremes, value degradation should be minimal.

CONCLUSION

In this article, a field theory view of capacitors was first presented. Practical examples and simulation results demonstrate how to select and use the most common types of capacitors. Hopefully, this information will help you develop a more complete understanding of the role that capacitors play in electronics and EMC design.

ACKNOWLEDGMENT

The author would like to thank Mr. Steve Berry for his technical support on this subject.

ENDNOTES

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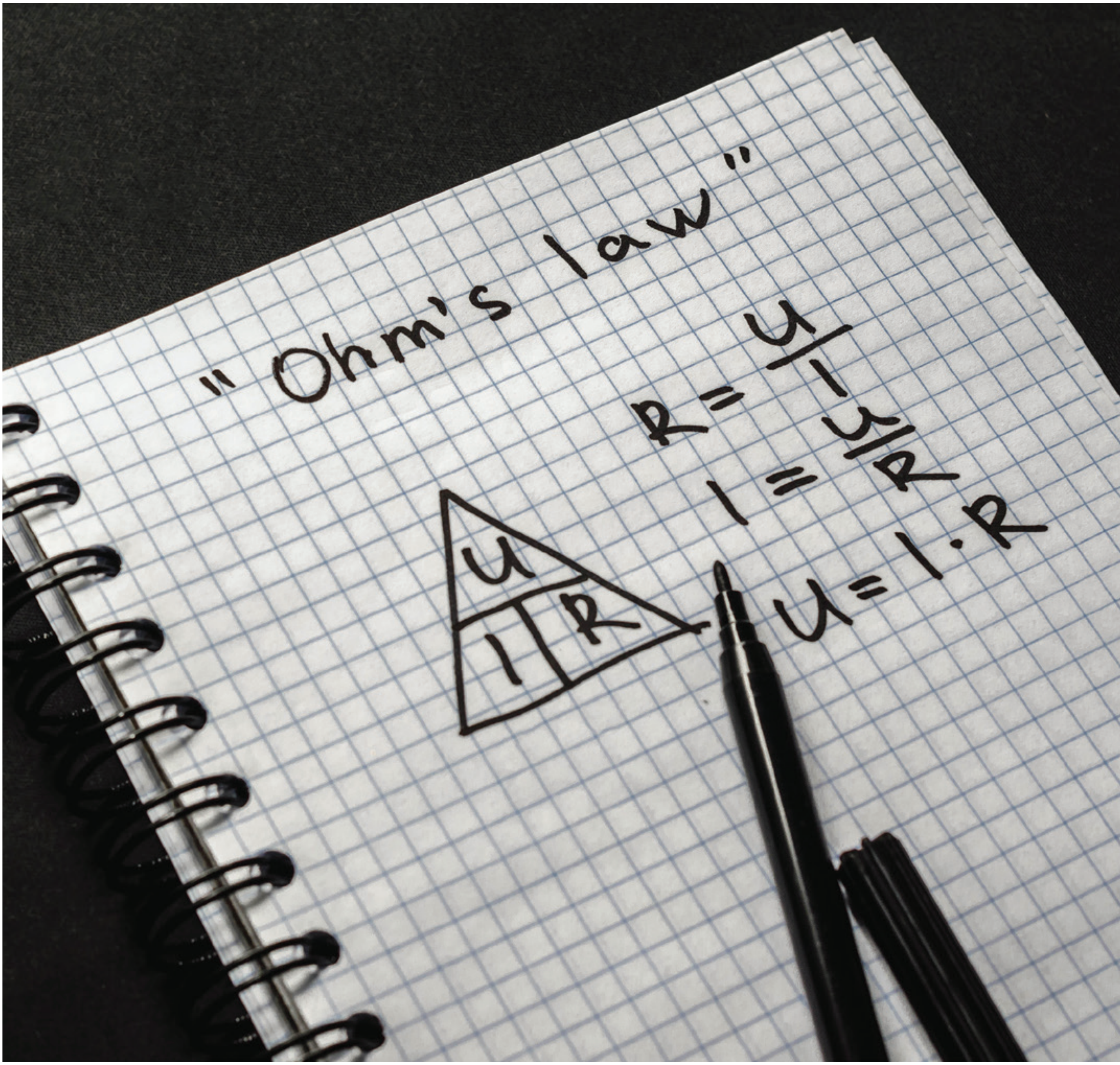
OHM'S LAW ALSO APPLIES TO ESD-INDUCED HEAT PULSES

Using Accessible Math and Computer Tools to Solve Heat Flow Problems



Timothy J. Maloney is a Fellow of the IEEE and the co-author of the book *Basic ESD and I/O Design* (Wiley, 1998). Maloney spent much of his 40-plus year career as a Senior Principal Engineer at Intel Corporation and has made numerous presentations at the annual EOS/ESD Symposia and other IEEE conferences. He can be reached at tjmaloney@sbcglobal.net.

By Timothy J. Maloney

One early contributor to semiconductor ESD research was Jack Smith of Lockheed, who was fond of stating that all ESD damage is, in the end, thermal [1]. This is because there is always conversion of electrical field energy into heat, into mechanical motion of atoms. Even in the case of voltage overstress, field energy knocks atoms out of place at defect sites, thus linking field energy to the heat equation on a microscopic scale at least.

Jack liked to start a presentation on, say, metal heating with a universal equation (Figure 1) and go from there to specific cases.

In this article, our approach will be to examine some ESD heating cases where the analysis becomes simple enough to derive significant insight and overview, without necessarily going into an extensive calculation or computer simulation. Indeed, we'll refer to some computer simulation work that was done with much-increased efficiency due to those insights.

The first thing to simplify in the general EOS/ESD equation is the 3-dimensional ∇^2 term; we'd like to find effectively 1-dimensional (1-D) cases where that term becomes a double derivative, spatially. The power input for EOS/ESD is commonly some kind of I^2R heating, so this is becoming manageable when we have a power input expression for a source at x=0.

Let's say it's an infinite planar source, units are per unit area. For 1D heating, the temperature of most interest in ESD is the highest, the surface temperature, a scalar number at the heat source, x=0. If there is a critical temperature for ESD failure, we're well on the way to calculating conditions for reaching it.

If this all sounds familiar, it is because we have just described the conditions for the famous Wunsch-Bell study of 1968 [2], the paper that showed a $t^{-1/2}$ relation between power to failure and pulse width t, using idealized 1-D heating of an infinite slab, and critical temperature Tc as a failure criterion. Semiconductor devices were fairly new at the time, and it was appropriate to apply some basic heat flow theory to the concept of an ESD zap causing a uniform heat pulse at a semiconductor surface.

The very same physics as described by [2] is embodied in the 1D RC transmission line, as I've described in [3, 4], whereby electrical quantities like V are analogous to T, I to power P, specific heat C_p to capacitance C, and thermal conductivity k to resistance R. Figure 2 is from [3, 4], where a transmission line is shown shorted at its far end, simulating a perfect heat sink. The Wunsch-Bell (W-B) treatment of [2] is for an infinitely long line,

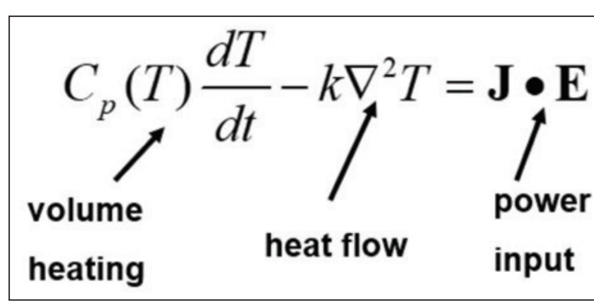


Figure 1: General EOS/ESD equation, where C_p=specific heat, k=thermal conductivity, J=vector current density, E=vector electric field, T=temperature

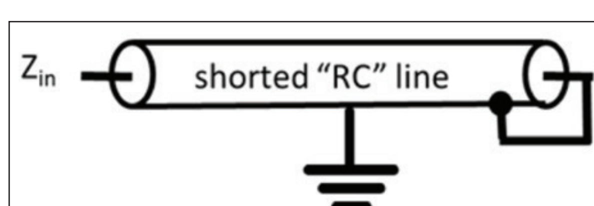


Figure 2: Shorted R-C line, simulating a heat slab above a heat sink, from [3]

or for a terminated line at short time, i.e., heat diffusion length that is very short compared to its electrical length.

Make no mistake; the RC transmission line being analogous to heat flow and vice versa goes all the way back to the 19th century, even before J.C. Maxwell's 1865 electromagnetics breakthrough. Early telegraph lines were thought to behave in accordance with heat flow equations and, of course, they do if signals are slow and inductive effects can be overlooked—in heat flow, there is no analogous magnetic effect. In the late 19th century, this was the source of much disbelief and consternation among telegraphy engineers even at the highest level, as described in accounts of the contributions of Oliver Heaviside [5].

By the early 20th century, things had settled down, and transmission lines were seen to be all of a piece, with or without inductance. Expressions for, say, Z_{in} of Figure 2 in the frequency and time domains were well accepted, with the understanding that Fourier/Laplace transforms and their inverses, plus the convolution theorem, help one to go back and forth between time and frequency domains.

The beginning student in electrical engineering may know little more about electricity than Ohm's Law, V=IR, but soon finds, in introductory courses, that it becomes generalized, with complex numbers applying to impedances (beginning with inductors and capacitors) as well as to voltage and current signals. Our student quickly learns that the generalized V=IZ, with multiplication, applies only to the complex frequency domain, as in V(s)=I(s)Z(s), where s=s+jw. Conversion to time domain requires transforms and multiplication is replaced by convolution, as in $V(t)=I(t)\otimes Z(t)$ or $V(t)=I(t)*Z(t)$, the notorious "sliding integral."

At this point, many students wish for a future full of simple resistors, able to migrate without difficulty between time and frequency domains. The mathematical treatment of an impedance with a time-dependent response can be challenging—also, there is well-meaning learning material on the internet with careless or incorrect statements about impedance and time/frequency domain. No, you will not see a reference to such misinformation here, given the influence of references on search engines. Just beware.

Now we are well-equipped to find surface temperature waveforms given the power input into a structure represented by Figure 2, where $Z_{in}(s)= Z_0(s)\tanh(\tau s)$, τ the line length, infinite for W-B conditions. Thus, the tanh factor becomes one for W-B, in which case we are left with $Z_0(s)$. Transmission line characteristic impedance for the general RLGC line is well known to be:

$$Z_0(s) = \sqrt{\frac{R+Ls}{G+Cs}} \quad (1),$$

But for our RC line, G=L=0, and therefore:

$$Z_0(s) = \sqrt{\frac{R}{Cs}} \quad . (2)$$

Thus, if the power input P(s) (resembling current I(s)) is a step function going as 1/s, finding the temperature (resembling voltage) waveform T(t) from T(s) means looking up the inverse Laplace Transform of $s^{-3/2}$, going as $t^{1/2}$. Thus, for a critical temperature Tc, the time to failure for a given input power P_0 goes as $t^{-1/2}$, the W-B result.

This simple and lucid way of reaching the W-B result through Laplace Transforms was overlooked by the authors of [2] although the attractiveness of Laplace methods for heat flow problems was documented in renowned texts much earlier, for example in Carslaw and Jaeger [6]. Even [6] can be annoying in its reluctance to use the Laplace method to show how simple problems, such as the above, become even simpler, preferring to reserve the Laplace method for very difficult heat flow cases. That choice may have made more sense in 1959 and earlier, when [6] was published in a world where we had fewer engineers versed in network theory who needed to know about heat flow. But once the Laplace "infrastructure" is available in one's mind from other studies, it is an attractive way to treat these heat problems.

If the heat slab is infinitely deep and the line in Figure 2 is infinitely long, the W-B result of a $t^{1/2}$ waveform means that T(t) increases without limit if constant power P_0 is continuously applied. But a resistive termination or short, as shown in Figure 2, means that a steady state is reached at some time scale, and the structure behaves like a constant thermal resistance (more precisely, conductance per unit area) to ground. This means that as the $P_0(t)$ pulse lengthens, the time to failure flattens out, as in Figure 3.

The complete curve is called the Dwyer curve, after a lead author who described it over 30 years ago [7, 8]. The transition from W-B region to a flat curve has been described in various ways, but my approach in 2016 [3, 4] was to invert the complete $Z_{in}(s)$ function in tanh form, as above, into the time domain. The result is a

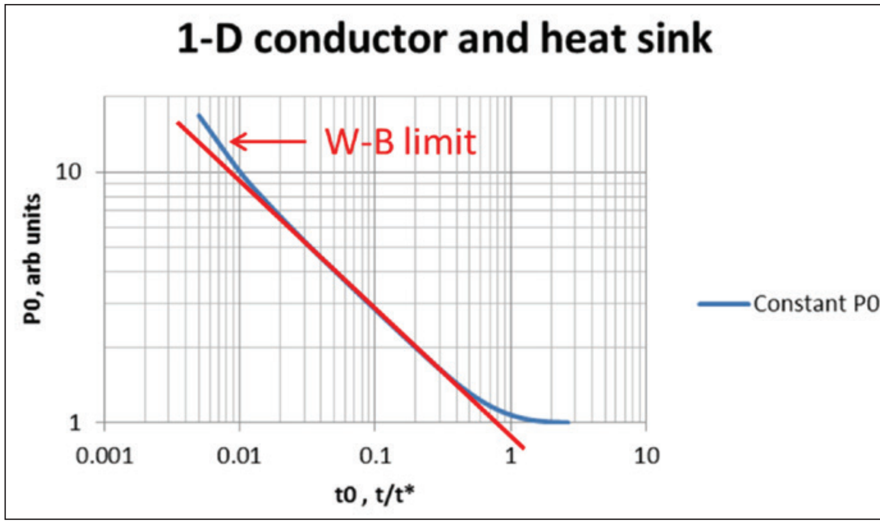


Figure 3: Dwyer curve [7. 8], blue, in log-log plot for normalized units, as derived from the shorted t-line model in Figure 2. Wunsch-Bell limit of t $^{-1/2}$ is seen at short times. Red line represents a way to find time scaling constant t* from plotted data, intercepting the flat-line level at 0.79t*.

smooth function (a centuries-old theta function due to Jacobi) with the expected asymptotic limits. This is a fine "discovery" if your situation really is close to a 1D heat slab with a heat sink underneath—not always the case. Still, if you need a smooth curve and a single time constant t* to characterize the depth of the semiconductor and flattening of the curve, this can work, as shown in [3, 4].

I'll close this article by summarizing some work done on integrated circuit metal heating during ESD, considering defined pulsed currents, self-heating of the metal due to positive temperature coefficient of resistance (TCR, or tempco), with attendant feedback effects on the power function $P_0(s) \Leftrightarrow P_0(t)$ and then the final waveform T(t).

Publications appeared at IRPS in 2013 and 2016 [9, 10], in which the heart of the analysis was the metal self-heating feedback situation as shown in Figure 4, from [10]. The objective was to find an efficient way to arrive at ESD design rules for metal cross-section given that standardized waveforms I(t) for the human body model (HBM) and charged device model (CDM) would be applied to the IC pins. As the power input is TCR and feedback-dependent, we had to arrive at self-consistent power and temperature functions.

These studies benefited from finite element modeling (FEM) of the temperature response to a heating step applied to a length of metal, embedded in a "typical" array of other metal lines, oxides, dummies, etc., in accordance with design rules. With that data, we have a step response, and thus an impulse response, to heat input that gives us Z(t) and, implicitly Z(s). Convolution in the time domain is done (with plugin Excel tools) to reach a self-consistent output temperature waveform T(t)—fortunately, convergence is fast.

The studies are aimed at formulating ESD design rules for IC metal at various metal levels in the on-chip stack, so we input the anticipated current waveforms for HBM and CDM and find conditions for staying below a critical peak temperature for the ESD test goal. FEM electrothermal sims are capable of incorporating the test current waveform and metal properties to give a T(t) waveform as well, but once we get going with the feedback model, FEM can be reserved for cross-checks and fine-tuning of Z(t) for a given metal layer.

Process corners and variations can all be examined quickly by the feedback model, which became further simplified (as discussed in [10]) by certain regularities found in T_{max} as produced by J_{max} for HBM and CDM waveforms. The result was a tremendous leveraging of the FEM data, and much increased confidence that aggressive ESD design rules for metal would result in low peak temperatures, even at process corners.

As shown, Figure 4 has a peculiar mix of time and frequency domain expressions although, as above, all calculations are time domain. I could have expressed the thermal Ohm's Law output as P(t)*Z(t)=T(t)—better use * as the convolution operator here, given our multiplier node in the feedback circuit. But I wanted to distinguish that concept, and operation, from the actual time domain multiplication that happens due to the metal tempco.

There is more in the references [9, 10] to clarify this, but the whole scheme requires some careful thinking—be glad we have FEM sims for cross-checking! Figure 4 and the work surrounding it in [9, 10] is the trickiest example I've encountered of thermal Ohm's Law in the time and frequency domains.

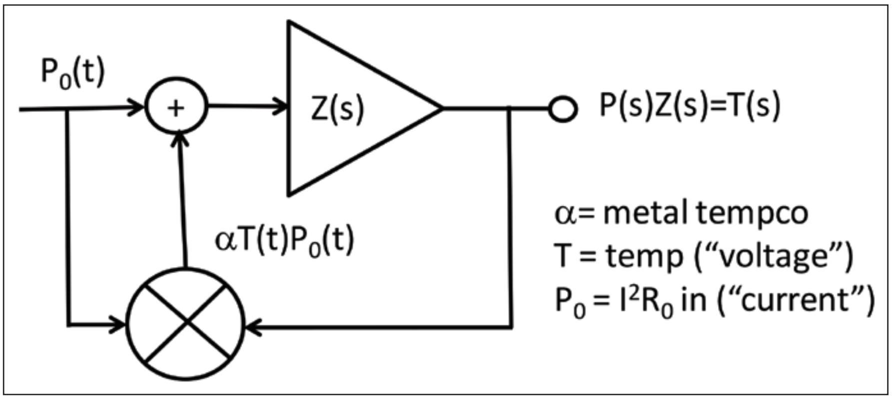


Figure 4: Feedback diagram for IC metal self-heating in the presence of positive tempco and thermal resistance $Z(s) \Leftrightarrow Z(t)$

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ARCHAEOLOGY AND XRF

Looking into the Past with "Elemental Vision"

King Solomon's secrets may be hidden in a shard of copper slag.

