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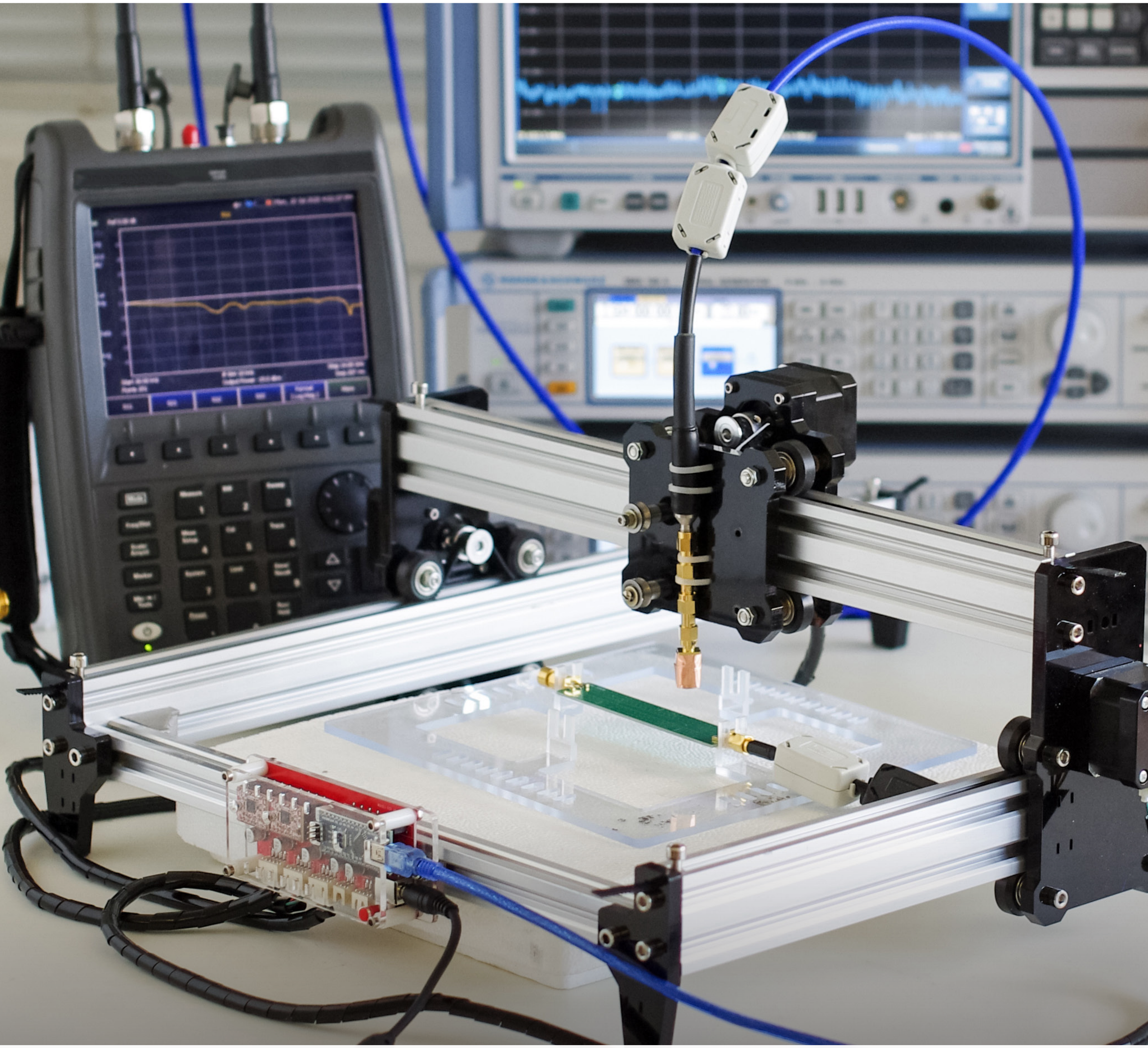
2021 EMC FUNDAMENTALS GUIDE



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ESRP · EMI TEST RECEIVER · 10 Hz ... 7 GHz