How, you may ask, would we know anything about a biblical King from a blacksmith's slag—his metallurgical waste pile?

Going deeper than you or I might, down into the slag's elemental composition, archaeologists have discovered evidence in the last decade that King Solomon may have had smiths skilled enough to build the Kingdom of Judah described in the Bible. A baptismal basin that stood on twelve bronze bulls. A hall of cedar. A magnificent ivory throne. Who knows what could have been possible?

A vision of history illuminated by a simple tool: the XRF gun.

Richard Freeland is a San Diego writer most recently fascinated by how archaeologists use new technologies as storytelling tools—breathing new life into ancient civilizations. Freeland works as the Marketing Team Lead for Advanced Test Equipment Corp. (ATEC) and can be reached at rfreeland@atecorp.com.

By Richard Freeland

MEET THE XRF GUN: AN ARCHAEOLOGIST'S STORYTELLING DEVICE

X-ray fluorescence (XRF) is a non-destructive measurement technique in which one fires x-rays at a sample with an XRF analyzer, a tool commonly known as an XRF gun. The sample responds by emitting x-ray fluorescence, with each element giving off its own 'fluorescent fingerprint.' The XRF gun then reads the fingerprints and gives the user a detailed profile of the sample's elemental composition. All of this happens in as few as 1-2 seconds—pretty good for laboratory-grade analysis.

Archaeologists use the "elemental vision" of XRF to discover historical secrets. The test method is simple: fire x-rays, study the chemical makeup, and consider what your findings reveal given the historical context.

King Solomon's secrets may not be so easy to discover, but expeditions to southern Jordan in the last decade by a joint team of archaeologists from Jordan and the University of California, San Diego (UCSD) have revealed that copper smelting in the neighboring kingdom of Edom, Judah's bitter rival, progressed to an industrial level.

Edomites lived in the highlands, according to sources dating back to the Book of Jeremiah. "Though you make your nests as high as eagles, I will bring you down from there," the author wrote. But according to the ELRAP team's findings, the people of Edom would swoop down into the dry river valleys below to mine precious copper.

Khirbat en-Nahas, or "ruins of copper," was the first site the archaeologist team excavated. What they unearthed was astonishing: a fortress formidable enough to rival those in Israel, Jordan, and Sinai, guarding 13 previously undiscovered copper mines, littered with more than 350 ancient mining tools.

According to Dr. Thomas E. Levy and Dr. Mohammad Najjar, co-directors of several expeditions and founders of the Edom Lowlands Regional Archaeology Project (ELRAP), copper smelting in Edom achieved a level of artisanry and a scale of operations large enough to make a biblical version of King's Solomon's kingdom viable.

"We have discovered a degree of social complexity in the land of Edom that demonstrates the weak reed on the basis of which a number of scholars have scoffed at the idea of a state or complex chiefdom in Edom at this early period—and, by extension, a state in Judah," Najjar and Levy wrote in their article "Edom and Copper" in *Biblical Archaeology Review Magazine*, 2006[1].

How could Judah have survived centuries of war with Edom without achieving a mastery of copper smelting to rival their neighbors? Wouldn't Judah have to be "a kingdom with ambition and the means of fighting off the Edomites," as the archaeologists described it to *The New York Times*[2] in 2006? Or so the theory goes.

"Edom and Copper" sparked its own war upon publication, with archaeologists battling it out quite civilly in papers and lecture halls, at least in comparison to bronze age warfare, but with no less fierceness and passion.

"One 'fortress' does not make a Kingdom," Eveline van der Steen, East Carolina University, and Piotr Bienkowski, University of Manchester, told *The New York Times*.

Another vision of 10^{th} century Judah exists, one in which ancient Jews were more of a pastoral people. King Solomon? A chieftain, perhaps, rather than a king. Once, this view was blasphemous to biblical history. Then, thanks to contemporary archaeology, it became a compelling theory. Now, this "low chronology" view of Edom and Judah grapples with groundbreaking evidence expeditions have been gathering for the last 15 years, findings that indicate Levy and Najjar may be on to something.

Israel Finkelstein of Tel Aviv University, an advocate of the low-chronology movement, voiced his dissent as well, telling *The New York Times* that Levy & Najjar's initial research did "not shed new light on the question of state formation in Edom."

Was the King Solomon of the Bible a myth? Or, for once in contemporary archaeology, is the religious text more accurate than we know? To answer that question, we must journey to Faynan, Jordan, one of many historical sites across the world given new life by x-ray fluorescence.

DISCOVERING KING SOLOMON'S MINES—OR RATHER, HIS NEIGHBORS' COPPER SLAG

Jordan is a part of what is known as the Levant. The term "levant" means rising in French, inherited from the Italian *levante*, which conjures up images of the rising sun in the East. In German, the term is translated as "morgenland," or morning land. Levant is the name given to a cultural region that encompasses parts of modern Lebanon, Syria, Iraq, Palestine, and Jordan, defying geopolitical boundaries. Western religion dawned here. Depending on who you ask, Moses parted the Red Sea, Jesus thirsted for wine at a wedding, and Mohammed took one last look at Jerusalem before he ascended to the heavens, all on Levantine soil.

Archaeology in the Levant began as treasure hunting. Now it's evolved into an endless quest for the historical treasures buried in the deserts and dry steppes where biblical kingdoms once flourished.

Here, archaeologists search for ceramics, which serve as veritable codices of historical data, as well as mud-brick homes and ruins of lost cities. And, as always, King Solomon's mines, the legendary gold mines belonging to Solomon himself that writer H. Rider Haggard fantasized about.

However, the team of San Diegan and Jordanian archaeologists set out in 2014 to learn about the past from a different source of historical evidence: copper slag.

Forgoing the search for lost cities themselves, the ELRAP team instead returned to the copper beds of Faynan in southern Jordan, where smiths, as they do, left their slag. Copper slag is mounds of metallic waste, a by-product of copper extraction by smelting. Impurities are cast away into what becomes small mountains of discarded metals. You may be thinking, "How can a monumental discovery have been found here, in a metallic mound? These aren't exactly Solomon's Mines," and you'd be right. But buried in the elemental composition of these humble mountains are gems of historical insight that rival the riches Haggard dreamed up over a century ago.

Brady Liss, an archaeologist from the UCSD Levantine and Cyber-Archaeology lab, was part of this expedition. He writes about the power of XRF's "elemental vision," as he calls it in his 2016 article: "Using X-Ray Fluorescence to Examine Ancient Extractive Metallurgy Practices: A Case Study from Iron Age Khirbat al-Jariya, Jordan."[3]

A newer dig site, Khirbat al-Jariya, was his destination: once a copper ore district in Faynan around the 12 – 10^{th} centuries BCE, the site may have forged copper for the biblical kingdom of Edom, similar to Khirbat en-Nahas. Now, it's home to 15,000 – 20,000 tons of slag. Khirbat al-Jariya is ideal for archaeometallurgy thanks to its "large copper smelting centers supported by networks of smaller, ephemeral mining camps." Copper mines they may be, but to archaeologists, they are veritable gold mines of history, especially because Khirbat al-Jariya has been "primarily undisturbed since its Iron Age abandonment, leaving a relatively pristine record for archaeological research."

Liss and his team used GIS, carbon dating, and lidar to study the smelting sites, but the key tool to their findings was XRF. Specifically, the Bruker TRACeR III-V+, a portable XRF gun.

"XRF has become a regular practice in investigating metallurgical remains and artifacts… both in the field and in the lab," Liss writes.

HOW ARCHAEOLOGISTS HARNESS THE POWER OF XRF

How, then, do you make historical discoveries with XRF? Well, it's quite simple really. Point and shoot. A piece of slag gives us an epic poem beginning in

An XRF analyzer only fires at a single point and may miss key discoveries if the sample is not homogenous.

sparks, with the first copper smelted at the site, and ending in empires, or in this case small kingdoms like Judah.

Let's take a look at how the ELRAP team made their discoveries.

First, they excavated a 1 x 1-meter rod of slag from one of the mounds, taking samples both from specific parts of the rod and from surrounding mounds. Digging down to the bedrock, the team retrieved enough slag to give them samples from every phase of copper smelting throughout the site's history.

An XRF analyzer only fires at a single point and may miss key discoveries if the sample is not homogenous. For example, fire one at a rock and it will measure the stone effectively but may miss a vein of gold that runs through the other side. To capture stray copper shards in the "inherently heterogeneous" ancient slag, the team crushed each sample into a fine powder, grinding them with a mortar and pestle until they were representative of that piece of slag's elemental makeup. Specifically, they were looking for how much copper each sample had, which would serve as an indicator of how successful copper smelting processes were at the time.

Once powdered, the copper slag sample was analyzed with the Bruker TRACeR III-V, which has "a rhodium anode to produce x-rays, and a SI-Pin detector for collecting fluorescence from the targeted sample." The x-ray beam is 3 x 4 millimeters. Users can "control voltage (up to 40 kV) and current (between 0 – 60 µA) to enhance the detection of desired elements… the XRF system can be tailored to target specific elements of interest, maximizing their detection."

Here are the test specifications the team used:

- Heavy elements: 40 kV, 13µA, with an acquisition time of 300 seconds
- Lighter elements: 15 kV, 35µA, with blue Titanium filter and a 300 second acquisition time

Once the testing was complete, they analyzed the results on a computer and found something remarkable: the smiths were getting better. Marked improvement in their copper smelting practices was evident.

A smith who has mastered the art of copper smelting will extract much more of the stuff in the process than a beginner. And their slag, their metallurgical waste, if you remember, will have much less precious copper. Looking at all the samples from throughout Khirbat al-Jariya, the archaeologists found a 70% decrease in copper waste in the slag over time.

Now, it is important to note that the team's findings do not definitively prove anything about Edom, Judah, or King Solomon, nor does Brady Liss make any such claims, beyond opening the doors to a palace of possibilities for metallurgically sophisticated Levantine societies in the 12^{th} – 10^{th} centuries BCE.

What we do know, though, is that XRF made the difference in this interpretation of historical truths. Only two phases of copper production were found, but XRF analysis revealed that there was a dramatic difference in how successful they were, hinting at an evolution of coppersmithing practices.

A small story to tell. But it may be the beginning of recreating the world in which King Solomon and his Edomite rivals lived, one piece of copper smith's slag at a time. And that is the power of XRF.

ILLUMINATING THE PAST WITH THE TECHNOLOGY OF THE FUTURE

Let us revisit our biblical mystery for a moment. We set out to discover who King Solomon was—a king? A myth? A Bedouin sheikh? Or something else.

"Only a complex society such as a paramount chiefdom or primitive kingdom would have the organizational know-how to produce copper metal on such an industrial scale," Drs. Levy and Najjar told *The New York Times* in 2006.

To Levy and Najjar, "the biblical references to the Edomites, especially their conflicts with David and subsequent Judahite kings, garner a new plausibility."

Since they spoke out in 2006, their international team of archaeologists has continued to research and write passionately on the subject, publishing additional findings in 2010, 2012, 2014, 2016, 2020, and beyond, that all build the case for a reinterpretation of the minimalist, low-chronology vision for the Levant of biblical times. Recently, Erez Ben-Yosef, an ELRAP team member, discovered fresh evidence of Iron-Age Edomite sophistication in the nearby Timna valley, a revelation in harmony with Levy and Najjar's Faynan findings. "The scale of production tells us that there was something bigger than a few tribes here," Ben-Yousef told *The New Yorker*.[4]

But not everyone is convinced.

"Is this early Edom?... Why not Midian; Amalek, Kedar, Paran, Teman?" low-chronology scholar Finkelstein wrote in a reply to Ben-Yosef's work in 2020,[5] once again casting shadows on the team's discoveries.

We have no answers. All we have are the strikes of the smiths' hammers. Each time, more accurate. Each age, more copper preserved. And in the days of King Solomon, perhaps just enough to armor the kingdoms of biblical legend.

"Archaeology is paradoxically rooted in the past but dependent on the future," Brady Liss writes, the future being technologies like XRF that make these discoveries possible.

We live in an age where people want to reconnect with their origins—we trace our family trees on Ancestry.com, map out our lineages with 23 and Me, and cultivate long-lost cultural identities.

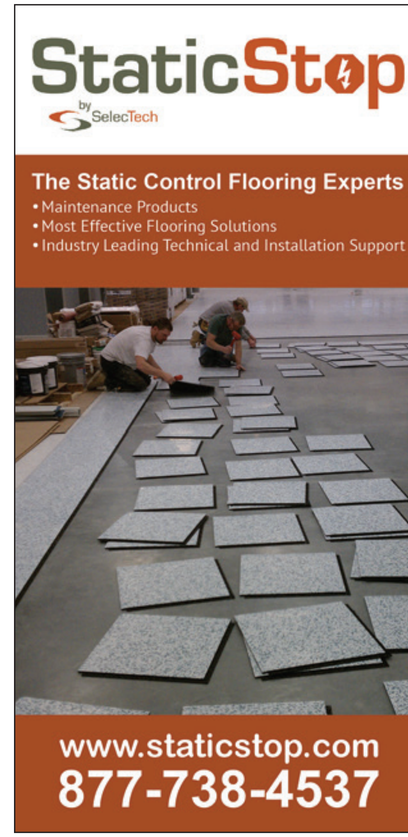
X-ray fluorescence and the technologies of the future can, as Liss so presciently wrote, connect us to that past, to our ancestors and our people.

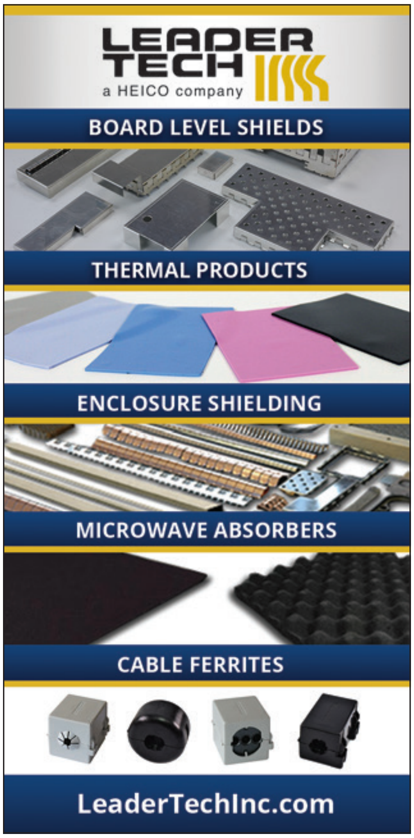
To our stories—and everyone, from smiths toiling in desert mining camps under the night sky, to Kings asleep in their beds, is connected.

We just have to look closer, ask the right questions, and the artifacts will answer—the truth written in their very elements.

To explore the Faynan dig site, its history, and the team's findings in a stunning interactive digital experience, visit the UCSD team's website at https://bit.ly/3DMYAAY.

PRODUCT Showcase





EVALUATION OF EMC EMISSIONS AND GROUND TECHNIQUES ON 1- AND 2-LAYER PCBs WITH POWER CONVERTERS

Part 5: DC/DC Converter – EMC Countermeasures – Conducted Emissions Results

By Bogdan Adamczyk, Scott Mee, and Nick Koeller

This is the fifth article in a series of articles devoted to the design, test, and EMC emissions evaluation of 1- and 2-layer PCBs that contain AC/DC and/or DC/DC converters, and employ different ground techniques [1-4]. In this fifth article, we are still focused on the DC/DC power converter board (2-layer PCB). In this article, we evaluate the implementation of several EMC countermeasures and present the conducted emissions results, for both voltage and current methods, according to CISPR25 Class 5 limits.

1. INTRODUCTION

In the first article in the series, [1], we defined the overall design problem. The second article, [2], focused on the details of the 2-layer DC/DC converter design. The third article [3] presented the radiated and conducted emission results from the baseline design which did not contain any EMC countermeasures. The results showed multiple failures in both radiated and conducted emissions. The fourth article [4] presented a systematic approach to improve these radiated failures by populating the PCB with optional EMC countermeasures on component pads that have already been designed into the PCB layout and showing their impact on the radiated emissions. The EMC countermeasures are illustrated in Figure 1, as purple dashed boxes labeled EMC-A through EMC-F.

This article discusses the impact of these countermeasures on the conducted emissions results using both the voltage and the current methods. The voltage method results are discussed first, followed by the current method results. The article concludes with a brief description of what can be expected in the next article in the series.

2. CONDUCTED EMISSIONS VOLTAGE METHOD RESULTS – SUPPLY LINE

The voltage method results are shown only for the supply line, as the ground line results were similar.

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2.1. EMC-A & EMC-E Input and Output Capacitor Impact

Conducted emissions were measured in the frequency range of 150 kHz – 108 MHz. The baseline results (Figure 2a) show a high level of emissions in the 1 – 2 MHz and 25 - 100 MHz bands. To attempt to reduce these emissions two capacitors C9 = 10 nF (EMC-A) and C4 = 10 nF (EMC-E) were populated. The conducted emissions measurement taken with these countermeasures populated is shown in Figure 2b. See Figure 6 in the third article in the series for a reference legend to interpret plots in this article [3]. This figure was not duplicated in this article in order to save space.

The 10nF capacitors are meant to help filter the noise in higher frequencies, As the plot in Figure 2b shows, the capacitors increase the conducted emissions in the frequency range of 25 MHz – 40MHz, and decrease the conducted emissions in the frequency range of 40 MHz – 100MHz. The additional capacitors have minimal impact on the conducted emissions in the 1 MHz – 2 MHz band. The 10nF capacitors are kept on the board for the next two sections as they had a positive impact in the 40 MHz – 100 MHz band.

2.2. EMC-A Input Inductor Impact

Next, we targeted the conducted emissions using an input filter. A 1 µH input inductor, L2 (EMC-A), was placed on the input to create a PI filter with the input capacitors. The conducted emissions measurement taken with this countermeasure in place is shown in Figure 3.

As Figure 3 shows, the inductor had a substantial improvement in the emissions in the 1 – 2 MHz range; additionally, it reduced the higher frequency emission by 2 – 4 dB compared to Figure 2b. To further reduce the emissions around 1 MHz, the input inductor L2 was changed to 3.3 µH. The emission results are shown in Figure 4 on page 32.

As Figure 4 shows, an additional 4 -12 dB reduction was achieved in the lower frequency range compared to Figure 3.

2.3. EMC-A Additional Input Capacitors Impact

Next, we added two additional 2.2µF input capacitors, C7 and C8 in order to increase the impedance of the input PI filter by lowering the frequency of the low pass filter. The emissions results are shown in Figure 5 on page 32.

As Figure 5 shows, an additional 6 dB reduction was achieved around 1 MHz compared to Figure 4.

2.4. EMC-A Input Inductor Impact

Next, the input inductor L2 was changed back to 2.2 µH IHLP magnetically shielded inductor. The emission results are shown in Figure 6 on page 32.

As Figure 6 shows, the change from 3.3 µH to 2.2 µH had virtually no impact, as compared to Figure 5.

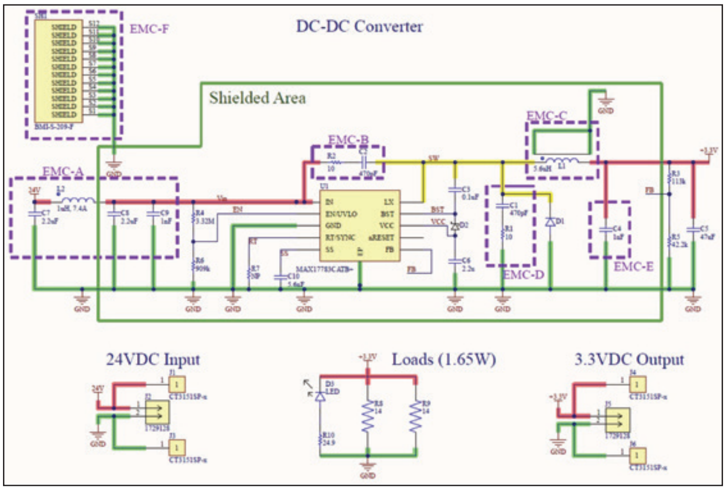

Figure 1: DC/DC schematic with EMC countermeasures

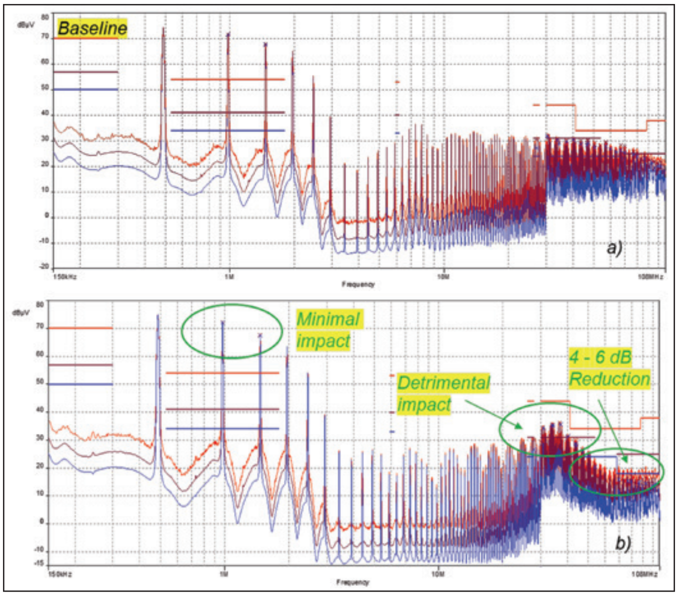

Figure 2: CE voltage method: a) baseline b) C9 = C4 = 10 nF

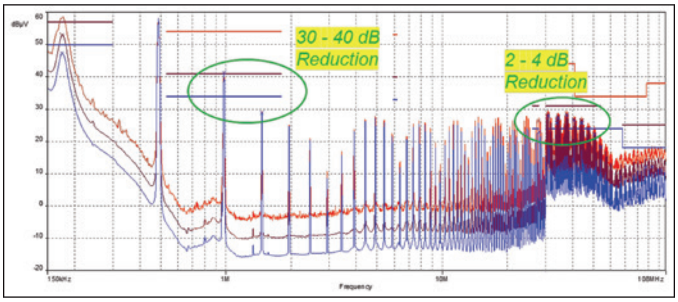

Figure 3: CE voltage method: L2 = 1 µH, C9 = C4 = 10 nF

This suggests that the increase in capacitance on C7 and C8 offers more improvement and the increase in inductance from 2.2uH to 3.3uH has a negligible impact, and therefore, we retained the 2.2 µH inductor in our design.

2.5. EMC-C Switching Inductor Impact

Next, the switching inductor, L1 (EMC-C), was changed to a Vishay 3232 IHLE 5.6 µH. These inductors have an integrated E-field shield that is tied to ground on two sides of the inductor. The conducted emission results are shown in Figure 7.

As the plots show, the inductor had a substantial impact in the 40-70 MHz range. At this point, the DUT is passing CISPR 25 Class 5, and initially, this is the solution that we used and is described in the previous article. [4] However, with the additional time we have had since the previous article, we decided to evaluate some other countermeasures that would be cheaper than the IHLE inductor. This approach is often used in debugging EMC issues for industry as we first prioritize finding a solution, then optimize the PCB assembly cost as time allows.

Next, we investigated the impact of the two series RC snubbers (EMC-B and EMC-D). The IHLE 5.6uH inductor was removed and replaced by L2 = 2.2 µH IHLP magnetically shielded inductor (in order to reduce the cost). The remaining EMC components were retained.

2.6. EMC-B & EMC-D Snubber Impact

One of the snubbers was placed across the catch diode D1: R1 = 10 Ω, C1 = 470 pF (EMC-D), and the other was placed across the FET that controls the switching, R2 = 10 Ω, C2 = 470 pF (EMC-B). This FET is inside of the IC package. The conducted emissions test results are shown in Figure 8.

With both snubbers in place, we observe a 4 - 6 dB decrease in emissions in the 30 – 100 MHz band. Next, the snubber across the catch diode (R1 and C1) was removed while the R2 and C2 snubber was retained. The conducted emissions results are shown in Figure 9.

As Figure 9 shows, the removal of the catch diode snubber (R1 and C1) results in a 2 -3 dB increase in emissions in the 30 – 100 MHz band. Next, the FET snubber (R2 and C2) was removed, while the catch

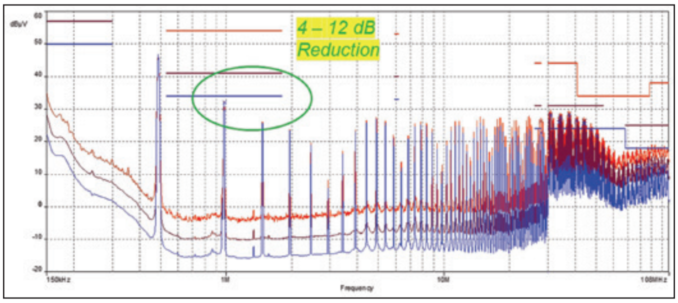

Figure 4: CE voltage method: L2 = 3.3 µH, C9 = C4 = 10 nF

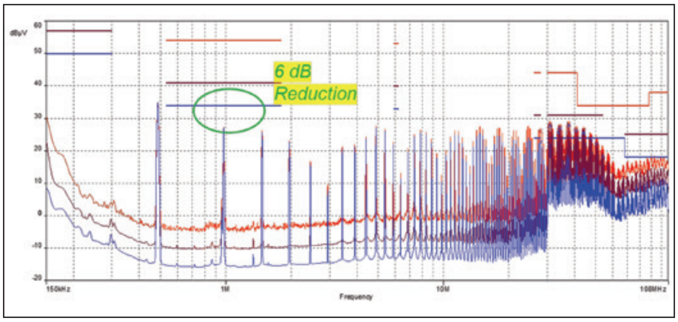

Figure 5: CE voltage method: L2=3.3 µH, C9=C4 =10 nF, C7=C8 =2x 2.2 µF

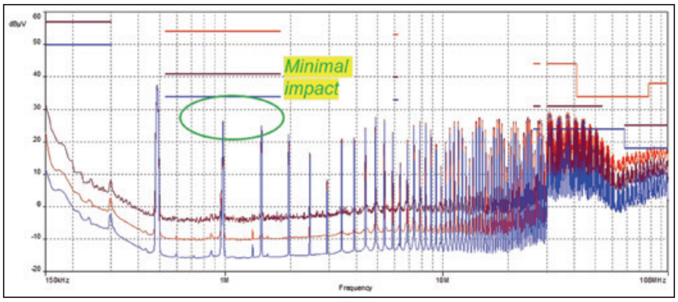

Figure 6: CE voltage method: L2=2.2 µH, C9=C4 =10 nF, C7=C8=2x 2.2 µF

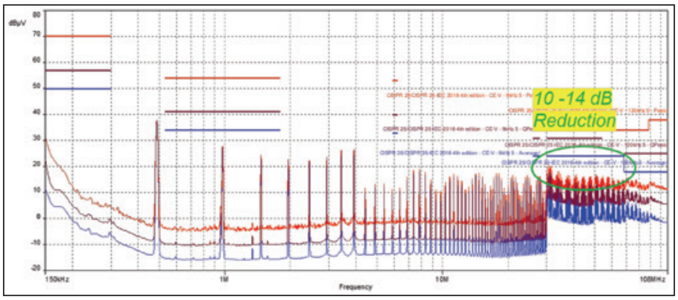

Figure 7: CE voltage method: L2 = 2.2 µH, C9 = C4 = 10 nF, C7 = C8 = 2x 2.2 µF caps, L1 = 5.6uH IHLE

diode snubber (R1 and C1) was repopulated. The conducted emissions results are shown in Figure 10.

Figure 10 shows this change had a 1 -2 dB increase in the 30 – 40 MHz band, as compared to Figure 9. We, therefore, retained both snubbers.

3. CONDUCTED EMISSIONS CURRENT METHOD RESULTS

The current method results are shown only for the 50 mm probe location, as the 750 mm results were similar.

3.1. EMC-A, EMC-C & EMC-E Input and Output Capacitor and Inductor Impact

Conducted emissions were measured in the frequency range of 150 kHz – 245 MHz using the current method. The configuration tested was as follows: C9 = C4 = 10 nF, L2 = 2.2 µH, C7= C8= 2.2 µF, L1 = 5.6 µH IHLE. This is the same configuration that was used in the radiated emissions testing discussed in the previous article of this series, [4]. The conducted emissions, current method test results are shown in Figure 11 on page 34.

We observe the emissions reduction across several frequency bands. This is not surprising as this configuration performed very well in the conducted emissions voltage method test.

3.2. EMC-B & EMC-D Snubber Impact

In order to address some of the higher frequency emissions, we again investigated the impact of snubbers. The IHLE 5.6uH inductor was removed and replaced by L2 = 2.2 µH IHLP magnetically shielded inductor. The remaining EMC components were retained. As it was done in the voltage method, one of the snubbers was placed across the catch diode D1: R1 = 10 Ω, C1 = 470 pF (EMC-D), and the other was placed across the switching node, R2 = 10 Ω, C2 = 470 pF (EMC-B). The conducted emissions test results are shown in Figure 12 on page 34.

The addition of the two snubbers had a minimal impact on the emissions at the lower frequency ranges but resulted in about 2 – 3 dB reduction in the 20 – 30 MHz range, and at the 180 MHz spike as compared to Figure 11b. This configuration does technically pass CISPR 25 Class 5, but in practice, we like to see more margin to prevent failures that can be caused by lab-to-lab variation in measurements.

Next, the FET snubber (R2 and C2) was removed, while the catch diode snubber (R1 and C1) was retained. It resulted in the increased emissions in the frequency range of 30 – 40 MHz and around 180 MHz. Subsequently, we repopulated the FET snubber (R2 and C2) and removed the catch diode snubber (R1 and C1). The result was similar.

The final snubber configuration tested was with R1 = R2 = 5.6 Ω, C1 = C2 = 470 pF. The test results are shown in Figure 13 on page 34.

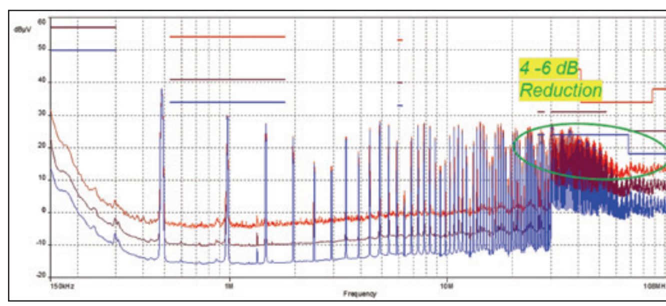

Figure 8: CE voltage method: R1 = R2 = 10 Ω, C1 = C2 = 470 pF

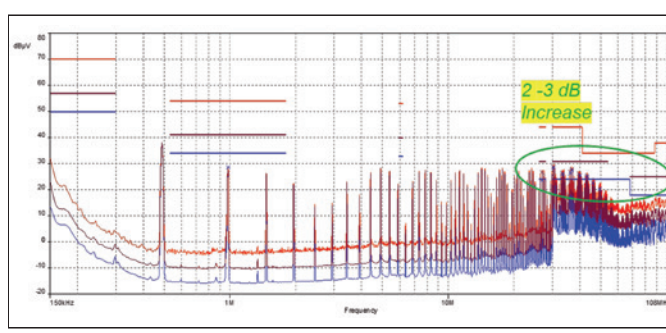

Figure 9: CE voltage method: R2 = 10 Ω, C2 = 470 pF

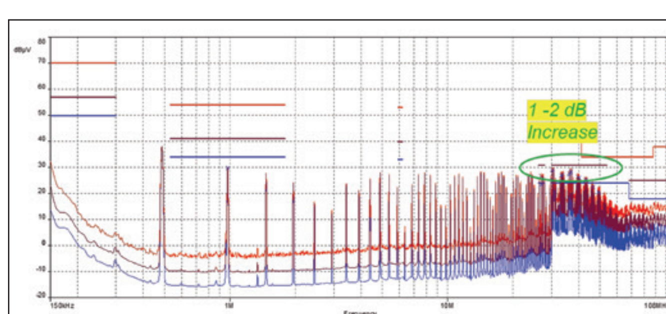

Figure 10: CE results voltage method: R1= 10 Ω, C1= 470 pF

As Figure 13 shows, this change had a positive impact in the 30 – 40 MHz range causing a 1-2 dB reduction in emissions, as compared to Figure 12. This configuration passes CISPR 25 Class 5 with 3 dB of margin.

The analysis of the conducted emissions testing and addition of EMC countermeasures show that in large part the failures identified in baseline testing can be mitigated through the use of front-end filtering and snubbers. However, a larger margin of passing results can be achieved by investing more in the Bill of Materials (BOM) by using an e-field shielded IHLE inductor and/or a PCB shield. Depending on the class performance desired a lower cost may be required to gain compliance with a comfortable margin.

4. FUTURE WORK

In the next article, we will discuss the challenges of 'grounding' or reference layout design in single layer and 2 layer PCB designs involving DC-DC and AC-DC converters.

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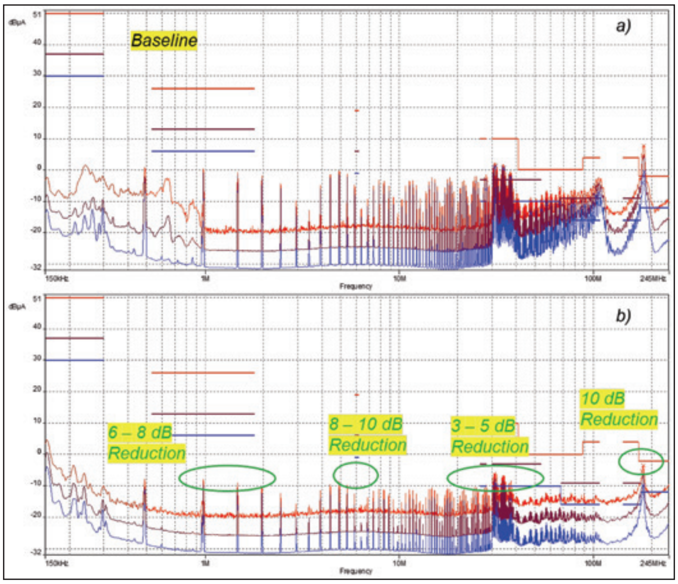

Figure 11: CE current method: a) baseline b) C9 = C4 = 10 nF, L2 = 2.2 µH, C7= C8= 2.2 µF, L1 = 5.6 µH IHLE

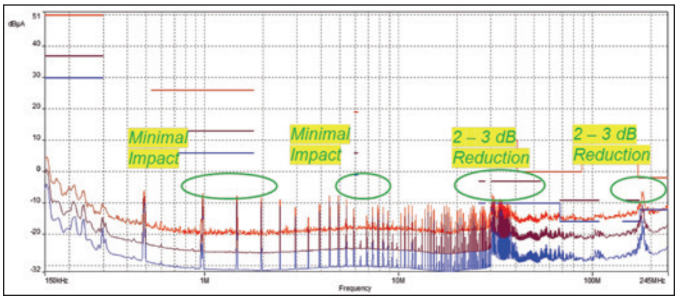

Figure 12: CE current method: R1 = R2 = 10 Ω, C1 = C2 = 470 pF

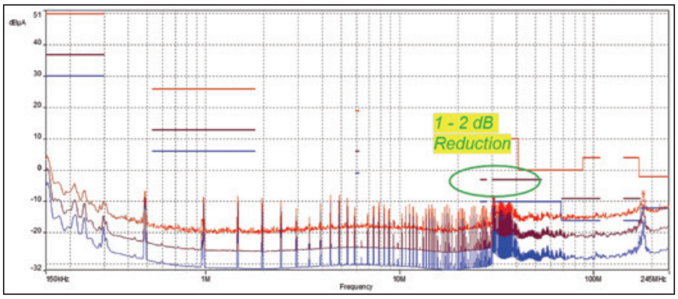

Figure 13: CE current method: R1 = R2 = 5.6 Ω, C1 = C2 = 470 pF

WHAT ARE THE ADVANTAGES OF CAPACITIVELY COUPLED TLP (CC-TLP)?