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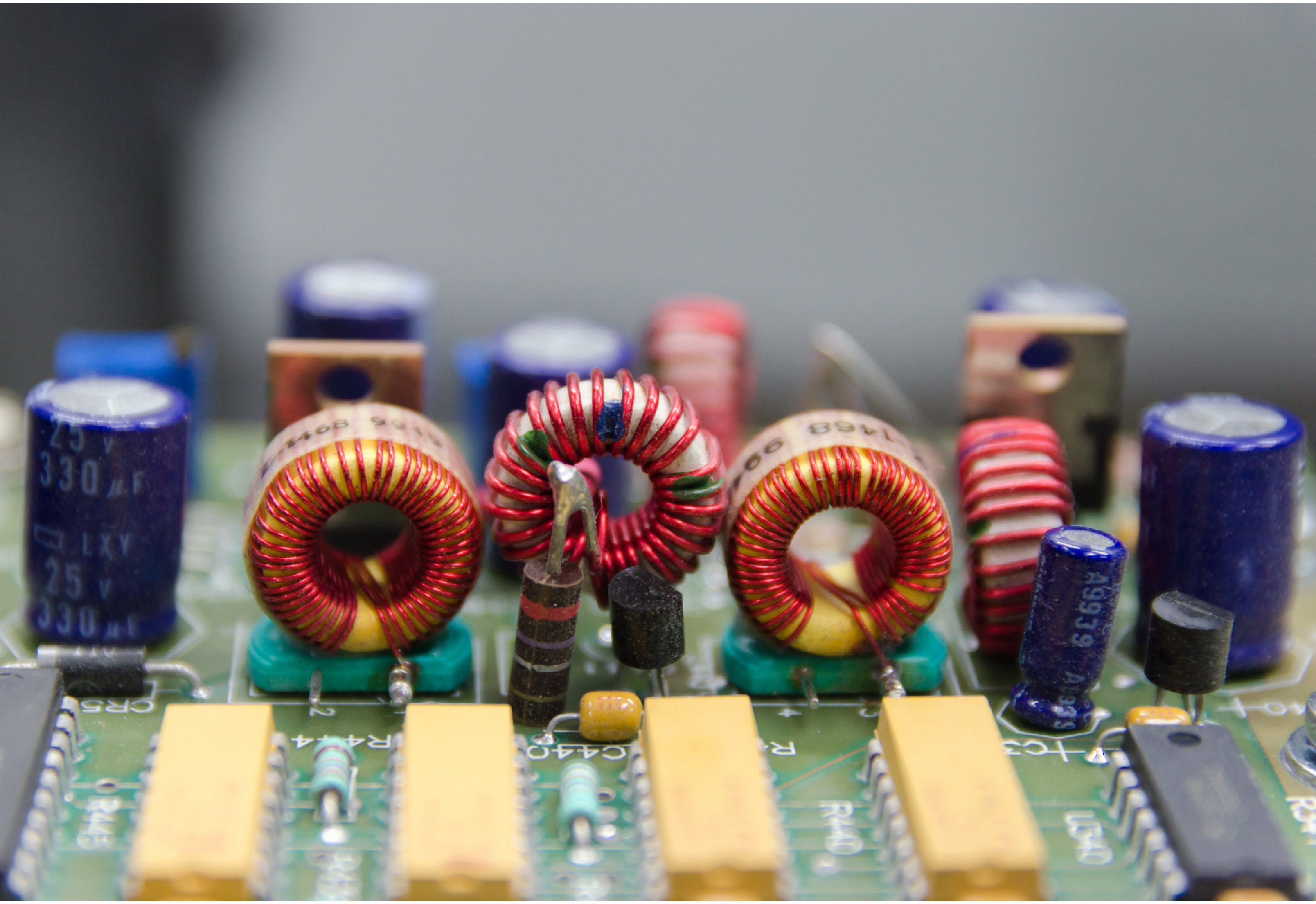
2020 EMC SUPPLIER GUIDE

Introduction

In this section, we provide a quick guide to some of the top suppliers in each EMC category–test equipment, components, materials, services, and more. To find a product that meets your needs for applications, frequencies, standards requirements, etc., please search these individual supplier websites for the latest information and availability. If you have trouble finding a particular product or solution, email james@lectrixgroup.com for further supplier contacts.