By Heinrich Wolf for EOS/ESD Association, Inc.

Heinrich Wolf received his degree in electrical engineering from the Technical University of Munich (TUM) and his PhD from the Technical University of Berlin. He works in the field of RF simulation and characterization in the frequency range up to 110 GHz. He also represents the German ESD-Forum in the standards working groups.

Founded in 1982, EOS/ESD Association, Inc. is a not for profit, professional organization, dedicated to education and furthering the technology Electrostatic Discharge (ESD) control and prevention. EOS/ESD Association, Inc. sponsors educational programs, develops ESD control and measurement standards, holds international technical symposiums, workshops, tutorials, and foster the exchange of technical information among its members and others.

Charged Device Model (CDM) discharge events are the major root cause for electrostatic Discharge (ESD) failures in a modern, automated production and test environment. The CDM stress testing is well established for product qualification. It simulates the possible charging of a packaged device during automated handling followed by the discharge stress event which is caused by contacting one pin with e.g. the grounded test equipment. However, due to the nature of the occurring air discharge, the CDM test shows a low reproducibility with respect to the resulting discharge pulse. The related standard [1] considers this fact by allowing a peak current variation of more ± 20 % during the tester verification process on special verification modules for pre-charge voltages below 250V. The test of real devices can show even a higher variation depending on the package and pin type. This lack of discharge repeatability can result in an expensive re-design if the device under test (DUT) does not meet the required CDM failure threshold. Thus, there is a demand for an improved repeatability stress method.

CC-TLP – A REPRODUCIBLE CDM-LIKE STRESS METHOD

The Capacitively Coupled Transmission Line Pulsing (CC-TLP) [2] [3] allows a much more reproducible CDM-like stress test. It uses a TLP pulse generator which produces a rectangular stress pulse and which is a well-known tool for the characterization of protection elements and circuits in the ESD domain. Unlike TLP for which both pins (signal and ground) are connected to the DUT establishing a well-defined stress path, CC-TLP connects only the signal pin directly to the DUT while the ground return path shows a capacitive connection (Figure 1).

Thus, like for the CDM, the stress pulse is injected via one pin (Pin Under Test PUT) and charges up the background capacitance Cb which represents the package capacitance with respect to the ground. This ensures the same stress current paths as in a CDM test. However, CC-TLP avoids an air discharge by contacting the PUT prior to the triggering of the stress pulse. Thus, the CC-TLP stress pulse shows a much better reproducibility which is only limited by

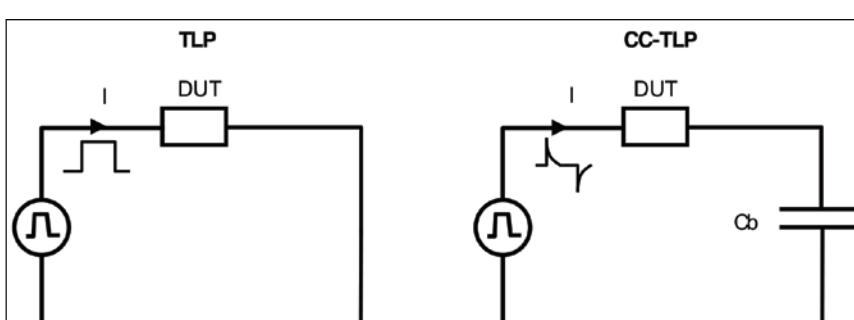

Figure 1: Principle of the TLP and CC-TLP.

> Within the past 18 years, many studies exploring 3 µm to 7 nm technologies have demonstrated the excellent correlation of CC-TLP with CDM in terms of stress current failure threshold as well as electrical failure and physical damage signature.

the pulse relay contact of the applied TLP generator. Figure 2 (left) compares the variation of more than 500 CDM stress peak currents for a CDM voltage of 110 V with the CC-TLP peak currents.

The CDM data in the 110V charge voltage area show a variation in a range of 30 % with some outliers in a range of 40%. In contrast, the variation of the CC-TLP peak currents is in a range of 5 % which demonstrates the clear superiority of this method. Figure 2 (right) compares measured CC-TLP pulses applied to a 30 pF CDM verification module with a CDM current pulse. By varying the TLP pulse width the CC-TLP pulse can be easily tailored to the required pulse width for the best match with the CDM waveform.

Figure 3 depicts a possible set-up for the CC-TLP method and a real CC-TLP probe.

The device under test (DUT) is placed on the chuck of a wafer prober. The TLP generates the pulse which passes the pick-off for the pulse voltage measurement and which is then injected into a semi-rigid 50 Ω transmission line TL. The TL ground shield connects to the ground plane and the signal line is connected to a probe needle which connects the PUT through a small hole in the ground plane. The measurement and superimposition of the incident and the reflected pulse are used to calculate the injected stress current.

With this setup, it is possible to perform tests not only at the package but also at the wafer level. This allows precise CDM relevant investigations e.g. at earlier product development stages without the need for packaging. Furthermore, the high reproducibility improves the determination of the exact failure threshold by applying smaller stress steps. This

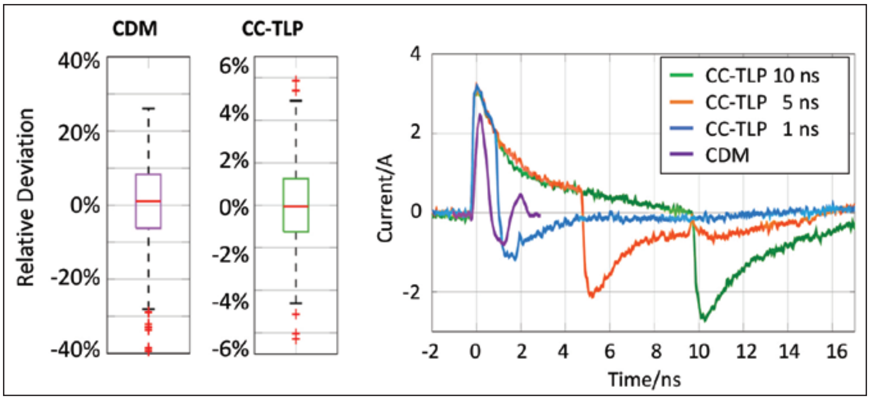

Figure 2: Variation of the CDM/CC-TLP peak currents [4] (left) and transient behavior [5] (right).

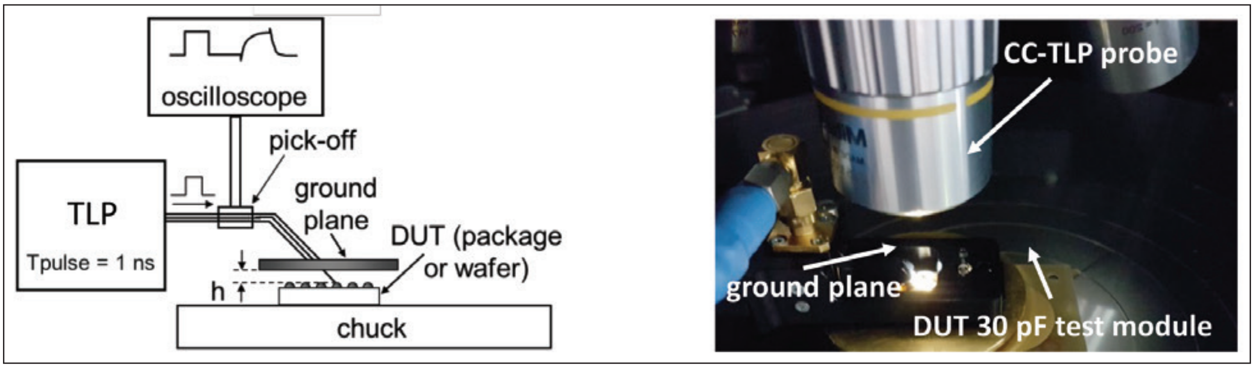

Figure 3: Set-up for a CC-TLP

becomes relevant regarding the trend to reduce the required CDM thresholds for modern deep submicron technologies [6].

Within the past 18 years, many studies exploring 3 µm to 7 nm technologies have demonstrated the excellent correlation of CC-TLP with CDM in terms of stress current failure threshold as well as electrical failure and physical damage signature [3] [5] [7] [8] [9]. Figure 4 shows the comparison of a physical CDM damage signature and its replication by CC-TLP at both the package and wafer levels.

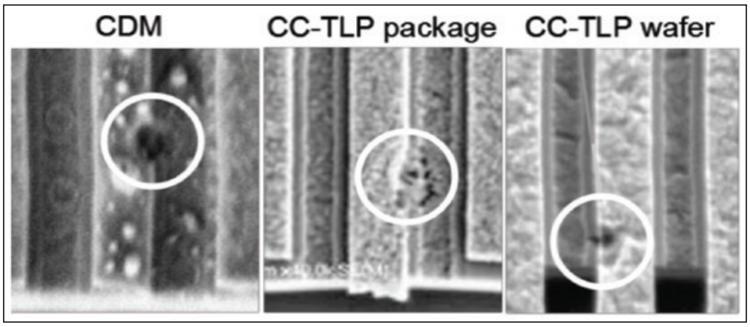

Figure 4: Comparison of CDM and CC-TLP replicated physical damage signatures [7].

These investigations prove that the CC-TLP method is capable of reproducing CDM-related damage signatures without the disadvantages caused by the CDM air discharge.

WHAT IS THE IMPACT ON FUTURE DEVELOPMENTS?

Further investigation has also identified a sensitivity of the failure threshold on the stress pulse rise time [9] which can become relevant especially for future high-speed applications. Unlike CDM, the CC-TLP method also allows for controlling pulse rise time in a very reproducible way. Thus, it would support the designers to develop the protection for an exactly defined stress level which optimizes the trade-off between functional performance and ESD protection. Moreover, the trend to integrate several dies (each with almost no internal CDM protection) into systems in a package (SiP) or Multi-Chip Modules (MCM) also requires a test method to evaluate the single components or chips prior to the integration into the complete system or module. For these new applications, CC-TLP has also been demonstrated to be a solution.

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PRODUCT SAFETY AND LIABILITY COMPONENTS IN FOCUS

From Risk Assessment to Warnings and Instructions – and the Synergy Between Them

By Erin Earley

The focus of these "On Your Mark" columns is visual safety communication related to equipment, machinery, and component parts – especially the symbols and content that make up on-product labels, warnings, and instructions. While we specifically hone in on these elements, they cannot – and should not – operate in a vacuum. That's because they're one, intertwined component in a comprehensive product safety strategy; looking at them separately could be detrimental to the safety of the product user and to the liability risk of the manufacturer. Here, let's explore the key components to keep in mind for your product safety strategy – from risk assessment to safety labels and manuals – and some of the ways that they all work together to improve safety and reduce risk.

Erin Earley, head of communications at Clarion Safety Systems, shares her company's passion for safer products and workplaces. She's written extensively about best practices for product safety labels and facility safety signs. Clarion is a member of the ANSI Z535 Committee for Safety Signs and Colors, the U.S. ANSI TAG to ISO/TC 145, and the U.S. ANSI TAG to ISO 45001. Erin can be reached at eearley@clarionsafety.com.

THE SYNERGY IN PRODUCT SAFETY AND LIABILITY

Today's equipment and machinery manufacturers have many concerns to contend with related to safety, risk, and compliance issues throughout the product lifecycle.

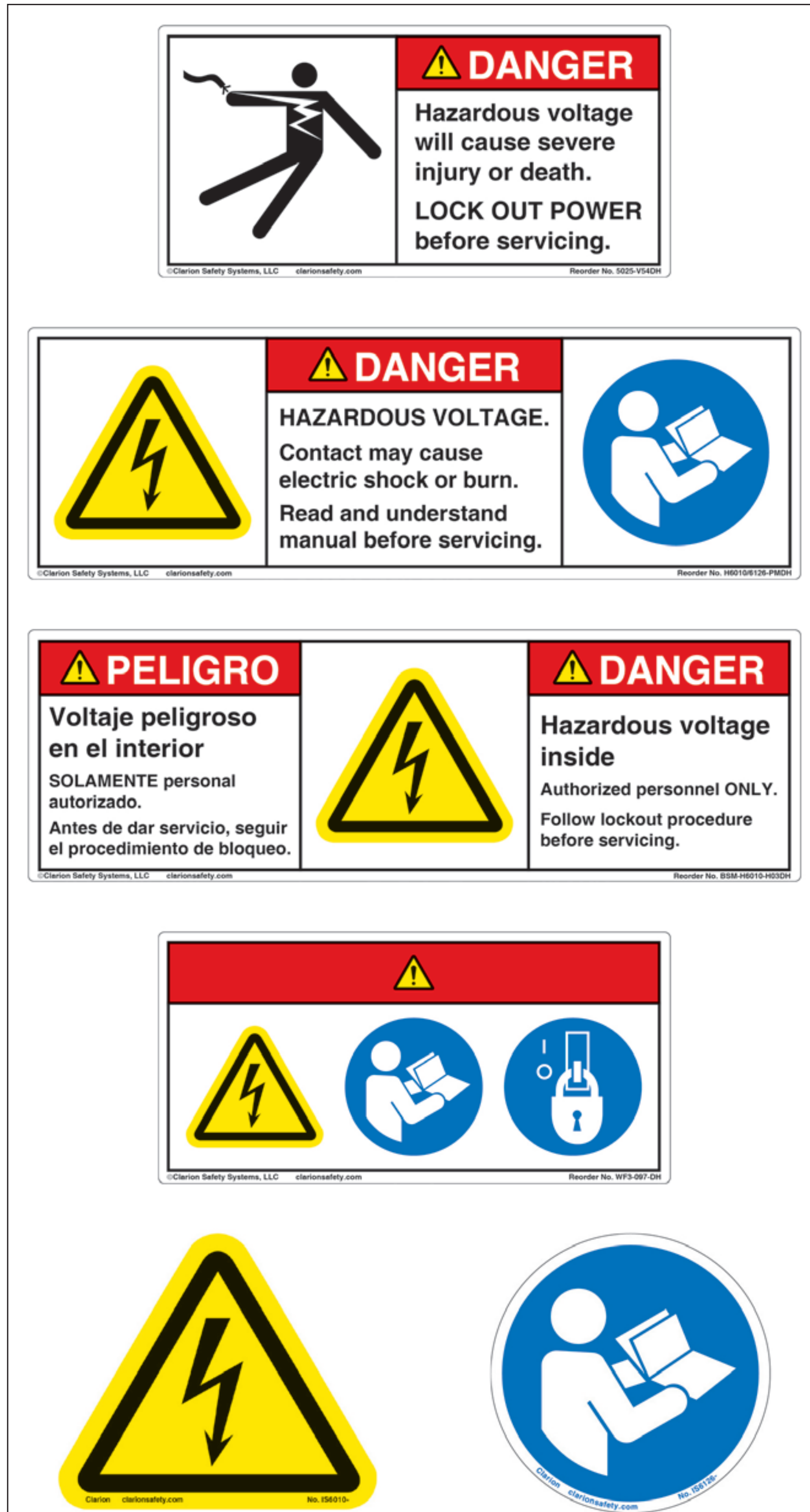
"Their main duties can be summed up simply as: provide a safe product, instruct in its safe use, and warn of its hazards," says Angela Lambert, who works with product safety teams on a regular basis through her role heading standards compliance at Clarion Safety Systems. "Executing on this throughout the design and manufacturing process, however, is much more nuanced, and mandates looking at key areas of product safety in a systematic way. This helps to ensure consistency and will situate a manufacturer in the best potential position should a liability claim arise."

According to Lambert, these areas include:

- **Risk assessment:** A thorough risk assessment identifies hazards, estimates the severity of injury presented by each hazard, and estimates the probability of the injury's occurrence. Then, for risks considered "unacceptable" due to applicable laws, regulations, standards, or public opinion, control measures should be applied to reduce risk. "This is the foundational element from both a product design and safety standpoint," says Lambert. "You can't control a risk through design, or provide safeguards or warnings unless you first assess it. The hierarchy of controls, used within the risk assessment process, is a guide in implementing hazard control measures beginning with the most effective measures down to less effective ones, and often uses a combination of all. These measures include guards, labels, PPE, instructions, and training."
- **Safeguards:** Safeguards are an outcome of the risk assessment process, used to mitigate risk and the potential for injury related to a product's use. When a hazard can't be eliminated or substituted, engineering controls like guards may be needed. In terms of the way this ties together with the other key areas, "The safeguards used may need to be referenced or explained through an on-product safety label. Additionally, the product manual and training should be thorough, including information and instructions related to the safeguard," says Lambert. Missteps in doing this effectively and in line with requirements are common; once again this past year, machine guarding placed in the

Occupational Safety and Health Administration's most recent top 10 list of the most frequently cited standards violations.

- **On-product labels, warnings, and instructions:** "On-product warnings or instructions are a particular risk reduction method that can be identified through the risk assessment process. Their development should not be a reactive process; they should complement and be consistent with your risk assessment," says Lambert. Best practice safety standards come into play here in creating the content for the warnings, including ANSI Z535.4 and ISO 3864-2.
- **Product manual:** Product safety labels work as a system with each other to convey safety information, but they also work in conjunction with all other safety and risk reduction documents and measures, including product manuals. "Many times, your on-product warnings are not detailed enough to cover all warnings and instructions. The product manual is the proper location to covey these additional details," Lambert says, noting that best practice standards here such as ANSI Z535.6 and industry-specific standards are important guides.
- **Training:** "Training that's tailored to your particular product's safe operating procedures and maintenance is an important way to protect the users of your equipment," Lambert says, noting that training should include information on proper and improper use, and align with both the product's safety labels and manual. This is another area where, per workplace safety statistics, there's room for improvement as efforts are falling short. According to the Electrical Safety Foundation International's most recent data,



A compilation of a few of the many format and content options available for safety labels.

"Constructing, Repairing, Cleaning" accounted for the leading worker activity for electrical fatalities at 52 percent; "Using or Operating Tools, Machinery" accounted for 27 percent of electrical fatalities.

BRINGING IT ALL TOGETHER IN YOUR WARNINGS

Since labels play a key role in communicating safety and hazard information and are one of the most visible methods of doing so, let's take a detailed look at how the areas above can intersect related to labeling.

- **ANSI/ISO formats and symbol use:** The format options or structure used for an on-product label is determined by what markets the product is being sold into (U.S. or international) – an outcome of the risk assessment process. Depending on whether you deem it more appropriate to follow the U.S.-based ANSI standards, the international ISO standards, or a combination of these, you have the option to use a word-message-only format, a symbol-only format, or a combination of symbols and text. Symbols used in on-product labels, and how their meanings are defined, should be consistent throughout the product manual and in all training in order to be most effective.
- **Translations:** Multiple languages for safety labels aren't mandatory for the U.S., but considerations need to be made related to export. For example, for products being sold into Europe, the EU Machinery Directive must be followed, and it has a requirement for translating warnings into the language of the country where the machine is placed on the market or into service. Understanding the intended audience, again as determined by the risk assessment process, and consistently incorporating that information across product safety and liability components is key. Manuals and training information should be translated or available in multiple languages in a uniform manner.
- **Depth of content and references to other safety tools:** References to engineering controls, warnings, and instructions should be presented consistently in the label's content, in the product manuals and in training materials. While there's not a prescriptive formula for this, labels, manuals, and training should work hand in hand to accurately and effectively convey the needed safety or instructional information. For example, your on-product warnings should be reflected in your manual and, in your training, you may focus a section on symbol meanings. In addition, if you have important information to convey that doesn't fit on the safety label itself, you can refer users to the manual and to further training. That can be communicated on the label through a message, symbol, or even a QR code linking to a digital asset like an online manual or training tool.

WHAT TO EXPECT

This interconnectivity of product safety and liability components, especially in terms of labeling, manuals, and training, is a trend that will likely continue well into the future, bolstered by the growth of increasingly complex products, including software integrations and autonomous features, as well as digitization in many areas of safety and training.

"These are certainly areas for product manufacturers and safety engineers to continue to monitor and strive to keep pace with. And, we can expect to see an evolution in the safety standards as well," says Lambert, who is also involved at the leadership level in the development of the ANSI and ISO standards for product safety, including as the chair of ANSI Z535.1 Safety Colors.

"This is a revision cycle year for ANSI Z535, with the standards due to be republished in January 2022, and I look forward to working together with the rest of the ANSI committee members to ensure the standards are up-to-date and reflective of our changing manufacturing and workplace environments. At the same time, a new ANSI Z535 standard is in development. ANSI Z535.7 focuses on safety information in electronic media; its scope is expected to include video materials, webpages, smartphones and tablets, and virtual reality. This is very indicative of our times – of 'blended' safety and learning approaches between labels, manuals, training and more. I believe it will highlight even stronger parallels in safety, risk and compliance information and documentation working together as a system."

2022

Product Resource Guide

Contents

The process of making informed purchasing decisions can be quite complex. From absorbers to testing, today's compliance engineer must be knowledgeable and well-versed in what to look for when selecting products and services that will work best for your needs.

This is where the Product Resource Guide comes in. In this year's Guide, we highlight nine product categories—offer guidance on the use of these products—and selection tips on how to choose the right product or service for your applications.

So, whether you're simply looking to replace an old piece of equipment, or are fully outfitting a brand-new lab, the Product Resource Guide is here to help.

We hope you'll find the 2022 Product Resource Guide an invaluable resource that you keep handy year 'round.

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ABSORBING MATERIALS

How Ferrites Are Specified for RF Performance

Ferrites are frequency dependent components used to attenuate unwanted high frequency RF signals that can cause failure of emission and immunity compliance tests. There is an endless variety of form factors for ferrites, including toroidal shaped cores, clamp-on cable shells, surface mount beads, leaded through hole components for installation on printed circuit boards, and other custom shapes and sizes for use in many different types of applications.

Choosing a Ferrite Suppression Component

Successfully choosing a ferrite suppression component involves knowing two critical items.

First, determine the frequency range that needs to be attenuated. This frequency may be obtained after having performed pre-compliance testing or perhaps discovered unexpectedly during full-compliance, run for record types of compliance testing. The former situation allows for successful integration of the ferrite component into the design prior to release to production of the end product. The latter situation usually involves adding the ferrite suppression device as an after-thought, usually attaching a clamp-on type of ferrite device to external cables to suppress the RF signal and obtain passing results.

Ferrites are manufactured using different compositions of materials. Each mixture provides different suppression capability over certain bands of frequencies. For example, mixture A might provide the most RF suppression from the lower frequency range of 100 kHz to 30 MHz (useful if the end-product is failing conducted emissions or immunity tests), mixture B might provide its best RF suppression from 1 to 300 MHz (where the noise is likely to emanate from cables attached to the end-product), mixture C might work best over the mid-range frequency band of 25 to 300 MHz, and high frequency material D might work best over the higher frequency range of 200 to 1000 MHz.

Pro Tip: Be sure to consult the manufacturer's data sheets for which mixture works best over the frequency range that needs attenuating. If there is more than one noise source, perhaps one at the lower frequency band and one at the upper, then the use of two different types of ferrites is likely required.

Second, determine the cable size for any signals that may be radiating from the cables attached to the end-product. Ferrite suppression cores are available in a wide variety of internal diameters that fit almost any possible cable size. Impedance is proportional to the square of the number of turns and the core geometry. Impedance, and therefore the suppression available, increases substantially as the number of turns through the core increases. The dimensions of the core also play a vital role in the amount of RF suppression available. Doubling the length or height of the core doubles the impedance. Larger cores provide more impedance and thereby more suppression than smaller ones.

Predicting the Amount of Attenuation from a Ferrite Core

Predicting the amount of attenuation from a ferrite core is possible if the source and load impedance of the offending signal (identified as Z_S and Z_L, respectively), along with the core's impedance (available from manufacturer's datasheet or catalog, identified as Z_{SC}) is known. This attenuation is predicated by taking 20 times the $\log_{10}$ of $(Z_S + Z_L + Z_{SC})$ divided by $(Z_S + Z_L)$.

To utilize this formula in practice you will need to refer to the ferrite manufacturer's website, datasheet, or catalog, knowing what particular frequency you need to suppress and the cable dimension. From there, select the appropriate material and size of ferrite choke required. Let's assume that you have a troublesome emission emanating from the power cable at 27 MHz and it is 5 dB over the emissions limit. Looking through the ferrite manufacturer's website, you determine that mixture C might work best over this frequency and for 2 turns of cable through the core that $Z_{SC} = 250\Omega$. You might also know or have reason to suspect that the offending circuit has $Z_S = Z_L = 50\Omega$. The predicated attenuation is then equal to 20 x $\log_{10}$ (50 + 50 + 250)/100 » 10.9 dB. The particular ferrite chosen in this example appears to have about 5 dB more attenuation than is required to successfully suppress the unwanted emission to the limit line plus provide another 5 dB for margin, allowing the end-product to pass with ease.

The next step in the process is obtaining samples of the ferrite identified above and repeating testing using the same exact setup (same EUT, same power supply voltage, same cable configuration, etc.) to confirm it works.

The above assumes you have a good understanding of both the source and load

impedances of the offending circuit. If the assumption is incorrect then the predicated attenuation will be in error. That's why it is important to test the chosen ferrite in the actual end-product configuration that the failure was originally observed on.

Pro-Tip: If you're unsure of the actual source and load impedances of the offending circuit then repeat the above calculation using several different impedance values and select more than one ferrite component that might work. Select impedance values on both the low and high-end of what you think might be possible. Obtain samples of several different cores based on your calculations of possible attenuation, then repeat testing with each different ferrite selected, noting which gives the best attenuation in the actual end-product application. Use that component on all production going forward.

Summary

- Ferrites are frequency dependent components used to attenuate unwanted high frequency RF signals.
- Many different configurations and material types are available.
- Choosing the correct ferrite is dependent upon the frequency of the offending signal and the size of the cable that it must attach to.
- The attenuation possible for a ferrite is dependent upon the material it is made from, its size and core geometry, number of turns through the core, the source and load impedance of the offending circuit, and the core's impedance.
- Predicting the amount of attenuation that any particular ferrite can provide involves a review of the ferrite's data sheet and plugging numbers into a simple formula.

References and Further Reading

1. "Predicting the Performance of Ferrite Suppression Cores," Fair-Rite Products Corp. YouTube Channel, November 24, 2020.

AMPLIFIERS

RF Power Amplifiers for Conducted RF Immunity Testing

Conducted RF immunity is a test method that subjects the equipment under test (EUT) to a source of disturbance comprising electric (E) and magnetic (H) fields, simulating those coming from intentional RF transmitters. These disturbing E and H fields are approximated by the E and H near-fields resulting from the voltages and currents caused by the test setup described in standards such as IEC 61000-4-6.

To ensure test repeatability and not cause either over or under testing, standards such as IEC 61000-4-6 have specific requirements for how the test is conducted. A small portion of the standard describes the requirements for generating the fields using a RF signal generator and power amplifier. If you're performing commercial conducted radiated immunity tests strictly by the book, you will want to utilize a radio-frequency (RF) signal generator and power amplifier combination that fully complies with IEC 61000-4-6.

For the RF signal generator, this means:

> *A generator capable of covering the frequency band of interest able to be amplitude modulated by a 1 kHz sine wave with a modulation depth of 80 %. The generator will have manual control (frequency, amplitude, modulation index), or in the case of RF synthesizers, programmable with frequency-dependent step sizes and dwell times.*

Note: For testing according to IEC 61000-4-6, the frequency band of interest mentioned above is 150 kHz to 80 MHz.

If the RF signal generator on its own is not able to generate the required severity level required by the standard, then an additional piece of equipment called a broadband power amplifier (PA) is necessary to amplify the output signal from the RF generator to obtain the required test level.

The focus of the remainder of this article is on the output power characteristics of the PA required to generate a test level of 10V.

Annex E of the standard provides further guidance on selection of the PA required to

generate a 10V test level. This is an informative annex, not normative, meaning it is there for clarifying purposes only, not part of the basic requirement of the standard.

Annex E states something to the effect:

> *The available output power of the PA is determined by taking into account the attenuator T2 (6 dB), the amplitude modulation depth (80 %), and the minimum coupling factor of the coupling-decoupling-network (CDN) or clamp used.*

Let's cover the last item in the above requirement – the minimum coupling factor.

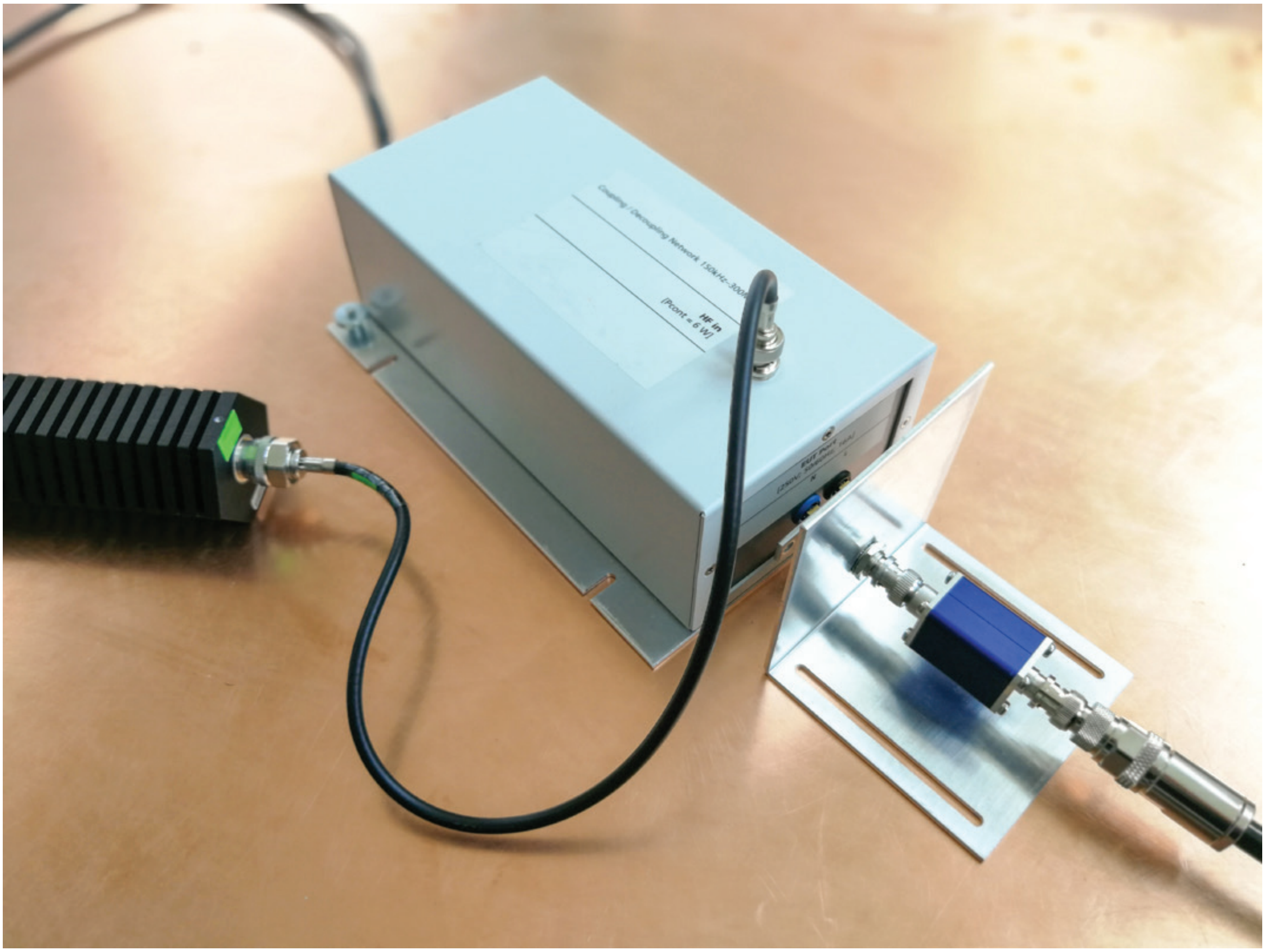
Minimum Coupling Factor

The minimum coupling factor is given as the ratio given by the open-circuit voltage obtained at the equipment under test (EUT) port of the coupling and decoupling device divided by the open-circuit voltage obtained at the output of the test generator.

Note: Examples of coupling and decoupling devices are:

- CDNs;
- direct injection networks (with decoupling);
- clamp injection devices (EM clamps).

The minimum coupling factor **(± 1.5 dB)** is measured by using the output level setting circuit (see IEC 61000-4-6 for details). The coupling factor is the ratio between the output voltage, obtained when using a coupling and decoupling device in



series with a 150 Ω to 50 Ω adapter and the output voltage when using two 150 Ω to 50 Ω adapters in series.

Required Power Output of PA for a 10V Test Level

Annex E states that a CDN has a minimum coupling factor of 0 dB and the required output power of the PA is just 7 W.

A current clamp winding with a ratio of 5:1 has a minimum coupling factor of -14 dB and the required output power of the PA is more substantial at 176 W.

An EM clamp has a minimum coupling factor of -6 dB, and the required output power is only 28 W.

As can be observed from the above, the choice of power amplifier depends a lot on what device is used for coupling and decoupling. An EM clamp is a popular choice for many test facilities and only requires a PA rated for a maximum of 28 W, however, CDN's are the preferred coupling and decoupling devices for reasons of test reproducibility and protection of the auxiliary equipment. If you have a product with a lot of inputs and outputs, you'll need a lot of different types of CDNs to cover all possible equipment configurations, but you won't require a PA that needs to output too much power.

To play it safe, picking up a PA with double or triple the necessary output power will ensure you always have enough power and won't always be running the PA at the top of its capability.

Summary

This was a quick run-through IEC 61000-4-6 for power amplifier specifications. For more information on this important subject, please see the following.

References and Further Reading

1. *Electromagnetic compatibility (EMC) – Part 4-6: Testing and measurement techniques – Immunity to conducted disturbances, induced by radio-frequency fields* (IEC 61000-4-6:2013).

ANTENNAS

Requirements of Antennas for EMC Testing

Antennas used for EMC testing possess several characteristics which make them ideal for use in a fast-paced, production-like EMC test environment. This article will briefly describe what these characteristics are, starting with the most important parameter – antenna factor.