	COMPANY	WEBSITE	AMPLIFIERS	ANTENNAS	CABLES & CONNECTORS	CERTIFICATION	CONSULTANTS	COMPONENTS	DESIGN / SOFTWARE	EMI RECEIVERS	FILTERS / FERRITE'S	LIGHTNING & SURGE	MEDIA	SEALANTS & ADHESIVES	SHIELDING	SHIELDED ROOMS	SPECTRUM ANALYZERS	TEST EQUIPMENT	TEST EQUIPMENT RENTALS	TEST EQUIPMENT OTHER	TESTING	TESTING LABORATORIES	TRAINING SEMINARS & WORKSHOPS
A	Aaronia AG	www.aaronia.com	X	X						X							X						
	Advanced Test Equipment Rentals (ATEC)	www.atecorp.com	X	X		X				X		X			X	X	X	X	X	X	X		
	AH Systems, Inc.	www.ahsystems.com	X	X	X													X	X	X			
	Altair- US	www.altair.com					X		X														
	American Certification Body Inc.	https://acbcert.com/				X	X		X												X	X	X
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	Anritsu Company	www.anritsu.com		X													X	X		X	X		
	API Technologies	www.apitech.com						X			X												
	AR RF/Microwave Instrumentation	www.arworld.us	X	X	X				X						X	X		X	X				
	Astrodyne	www.astrodyneTDI.com									X												
B	Beehive Electronics	www.beehive-electronics.com																			X		
C	Captor Corporation (EMC Div.)	www.captorcorp.com									X												
	Coilcraft	www.coilcraft.com						X			X												
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D	Dassault System Simulia Corp	www.3ds.com/							X														
	Delta Electronics (Americas) Ltd.	www.delta-americas.com									X												
	DLS Electronic Systems, Inc.	www.dlsemc.com																				X	
E	Electro Rent	www.electrorent.com	X							X				X			X		X				
	Elite Electronic Engineering Co.	www.elitetest.com																				X	
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	Empower RF Systems, Inc.	www.empowerrf.com	X																				
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	Exemplar Global (iNarte)	www.exemplarglobal.org																					X
	EXODUS Advanced Communications	www.exoduscomm.com	X	X	X													X					
F	F2 Labs	www.f2labs.com				X	X														X	X	X
	Fischer Custom Communications	www.fischercc.com																		X			
	Frankonia Solutions	www.frankonia-solutions.com													X	X		X				X	

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	Gowanda Electronics	www.gowanda.com						X															
H	Haefely	www.haefely.com							X									X			X		
	Heilind Electronics, Inc	www.heilind.com									X												
	Henry Ott Consultants	www.hottconsultants.com					X																
	HV TECHNOLOGIES, Inc.	www.hvtechnologies.com	X	X						X		X				X	X	X		X			
I	Instrument Rental Labs	www.testequip.com	X							X							X		X				
	Interference Technology	www.interferencetechnology.com																					X
	Intertek	www.intertek.com																				X	
	ITG Electronics, Inc.	www.itg-electronics.com						X			X												
K	Keysight Technologies	www.keysight.com/us/en								X							X		X	X			
	Krieger Specialty Products	www.kriegerproducts.com														X							
L	Laird Electronics	www.lairdtech.com/									X			X									
	Langer EMV-Technik	www.langer-emv.de/en/index																		X			
M	Magnetic Shield Corp.	www.magnetic-shield.com													X								
	Master Bond Inc.	www.masterbond.com												X									
	MBP Srl	www.mbp.it/en/							X											X			
	Microlease	www.microlease.com	X							X							X		X				
	MILMEGA	www.ametek-cts.com	X																				
	Montrose Compliance Services	www.montrosecompliance.com					X																
	MVG Microwave Vision Group	www.mvg-world.com		X							X				X	X							
N	Narda Safety Test Solutions	www.narda-sts.com	X	X						X							X			X			
	Noise Laboratory Co., Ltd.	www.noiseken.com																				X	
	NTS	www.nts.com																			X		
O	Ophir RF	www.ophirrf.com	X																				
P	Parker Chomerics	www.chomerics.com													X								
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	PPG Cuming Lehman Chambers	www.cuminglehman.com													X	X					X		
	PPG Engineering Materials	www.dexmet.com													X								
	Prana	www.prana-rd.com	X																				
	Pulse Power & Measurement Ltd	https://ppmtest.com/																		X			
Q	Quell Corp.	www.eeseal.com			X						X	X									X		

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R	Radiometrics	www.radiomet.com																				X	
R	R&B Laboratory, Inc.	www.rblaboratory.com																				X	
R	Retlif Testing Laboratories	www.retlif.com																			X	X	X
R	RIGOL Technologies	www.rigolna.com	X					X									X	X		X			
R	R&K Company Limited	www.rk-microwave.com	X					X															
R	Rohde & Schwarz GmbH & Co. KG	www.rohde-schwarz.com/de	X	X						X					X	X	X	X					
R	Rohde & Schwarz USA, Inc.	www.rohde-schwarz-usa.com	X	X						X					X	X	X	X					
S	Schaffner EMC, Inc.	www.schaffner.com						X			X										X	X	
S	Schurter, Inc.	www.schurter.com			X						X												
S	Schwarzbeck Mess-Elektronik	www.schwarzbeck.com		X																			
S	Select Fabricators	www.select-fabricators.com													X	X							
S	Siglent Technologies	www.siglentna.com																X					
S	Signal Hound	www.signalhound.com						X		X							X				X		
S	Solar Electronics	www.solar-emc.com		X																			
S	Spira Mfg. Corp.	www.spira-emi.com													X								
T	TDK	www.tdk.com						X			X					X				X			
T	Tektronix	www.tek.com																X					
T	Teledyne LeCroy	www.teledynelecroy.com																X					
T	TESEQ Inc.	www.teseq.com																X					
T	Test Equity	www.testequity.com/leasing/	X							X							X		X				
T	Thurlby Thandar (AIM-TTi)	www.aimtti.com								X							X						
T	Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X							X						
T	TPI	www.rf-consultant.com					X																
T	Transient Specialists	www.transientspecialists.com																	X				
T	TRSRenTelCo	www.trsrentelco.com/categories/spectrum-analyzers/emc-test-equipment	X	X						X							X	X	X		X		
V	Vectawave Technology	www.vectawave.com	X																				
V	V Technical Textiles / Shieldex US	www.vtechtextiles.com													X								
W	Washington Laboratories	www.wll.com				X	X		X			X									X	X	X
W	Windfreak Technologies	www.windfreaktech.com																X			X		
W	Würth Elektronik eiSos GmbH & Co. Kg	www.we-online.com		X	X			X	X		X	X			X								
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WHAT IS EMC?

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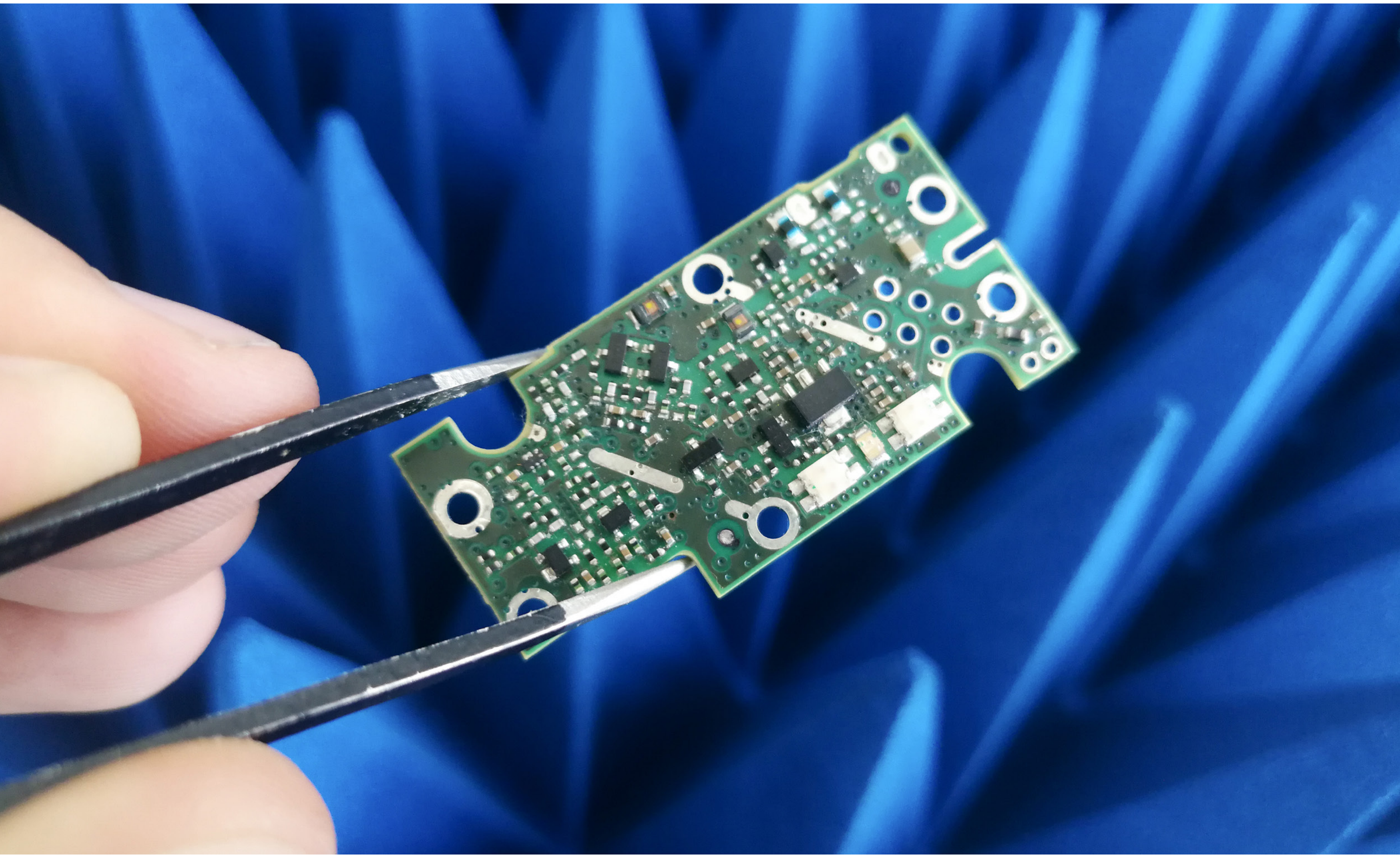
Introduction
This article will serve as an introduction to the topic. It is aimed at the people who have been told by their management, "You are now my EMC person. Go figure out what it is and how we must deal with it!" It will not be an all encompassing treatment of the subject, but it will provide the reader with a start and some ideas of where to go for more information.