Antenna Factor

The EMI receivers, spectrum analyzers, cables, attenuators, and other paraphernalia used in EMC testing are specified with a characteristic impedance of 50 Ω. Therefore, an antenna used to measure emissions must be calibrated in terms of volts output into 50 Ω in order to supply a given field strength at each test frequency. This characteristic is called antenna factor.

Antenna factor units are dB/m for E-field antennas. Make sure the antenna you choose is provided with a table of the antenna factor versus frequency because in order to convert (in software) the measured voltage at the antenna terminals into the actual field strength at the antenna, you have to add the antenna factor and cable attenuation (also a function of frequency). Here is an important equation to remember in case you need to troubleshoot a problem with your measurement system not measuring correctly:

E (dBμV/m) = V (dBμV) + Antenna Factor (dB/m) + Cable Attenuation (dB) – Preamp gain (dB).

Note 1: Ignore preamp gain if a preamp is not used.

Operating Frequency

The most accurate reference antenna for emissions measurements is the tuned dipole. The problem with using this type of antenna in an EMC test facility is the need to re-tune the dipole for each frequency to be measured. In order to speed up the measurement process, broadband antennas that cover multiple of frequency ranges are used. Their use eliminates the need to re-tune at each measured frequency. Simple examples of broadband antennas are the biconical (30-300 MHz typical), log periodic (300 to 1000 MHz typical), or the combined BiLog (30 to 3 GHz typical).

Note 2: Military standards do not allow use of the BiLog and stick to using other broadband antenna types like the horn antenna.

Note 3: Log-periodic antenna designs with the same dimensions will provide largely matching performance.

Polarization

CISPR requires use of "plane" polarized antennas such as the biconical, log periodic, or BiLog that can be positioned either in the vertical or horizontal polarity for testing. Circularly polarized, log-spiral-type antennas are not permitted.

Power Handling Capability

Although not always recommended, the same antennas that are used for emissions can also be used for immunity testing. However, they must be able to handle the amount of power they will need to deliver to generate the required field strength. This capability is achieved by using a properly rated wide-band ferrite core 1:1 transformer placed at the antenna's feed point. Because this item converts the **bal**anced feed of the dipole to the **un**balanced connection of the coaxial cable, it's been given the unique name balun.

Since the balun could get fried by supplying it too much power during immunity testing, many have separate antennas devoted to just emissions and/or just immunity testing.

Low Voltage Standing Wave Ratio (VSWR)

Antennas such as the biconical have high VSWR ratings at their lower frequency range. High VSWR means more power is required to generate any given field strength, so a lower VSWR is desirable.

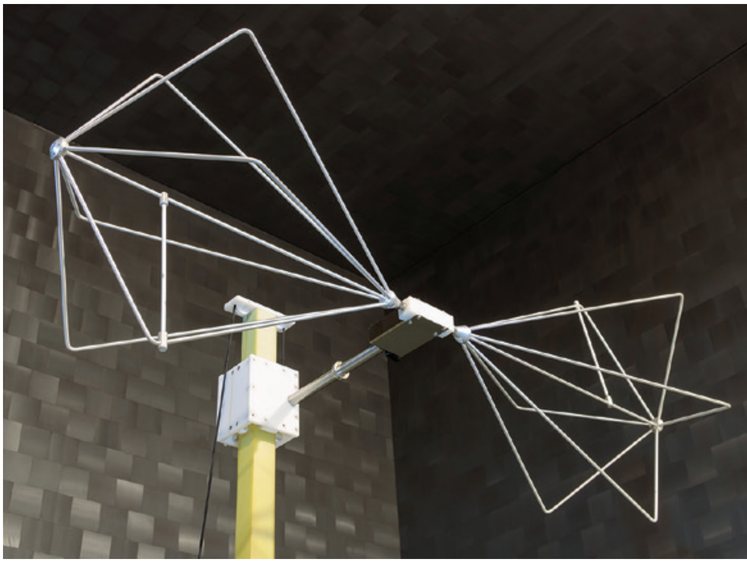
Antenna Gain

For an antenna used for immunity testing, low gain means needing a bigger amplifier to generate the required field strength. Be sure to check the antenna gain over the entire frequency range of interest to ensure there is enough power available in the amplifier chosen.

Other Considerations

To a lesser extent, some other characteristics that are important in selecting antennas for EMC testing include:

- Quality – Does the antenna have a rugged design, and is it able to withstand the normal wear and tear of daily use and survive shipping in a protective box back to the manufacturer for repair or to a calibration facility for calibration?
- Cost – Will the lab go broke outfitting the entire facility?
- Customer support – If I have a question, can I get a hold of someone, and can they help me with my technical problem?
- Availability – If it breaks, can I get another one just like it? I want to buy a new one now, is it available?



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CHAMBERS

Non-Technical Considerations Often Overlooked When Determining ROI for an In-House EMC Chamber

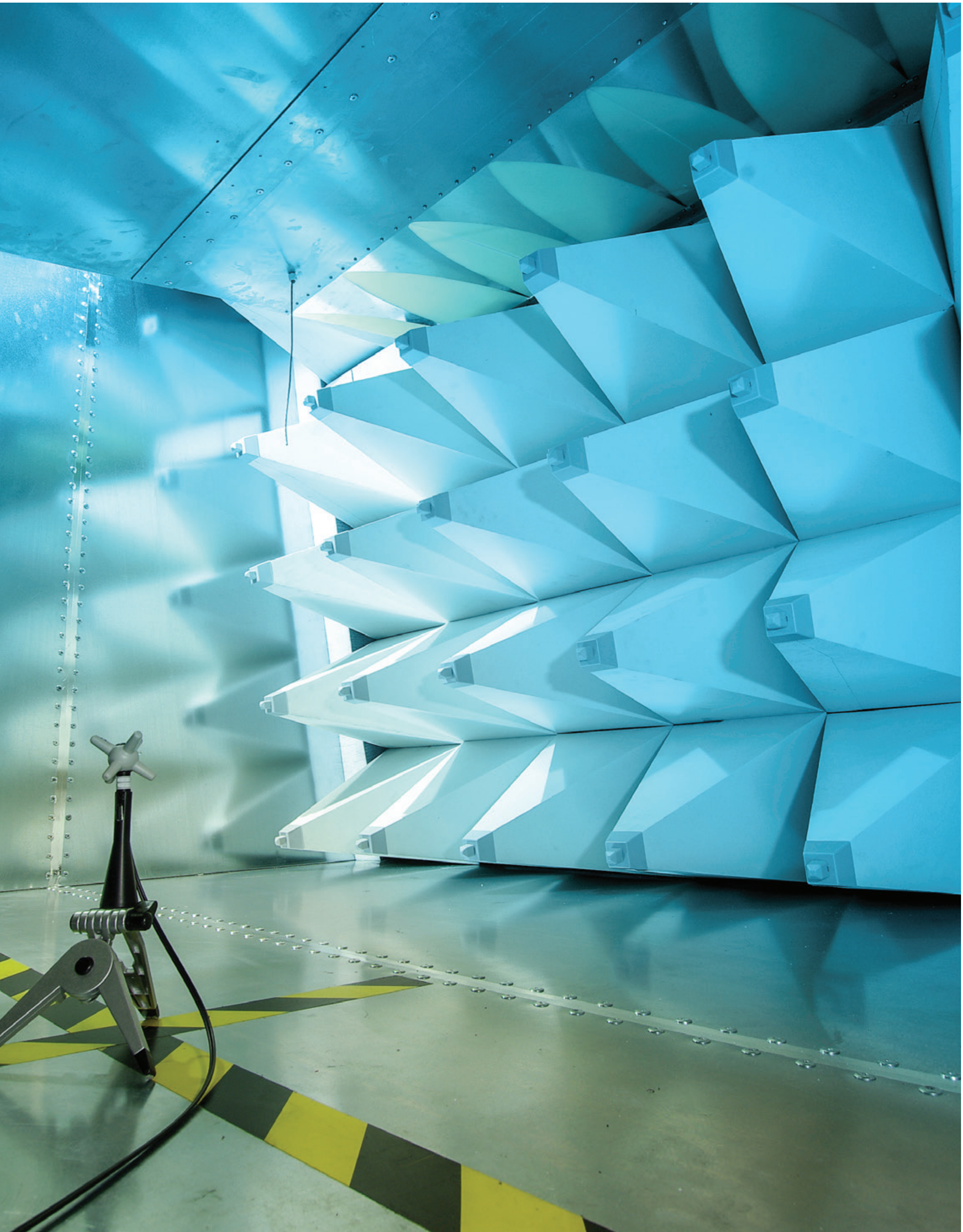
Disclaimer: This article describes unique situations where it might be beneficial for an organization to develop its own in-house EMC test capability and purchase an EMC chamber. It is in no way meant to disparage the many excellent third-party test facilities that exist throughout the world today.

Are you considering the purchase of an EMC chamber for in-house testing? If so, what factors should you consider for determining if the investment is a wise choice or if the continued utilization of a third-party test facility is the better option? For some, the decision is easy. The volume of products they intend to develop that require EMC testing is so low that the cost to bring EMC testing in-house is clearly not justified. For others, they may have a lot of new products in development (or plan to) and taking them to an outside EMC testing facility on a regular basis is not only costly, it is inconvenient and time-consuming. For those in this latter group, trying to decide if they should bring EMC testing in-house is not always a straight-forward decision.

To ease some of the thought process that is involved in making this decision, this brief article can be consulted as it highlights important things to consider when determining the return on investment (ROI) for an in-house EMC chamber.

Return on Investment Calculation

Management will likely require some form of ROI calculation before they will release corporate funds to purchase such an expensive item. The calculation is basic and can be found on the



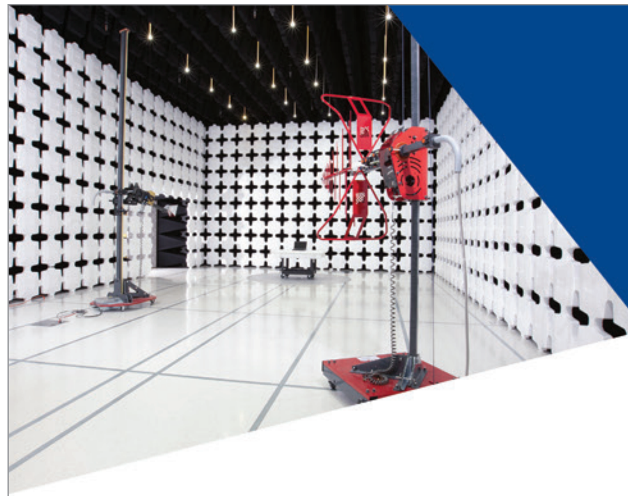
internet however, your firm may already have their own unique form and calculation that must be completed and reviewed by an accountant (or other business professional) prior to requesting management approval to purchase an EMC chamber. What are some of the things that should go into your unique and customized ROI calculation?

Here are some of the basic items to consider for inclusion in the ROI calculation:

1. Number of expected test events over the next x number of years (x might be three, four, or five, for example).
2. Cost of item 1 above if conducted out-of-house at a third-party test facility (include travel cost and time, lodging, meals, flights, in addition to test fees for each expected test event).
3. Cost of the EMC chamber and all associated equipment (antennas, turntable, amplifiers, spectrum analyzers, cables, filters, line impedance stabilization networks, etc.).
4. Cost to install the chamber.
5. Cost of calibration and chamber verification tests over the next x numbers of years.
6. Cost of in-house labor and staff to run and maintain the EMC chamber and all associated equipment over the next x number of years.
7. Cost for electricity to run and light the chamber over the next x number of years.
8. Cost to train in-house staff to run the chamber.
9. Cost for accreditation of the tests to be performed in the chamber and laboratory management.
10. Depreciation of the chamber over x number of years.
11. Cost of any other item you can think of.

Ambiguous Items to Include in the ROI Calculation

After you put all of the above basic items into your ROI calculation you may still end up, on paper, with a number that does not fully justify



the procurement of an EMC chamber. That does not necessarily mean that it is a bad decision. You may need to include some of the more ambiguous items in your ROI calculation before you can justify the purchase. For these ambiguous items it's often tougher to put a hard dollar amount to them, but they can and should also be used to make the decisions to purchase an in-house EMC chamber.

Below are some of the more ambiguous items to consider when developing the ROI calculation for an in-house EMC chamber.

1. With an in-house chamber, you can customize the configuration of filtering, power, turn-table size, size of the chamber, cooling, heating, size of the doorway, lighting, EUT monitoring, size of antennas, etc. to accommodate the unique requirements that only your EUT has. When using a third-party facility, you must utilize whatever configuration they have available, which may or may not require extra effort on your part to "make it work" for your unique EUT setup.
2. Your in-house chamber is available for testing any time you need it (24/7).
3. If your EUT fails testing and you need to go into troubleshooting mode, you don't have to worry too much about the clock ticking and over-time, getting removed from the chamber, and wasting expensive third-party lab test fees.
4. You will never again go back to your organization with a non-compliant product, after having spent a lot of time and money testing it at a third-party test facility trying to obtain passing results.
5. Engineering expertise (those who know the product and the design), are on-site, nearby, and available to help troubleshoot the EUT as required.
6. Your facility has more options for fixes (capacitors, ferrites, resistors, etc.) should they be required.
7. There are technicians on staff who are well-trained in making modifications on the fly should modifications to pass be required.

8. Determining if a minor modification to the product or if a part replacement for an end-of-life component causes a non-compliance is much quicker and easier.
9. The time required to get the product to market is much quicker.
10. Maintaining continued compliance is easier. You can re-test your device anytime you suspect a change might have been implemented that may affect compliance.
11. Customer-witnessed tests can be scheduled anytime it is convenient for you and your customer.

Conclusion

These and other luxuries often do not exist when you take your product to a third-party test facility. What value proposition do they provide and how do you incorporate them into an ROI calculation? That is a question that only you and your firm can decide.

TIPS FOR SELECTING Chambers

1. Selection of a chamber is determined by the standard being tested to. Some types of EMC Chambers are: Commercial, MIL STD/DO-160, CISPR 25 and Reverb.
2. Commercial chambers are used for IEC and CISPR standards for Emissions and Immunity testing. Typically, "Semi – Anechoic" and achieve CISPR16 (Emissions) and IEC 61000-4-3 (Immunity) chamber performance requirements.
3. Semi-Anechoic Chambers are strategically lined with absorber and ferrite to meet specifications without fully lining all surfaces.
4. Verification for CISPR 16 compliance is Normalized Site Attenuation (NSA) (26 MHz-1 GHz) and Site Voltage Standing Wave Ratio (sVSWR) (1-40 GHz). This verifies the chamber "Quiet Zone". Quiet zones are normally equal to the turntable diameter. EUT's can't be larger than the quiet zone.
5. For compliance, variations in the quiet zone performance cannot exceed +/-4db for NSA and 6dB for sVSWR.
6. Verification for IEC 61000-4-3 is a field uniformity test. Typically, a 1.5m x 1.5m vertical plane consisting of 16 points spaced 0.5 m apart is the measured area. At least 12 Points must vary by <6dB.
7. MIL STD and DO-160 chambers can be Semi-Anechoic or Fully Anechoic. Standards require the absorber have a minimum absorption of 6dB from 80MHz to 250MHz and 10dB above 250Mhz. A table with a conductive top is used for testing the EUT and is bonded the shield ground.
8. CISPR 25 chambers are fully lined on walls and ceiling, contain a similar table with metal lining on top, and must pass the Long Wire Test or the Reference Site Method test to meet the Standard.
9. Reverb chambers rely upon the reflectivity of the walls and an internal movable paddle to reflect generated signals and increase the value of V/m generated from the transmit antenna.
10. Information needed to design a reverb chamber is the lowest frequency, the test volume, maximum V/m, and standard to be tested to (MIL STD, DO, ISO).

These tips are presented by

RAYMONDEMC

ESD SIMULATORS

A Non-Typical Use for an ESD Simulator

After a spectrum analyzer or EMI receiver, an electrostatic discharge (ESD) simulator is often one of the other most expensive items required for a compliance test lab or contained in a precompliance tool kit. If you have to purchase one, you might as well get as much mileage out of it as you can, right?

ESD Simulator Usage

You may have thought that ESD simulators could only be used for performing ESD testing in accordance with published ESD test compliance standards such as IEC 61000-4-2. It turns out there is another application for ESD simulators besides performing compliance tests strictly in accordance with the rules.

Here's a list of a few of the things ESD simulators can do:

- *Test products in accordance with published standards (full compliance testing).*
- *Aid in troubleshooting ESD compliance test failures at the bench (precompliance testing).*
- *Aid in troubleshooting electrical fast transient/burst (EFT) test failures at the bench (precompliance testing).*

EFT Precompliance Testing

This last item is one that you might not have thought about before. EFT pulses, as described in IEC 61000-4-4, are very similar to the pulses produced by ESD generators. If you don't possess an expensive EFT generator, but you do own an ESD simulator, and your product is failing the EFT compliance test, you can try to induce EFT failures by using the ESD simulator to generate transients onto the cables of the EUT. One way to accomplish this is to take a "source" cable grounded at one end and tie it to a "victim" EUT cable for a length of at least 1 m. Apply ESD pulses of 10 to 20 pulses per second to the non-grounded (open-end) of the source cable, and then look for failures of the EUT. EFT test failures are replicated more precisely when the ESD simulator is set to double the desired EFT test voltage (i.e. a 4 kV EFT pulse is more closely replicated when the ESD simulator set to 8 kV). Next time you experience this situation, give this quick and dirty experiment a try.

Other Alternatives

If you don't own a real ESD simulator, there are several books that describe less-expensive and simple alternatives that can be easily constructed.

These include fabricating an ESD simulator from a butane fire starter utilizing its piezoelectric element or placing a few coins inside a plastic bag and shaking around the EUT to produce intense EM fields. In fact, the above-mentioned simulation of EFT failures using a real ESD simulator might be replicated more easily and less-costly by setting up what is referred to as the chattering-relay test. Consult the references for details on how to fabricate these alternative ESD test methods.

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FILTERS

How EMI Filters Are Specified for RF Performance

Electromagnetic Interference (EMI) filters (also called a power line filters), are passive, frequency selective, bi-directional (two-port) networks comprised of inductors, capacitors, resistors and ferrites.

These low pass filter devices are often thought of as just components whose sole purpose is to suppress unwanted emissions emanating from the electronic devices they're installed in, so these products can pass regulatory compliance emissions tests.

Don't overlook the fact that EMI filters can also be used to prevent unwanted RF noise (such as electrical fast transient burst, conducted RF, and some surges) from entering susceptible devices, especially if the EMI filter is combined with proper device shielding in a kind of "belt and suspenders" approach to electromagnetic compatibility. In this case, EMI filters help make RF susceptible devices more rugged in their surrounding environments, if these environments happen to also be heavily polluted with RF noise. EMI filters come in handy when the electronic products they are paired with must comply with national and international standards for **both** emissions and immunity (susceptibility).

Pro Tip: *Not always, but typically, common-mode (CM) noise predominates up until ~ 30 MHz, whereas differential-mode (DM) noise prevails up until ~ 1 MHz. EMI filters help suppress both types of noise (CM and DM).*

Placement

EMI filters for power line filtering are placed between the AC (or DC) power supplied to the end-product and its power supply input (i.e., typically placed ahead of noisy switched-mode power supply inputs).

Ideal EMI Filter

If installed correctly, an ideal (perfect) EMI filter should be able to substantially reduce the amplitude of all noise frequencies greater than the filter's cutoff frequency (the stopband or reject band) and pass all low frequencies signals (the passband).

Source and Load Impedances

For the EMI filter to do its job, it's important to understand both the source and load impedances (Z) it will be connected to. The wrong configuration of EMI filter will only work if there is a Z mismatch between source and load.

See Table 1 where

L = Inductor

R = Resistor

F = Ferrite

C = Capacitor

Pro Tip: *The number of passive components (elements) in an EMI filter will impact the amount of insertion loss (dB) it can provide. One-element filters provide roughly 20 dB/decade of roll-off or attenuation, two-element filters provide ~ 40 dB/decade, and three-element filters provide ~ 60 dB/decade of attenuation. If more attenuation is required, select a multi-element filter.*

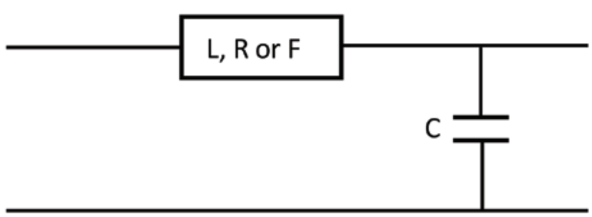
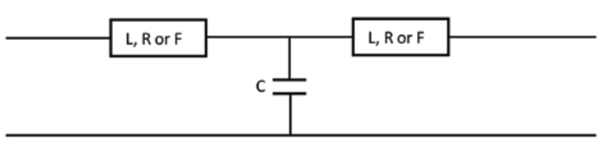
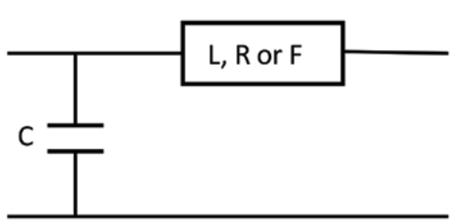
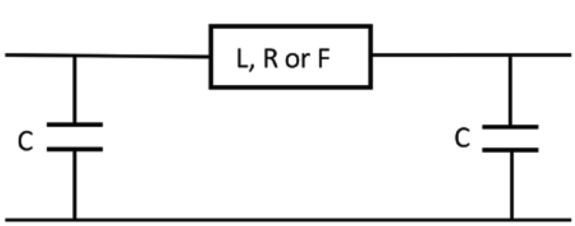
Source Z	**Filter Configuration**	**Load Z**	**Analysis**
Low (<100Ω)		High (>100Ω)	Shunt element faces High Z load and series element faces the Low Z source.
Low (<100Ω)		Low (<100Ω)	Use inductive series element or T filter for greater roll-off.
High (>100Ω)		Low (<100Ω)	Shunt element faces High Z source and series element faces the Low Z load.
High (>100Ω)		High (>100Ω)	Use shunt capacitive element or π filter for greater roll-off.

Table 1

Choosing an EMI Filter

When considering an EMI filter, several important specifications come into play. These specifications include the following:

1. End-use voltage rating: operating voltage, nominal voltage, rated voltage, etc.;
2. End-use current rating: operating current, nominal current, rated current, etc.;
3. Rated frequency: typical frequencies are 50 or 60 Hz and 400 Hz for military applications, and DC.
4. Insertion Loss (dB) or IL (dB): The filter's attenuation – specified in dB;
5. Size and structure: many shapes and sizes available;
6. Environment: temperature range – operation and storage;
7. Safety certification standards: required by most end-product applications;
8. Dielectric Strength Voltage: Hi-pot or the high potential insulation test voltage;
9. Leakage current: critical in medical device applications where patient safety is paramount.

Example EMI Filter Specifications (Source: Schaffner FN 2090 Datasheet)

- **Rated Voltage:** 250 VAC (50/60 Hz), or 250 VDC
- **Rated Current:** 1-30A @ 40°C Maximum
- **Insertion Loss (dB):** Per CISPR 17; CM=50 Ω/50 Ω sym; DM=50 Ω/50 Ω asym *(provided on manufacturer's datasheet in the form of bode plots with attenuation listed on the vertical axis and frequency on the horizontal axis).*
- **Size and structure:** *Unique to each filter. See manufacturer's datasheet.*
- **Temperature range (operation and storage):** -25°C to +100°C (25/100/21)
- **Certified to:** UL 1283, CSA 22.2 No. 8 1986, IEC/EN 60939 (applies to AC and DC applications)
- **High potential test voltage:**
  - P –> PE 2000 VAC for 2 sec (equiv. cap <88 nF)
  - P –> PE 2550 VDC for 2 sec (equiv. cap >88 nF)
  - P –> PE 2500 VAC for 2 sec (B types)
  - P –> N 1100 VDC for 2 sec
- Leakage current: @ 250V AC/50 Hz = 0.45 mA; @ 120V AC/60 Hz = 0.26 mA.

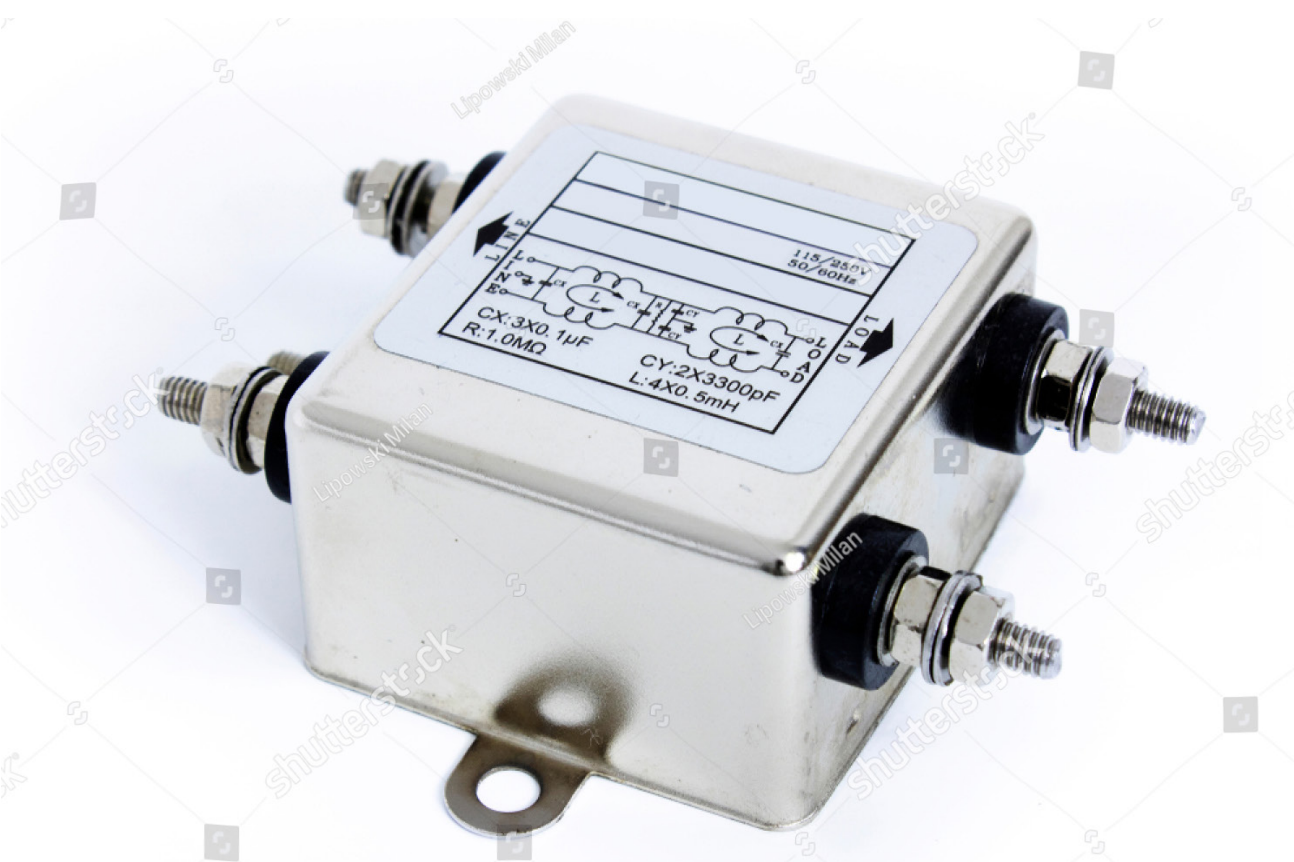
Pro-Tip: *Insertion Loss (dB) is one of the most important parameters to select when specifying an EMI filter for any given application. See Reference 7 for more on this important topic.*

Leakage Current

The amount of leakage current present on the power supply lines to ground is highly dependent on the voltage on the conductor, capacitance reactance (X_C) between the conductor and ground, and the resistance between the conductor to earth. Be sure to thoroughly review the manufacturer's specifications for this critical parameter, especially if the filter is to be installed into a medical device.

Summary

- EMI filters are passive, low pass devices.
- They help suppress RF noise emanating from or to any electronic device.
- They are comprised of inductors, capacitors, resistors, and ferrites.
- EMI filters help suppress both common-mode and differential-mode noise.



- They are placed between the AC (or DC) power supplied to the end-product and its power supply input.
- A perfect EMI filter will substantially reduce the amplitude of all noise frequencies greater than the filter's cutoff frequency and pass all wanted low frequencies signals.
- For the EMI filter to best do its job, it's important to understand both the source and load impendances (Z) it will be connected to.
- A multi-element filter will provide more IL (dB) than a single-element filter.
- The following specifications are important should be considered when specifying an EMI filter:
  - Rated Voltage
  - Rated Current
  - Rated Frequency
  - Insertion Loss (dB)
  - Size and structure
  - Operating environment
  - Safety certifications
  - Dielectric Strength Test Voltage
  - Leakage Current

References and Further Reading

1. "Three Essential Parameters to Check While Selecting Power Line EMI Filters," Croydon EMC Solutions YouTube Channel, May 2, 2020.
2. "Most Important Criteria to Select EMI EMC (EMV) Filter," Croydon EMC Solutions YouTube Channel, March 29, 2020.
3. "Multi-stage AC/DC EMI Filter with Excellent Attenuation Performance, Schaffner Two-Stage Filters FN 2090 Datasheet.
4. Montrose, M., *EMC Made Simple, Printed Circuit Board and System Design*, Montrose Compliance Services, Inc., 2014
5. MacArthur, D., "What Every Electronics Engineer Needs to Know About: Filters," *In Compliance Product Insights*, November 2018.
6. MacArthur, D., "Let's Talk About Why Filters Fail," *In Compliance Product Insights*, November 2019.
7. MacArthur, D., "An Alternative Approach to Specifying an EMI Filter," *In Compliance Product Insights*, November 2020.

SHIELDING

The Importance of Considering RF Suppression Techniques Early in Design

This article briefly describes why it's important to consider what RF suppression/filtering techniques will be applied to your product as early in the design process as possible.

Scenario

Let's say that for whatever reason, you developed a product for the non-residential, industrial market where it is clear that Class A radiated and conducted emissions are required. Sometime after the product meeting, Class A emissions is introduced, a new market emerges with the potential for a lot of sales, but it requires the same product now comply with Class B requirements, which are about 10 dB more restrictive in the emissions allowed to be emitted from the device. This Class A product must be redesigned to meet Class B or somehow made to comply with Class B requirements before it can be shipped into that market.

Let's also say that you do not want to redesign this already existing Class A product to meet Class B emissions because it's too cost prohibitive and time consuming (you want to start designing the next new product, not fix the old ones). In this situation, what do you do?

Depending on what the source of the emissions are and where they are emanating from the device, the best approach may be to determine if adding ferrite choke(s) to the cable(s), using an RF absorbing pad(s), applying shielding can(s) to a noisy chip(s) or other area(s) or a combination of all of the above may allow your product to pass Class B.

Following are some issues to consider with applying this "adding on fixes" methodology.

Issues with "Adding on Fixes" After a Design Freeze

- **The "ferrite" solution**

  The sources of emissions/offending signals may be spread out in frequency (some low, some high) and you may not be able to find one solution, like adding a single ferrite choke to a suspect cable, that is able to suppress emissions over both low and high frequencies.

  In this situation, you need more than one ferrite choke, and you probably have to select one choke that is made of one type of ferrite material that is only useful for suppressing lower frequency emissions, and another choke made of another type of material that tackles the higher frequency emissions. One problem with this solution is that adding more than one choke may appear "kludgy" and would not likely be accepted by product management or the end customer.

- **The "ferrite plus absorber" solution**

  If the offending frequencies are spread low and high as in the above scenario, an alternative to using two ferrites of differing materials and suppression capabilities would be to use a combination of low-frequency clamp-on ferrite choke for any emissions emanating from cables and a high-frequency RF absorber sheet to suppress emissions at the source, such as those emanating from fast clock chips or microprocessors.

  This solution may not appear as kludgy to product management and the customer as the two-ferrite solution described above but may involve more experimentation and design effort to figure out where the best location is to place the absorbing pad to reduce emissions and how to effectively incorporate it on a production basis.

There may also be heat issues to contend with depending on the end-use environment of the product and how hot components may get underneath the absorber pad. Re-doing temperature testing may be in order if this solution works.

Other tests such as vibration, shock, and bump may also be required depending on how the absorber pad solution is implemented. You want to make sure by adding the absorber pad, you don't create a new problem elsewhere.

- **"Other" Solutions**

  You may be able to incorporate a shield can over offending high-frequency noise source and use a clamp-o ferrite for lower frequency emissions. Reference 2 covers more on the subject of shielding at the PCB level.

  Since our original goal was to do as little as possible (not go back into layout), adding a shielding can over offending sources of emissions may not be a viable solution depending on the original design and how much room you have. If room is tight, you may not be able to effectively add a shield can.

Final Thoughts

No matter what the RF suppression/filtering solutions chosen as add-on fixes to an already production-released product are, the chances of them working on the first try are slim to none. Plan for the "adding on fixes" approach to take a lot of time. It may be easier than relaying out a board, but you still need to figure out what types of ferrites would work best, including size, types of materials, cost, lead-time, etc. The same is true for selecting RF absorber pads.

Had the requirement for Class B emissions been specified and included as part of the original design, there would have been much more freedom to implement more effective solutions sooner and at lower levels of the design, such as at the circuit board level. This "adding on fixes" and hoping for the best approach would have been unnecessary and you would have already started working on your next new design.

References and Further Reading

1. MacArthur, D., "Let's Talk About Flexible Absorber Sheets," *In Compliance Product Insights,* October 2019.
2. MacArthur, D., "Let's Talk About Shielding at the PCB Level," *In Compliance Product Insights,* August 2019.
3. MacArthur, D., "What Every Electronics Engineer Needs to Know About: Filters," *In Compliance Product Insights,* November 2018.
4. MacArthur, D., "What Every Electronics Engineer Needs to Know About: Shielding," *In Compliance Product Insights,* August 2018.

SPECTRUM ANALYZERS

How Not to Blow Up Your Spectrum Analyzer

Spectrum analyzers are expensive pieces of equipment that should be handled with care, especially when it involves applying signals to the RF input. Some new users may not know what "care" means and how to go about ensuring the spectrum analyzer they're using is protected from overloading and damage. The intent of this article is to describe how not to blow up your spectrum analyzer. Those new to the subject of spectrum analyzers and measurement receivers may first want to review references 1 through 3 which cover some of the basics concerning spectrum analyzers and measuring receivers in general.

RF Spectrum Analyzer Partial Front-End

Figure 1 shows the components of a partial "front-end" to a spectrum analyzer.

It is usually the mixer that is most susceptible to damage, followed by some of the other components identified in Figure 1.

RF Input

The RF input port (usually located on the front of the spectrum analyzer) is where the signal desired to be measured goes. Before applying any signal to this port, it is prudent to first ask ourselves, "What can we do to this input? and "What can we apply here safely?"

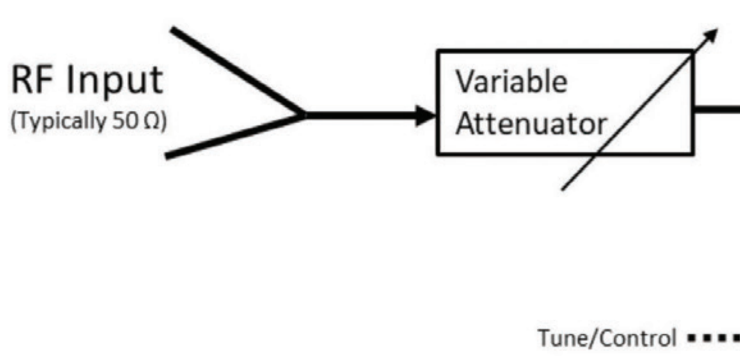


Figure 1: RF Spectrum Analyzer Partial Front-End

These questions and their answers should be revisited each time we set up the spectrum analyzer to take a new measurement, especially if they are radically different measurements from ones we're normally used to taking. Complacency in not following these rudimentary steps could spell disaster and embarrassment if we're found guilty of blowing up an expensive spectrum analyzer. Spectrum analyzer users should also consider the potential loss in revenue due to the cost to repair and test/product development time lost if a backup is not available when a spectrum analyzer is damaged.

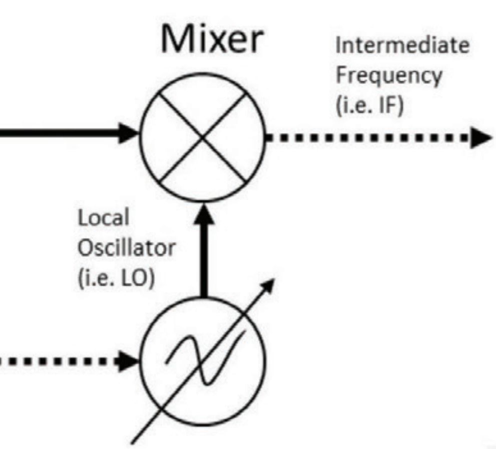
RF Input Warning Label

The good news is that preventing such a catastrophe, such as an overloaded RF input port, isn't that difficult. There is usually some descriptive label near the RF input port that indicates what the input capabilities for the RF input are. This label is identified with the familiar exclamation point inside a triangle warning symbol as shown in Figure 2 on page 72.

It's VERY important to carefully read and understand what it says on this label before attempting to measure any signal! The warning label will typically tell you the maximum RF signal levels that it can handle and also the maximum DC voltage levels it can handle.

Maximum RF Input Level

Check the warning label to determine what it indicates as its maximum RF input level. A typical value is +30 dBm (1 Watt). Depending on the



strength of the signal you want to measure, you may have to install an external attenuator or RF sampler (if measuring signals with high RF power) to ensure the maximum level seen by the spectrum analyzer is always maintained below its specified maximum RF input level of +30 dBm.

Maximum DC Voltage

Be careful because a lot of microwave spectrum analyzers only allow a maximum DC voltage level of zero volts! Some other RF spectrum analyzers only allow a couple of DC volts maximum (there are exceptions, that allow hundreds of DC volts). The maximum DC voltage the spectrum analyzer can handle is also typically printed on the warning label.

In the situation where zero DC volts is the maximum DC input level you can ensure that the signal you want to measure is AC coupled. This is accomplished by inserting a coaxial DC block in front of the RF Input port to ensure no DC voltage can "get through" to damage the mixer and other front-end components.

Instruction Manual

It is probably also prudent to confirm the maximum DC voltage level and maximum RF input levels in the spectrum analyzers instruction manual before applying any signal. There may be more information found in the instruction manual and if there is a discrepancy between the front label warnings and the instruction manual, a call to the manufacturer is probably in order.

Summary

By combining knowledge of the specified input levels to a spectrum analyzer for both the maximum DC voltage level and maximum RF input level, and ensuring that we do not exceed both, we are able to safely operate our spectrum analyzer, accurately measure the signals we want to measure, and have a reliable measurement tool available the next time we need to use it. Trips to the "front office" to explain why we damaged the most expensive piece of test equipment in the facility are also minimized.

Figure 2: Warning Symbol found next to the RF input port

References and Further Reading

1. MacArthur, D., "EMI Measurement Receiver Requirements (CISPR 16-1-1)," *In Compliance Product Insights,* September 2020.
2. MacArthur, D., "Let's Talk About Real-Time Spectrum Analyzers," *In Compliance Product Insights,* September 2019.
3. MacArthur, D., "What Every Electronics Engineer Needs to Know About: Measuring Receivers," *In Compliance Product Insights,* September 2018.
4. "#51: Basic Spectrum Analyzer Do's and Dont's...," w2aew YouTube Channel, June 19, 2012.

TEST LABORATORIES

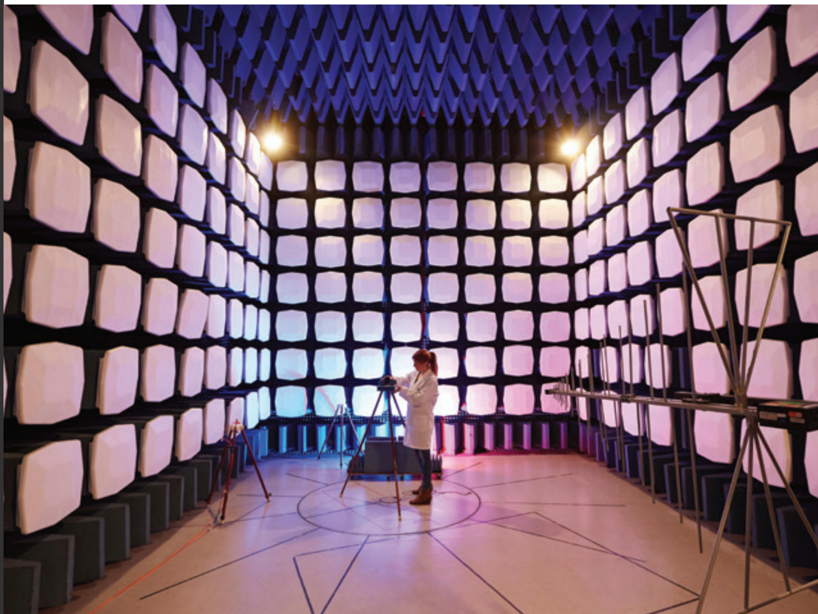
Trust but Verify

Whether you're trying to get a product through safety approval from one of the many Nationally Recognized Testing Laboratory's (NTRLs) or having full compliance EMC testing performed at an accredited or non-accredited third-party laboratory or an internal in-house test facility, it's imperative for successful completion of the project that as a compliance engineer or technician leading a product certification effort, you trust but verify the work of these other entities. For the remainder of the article, we'll call these other entities "service providers."

What is meant by the phrase "Trust but Verify"?

Trust means trusting those who may be doing work for us. We have already been through the process to qualify our service providers – we don't need to keep repeating that process each time we open a project with them. We know they are fully qualified and competent enough to carry out the activities we have asked them to do. We trust them to deliver the output of their work to the quality levels expected for our type of industry.

Verify means following through with those we have entrusted to make sure they have completed the tasks we asked for, fully and accurately, before we sign off on completion.



Why is "Trust but Verify" Important?

"Trust but verify" is important for several reasons:

1. **You know the product better than the service provider.**

   Those we've entrusted to do work for us don't know the product as well as we do and may miss important aspects that result in inaccurate testing or subpar certification or documentation.

   One example is when EMC test personnel don't fully exercise the EUT during emissions testing, passing results are obtained, and the non-compliant product is allowed to ship. When in reality, had the EUT been exercised correctly, it would have failed, and a non-compliant product would not have been allowed to ship until a fix was in place. Whose fault is it that the product wasn't exercised correctly during EMC testing? One guess – it's not the service provider's fault. It's your fault!

   Another example is having a safety agency review spacings on printed circuit board (PCB) and declare the board didn't meet the spacings requirements for the declared over-voltage category. The project was closed before you had a chance to react, and you had to accept a lesser over-voltage category rating for the product. Whose fault was it that the safety agency wasn't even reviewing the correct PCB layout in the first place? Yours!

2. **Service providers have other customers besides you.**

   Whether it be internal or external service providers, service providers all have other customers they are working for besides just you.

A lot of times, this means information overload for the service provider. Although your project might be important to them, if you're project is disorganized, it's going to take them a long time to sort through any issues given their heavy workload and all of the other projects they have going on at the time.

3. Service providers have limited resources – just like you.

Similar to item 2 above, service providers don't have extra resources to put into figuring out every aspect of testing your product. You need to take ownership and not assume you can just hand it over the wall for them to take care of for you. You need to be highly engaged, heavily involved, and be ready to supply information to your service provider before it's even asked for.

4. Service providers are always told schedule is a high priority.

Almost every project is a high-priority project if you're a service provider. One way to show service providers that your project is in fact, a high priority is to communicate with them on a regular basis as much as possible. Provide service providers with any information they're missing as soon as possible, hold regular status update meetings with them (at least weekly, more frequent if required), commit and deliver, and last but not least… continually "Trust but Verify."

References and Further Reading

1. Willink, J. & Babin, L., *Extreme Ownership – How U.S. Navy Seals Lead and Win*, St. Martin's Press, 2017.

PRODUCT MARKETPLACE

AK-40G Antenna Kit 20 Hz- 40 GHz

A.H. Systems' AK-40G Portable antenna kit offers the best frequency range and performance in one case. This is the antenna kit you need for everyday testing. Just grab it and go. Inside the case is all the reliable antennas, current probes, and cables needed to satisfy a wide array of customer requirements. The antenna kit also comes with a tripod with azimuth and elevation head for antenna positioning and a tripod carrying case. Excellent performance, compact size and a lightweight package make this kit a preferred choice for field-testing and can ship with next-day, on-time delivery. Other antenna kits available.

New AR Amplifier Designed for EMC Applications

The new 75S1G6C achieves at a minimum 75 W CW, from 1 - 6 GHz. The 75S1G6C, when combined with a U series amplifier, forms a unique two amplifier solution covering 10 kHz - 6 GHz, a testing range typically requiring three to four amplifiers. Features include class A Solid State design, 100% mismatch tolerant without the aid of foldback circuity, excellent harmonic performance, air cooled design with self-contained fans and low acoustical noise, and more. Learn more at https://bit.ly/3yHjOMZ.

Coilcraft Data Line Common Mode Chokes

Coilcraft data line common mode chokes provide general purpose EMI filtering from lower-speed data rates to ultra-high speeds such as USB3.x, HDMI2.0, and IEEE 1394. Eliminate CM noise in CAN, CAN FD, and FlexRay automotive bus systems. Our 1210CAN Series filters a broad frequency range of common mode noise with 50% lower DCR and higher current handling than other CANbus chokes in the market. They are ideal for CAN or CAN FD lines in automotive or general industrial automation applications.

IPX1 / IPX2 Drip Box System

Products intended for outdoor environments, or wet environments, often require Ingress Protection (IP) Code testing. ED&D's cutting-edge solution for the IPX1 and IPX2 tests is the DBX Series Drip Box Test Systems. ED&D also invented IP Code Turntables, including a mini-turntable (shown) that allows for meeting requirements of the IP Code. ED&D also offers the device mounted in a chamber or it can be offered in combination with the Spray Test Chamber (STC-DBX Series). Other products for the IP Code include Dust Chambers, Spray Test Chambers, Spray Nozzles, Jet Nozzles, Accessibility Probes, and Oscillating Spray Testers.

DuraSorb™ Hybrid Anechoic Absorber Combines Durability with Broadband Performance

ETS-Lindgren's DuraSorb is a low profile, hybrid anechoic absorber for test applications including the MIL-STD-461, ANSI C63.4, CISPR 16 and CISPR 25 standards. DuraSorb is constructed using substrates with rigid, closed cell foams, which are loaded volumetrically and uniformly throughout. Featuring durable construction and non-hygroscopic design, it is designed to work with ferrite tiles to cover a broadband frequency range from 30 MHz to 40 GHz. All EMC absorber manufactured by ETS-Lindgren is 100% factory tested before shipment.

Exodus, Your Solution for EMC!

Exodus Advanced Communications provides the best solutions for 10kHz-51GHz serving commercial and government entities worldwide. Exodus SSPA's provide unprecedented reliability & performance and simplify EMC testing with the latest features for user-availability. Exodus provides the widest range of stand-alone modules, integrated amplifier chassis configurations, and full turn-key systems as needed for specific applications. Learn more http://www.exoduscomm.com.

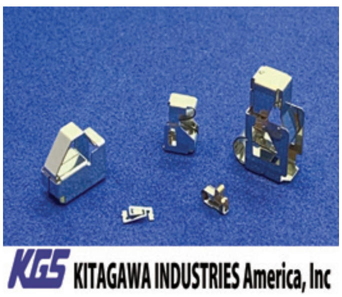
All New Multifunction Generator

Conducted immunity testers according to IEC standards (IEC 61000-4-x) up to 8kV Surges and 7kV EFT/Burst pulses. Ready for Surge, EFT/Burst, Ringwave, 10/700, Common Mode testing, Differential Mode Testing, Dips, Variations, Interrupts and more. Wide range of accessories (3 Phase CDN's, Data Line CDN's, Magnetic Field, ANSI coupling, etc). Modular architecture enables customized configuration. Powerful TEMA3000 automation software. Contact HV TECHNOLOGIES for more information.

Kikusui Electronics PCR-WEA2 Series AC & DC Source

Kikusui's new AC source, the PCR-WEA2 Series, provides the best reliability and performance on the market for applications ranging from avionics, EV, renewable energy, IT, compliance testing, and more. It outputs single and three phase up to 5kHz with a maximum power of 144kVA. It combines accuracy and power in an ultra-compact design. Its regenerative capability allows a wider application such as motor or bidirectional inverter testing. Improve your test results with the PCR-WEA2 series from Kikusui, a brand trusted by engineers.

PRODUCT MARKETPLACE



On-board EMC Grounding Contacts

KITAGAWA INDUSTRIES America's on-board contacts are all SMT (Surface Mount) type contacts, designed for PCB-level EMC grounding, shielding, and ESD.

- Effective for suppressing emission and immunity reduction
- All EMC mitigation can be done at the board-level
- Space-saving and robust design
- Easy to incorporate even where screws are included
- Tape-and-reel design allows for use with automated pick-and-place machine to increase efficiency and reduce manual labor

Nolato Jabar Compashield® EE Gaskets

- Combination of conductive and non-conductive materials for excellent shielding effect and environmental sealing, in one single gasket
- Thin layer of nickel graphite or silver aluminum co-extruded on to a high-performance silicone base
- Designed for 5G frequencies and will meet future shielding demands
- Offers flexible solutions in terms of material, construction, and function
- Better compression set, compared to traditional materials. The gasket will return to its original shape much more successfully than previously possible.

Undisputed Leader in EMI/EMC Testing

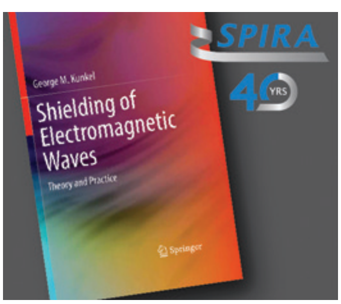
With 28 labs in North America, NTS owns the most EMI/EMC chambers on the continent. With the world's top EMI/EMC experts, NTS customers get immediate access to thought leaders who contribute to the development of industry standards for EMI/EMC testing. In fact, the experts at NTS are intellectuals who sit on advisory boards, create testing standards, and author reference material. Visit http://www.nts.com or call (844) 332-1885—and discover what it means to operate at a higher standard.

RAYMOND EMC QuietDoor™

The QuietDoor™ line of shielded doors are proven to be easy to operate, reliable and long lasting. QuietDoor™RCM includes revolutionary innovations such as forward-mounted fingerstock, safe and secure latching hardware and easily serviced components. Single leaf models have a fully reversible swing which can be changed on site with no modifications to the door. A programmable logic control combined with the reliability of pneumatics can be added to create the most advanced shielded door automation system on the market. ADA compliant and other thresholds are available. Additional customized solutions are available.

Ultrafast Measurements

The R&S®ESW EMI test receiver offers outstanding performance, including high dynamic range and measurement accuracy. It meets the most stringent requirements for certification measurements in line with CISPR, EN, MIL-STD-461, DO-160 and FCC. With its FFT-based time domain scan, it captures and weights disturbance spectra in virtually no time. It offers preselection with selectable high pass filters and notch filters for the ISM bands.



Groundbreaking NEW Book on EMI Shielding:

Shielding of Electromagnetic Waves – Theory and Practice

International Shielding Expert George Kunkel discovered a critical error: the accepted theory of electromagnetic shielding violates the basic laws of physics. This new book, the result of over 50 years of research, provides a more accurate, efficient way for design engineers to apply electromagnetic theory in the shielding of electrical and electronic equipment. Learn more at http://www.spira-emi.com.

DO160 S22 Series Indirect Lightning Induced Transient Susceptibility Test System

The 3ctest's DO160 S22 series test system is designed according to RTCA/DO-160 Section 22 and MIL-STD-461G (CS117). It is capable of generating waveforms 1, 2, 3(1 MHz &10 MHz), 4, 5A/5B and 6 with test level from 1 to 5 for pins injection and cable bundle test. Together with remote-control Corelab software, your test operation will become easy and convenient. It supports powerful function of automatic test sequence, user-defined parameter setup and saving, standard library update and test report generation & print etc. For more information, please visit our official website: https://www.3c-test.com.

Vitrek New DL Series Electronic DC Load

The DL Series supports the testing requirements for the latest generation of off-line power supplies, DC-DC converters & LED Drivers. A variety of power ratings and input voltages available to meet your specific application. For a FREE demonstration visit http://www.vitrek.com/incompliance.

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Fundamentals of Random Vibration and Shock Testing

November 17-18
The Battery Show Digital Days

November 30 - December 2
The Battery Show Europe

Due to COVID-19 concerns, events may be postponed. Please check the event website for current information.