WHAT IS EMC?

EMC stands for electromagnetic compatibility. You will see some people refer to EMC/EMI, but this is partially redundant. EMI (electromagnetic interference) is just a part of EMC. The two major parts of EMC are EMI and EMS (electromagnetic susceptibility) as it is called in the aerospace and military world and electromagnetic immunity (as it is called in the commercial world). Susceptibility and immunity are pretty much the same thing, just called by different terms. Susceptibility is a measure of how a device reacts to various items in the electromagnetic environment and immunity is simply a demonstration of its failure to react to certain levels of these phenomena. Emissions are regulated in the commercial world in various ways and immunity for commercial products is regulated in certain countries and not at all in many others.

In the aerospace and military world, a common standard for emissions and susceptibility is MIL-STD-461G. Various tests and levels are called out for various services and products. In the commercial world, it depends on what product is being discussed, but for information technology equipment (ITE), broadcast receivers, and multimedia equipment, CISPR 32 provides limits for emissions and CISPR 35 provides tests and test levels for immunity. In the U.S., the FCC in Part 15 of its rules provides limits for emissions and does not mandate immunity for digital devices. In fact, the rules specifically state that a Part 15 device must accept any interference received. Countries that mandate immunity, on the other hand, require that products not suffer inference when tested to the levels called out in the applicable standards.

WHAT CAUSES ELECTROMAGNETIC EMISSIONS IN THE FIRST PLACE?

Various functions within a product may contribute to the generation of emissions. These emissions may be radiated from the product, typically as radio waves, or they may be conducted from the product via the power mains cable or other I/O cables connected to the product. Limits on the magnitude of these emissions are specified by regulatory bodies in many countries to protect licensed and unlicensed users of the radio spectrum from harmful interference.

Emissions from the product may be created by various means within the product. The two major means by which these may be generated are harmonics of intentional signals or parasitic emissions, which can come from improperly terminated transmission lines and the lengths of these lines.

In the case of harmonics of clocks and other signals, these emissions will be related to the fundamental frequency and integral harmonics of these signals. *Figure 1* shows the relationship of these signals. An envelope, which will not be exceeded in level by these signals is shown in *Figure 2*. They may not get up to this envelope in value, but they will not exceed it. The example shown is for a 50% duty cycle signal with a frequency of 500 MHz, a rise and fall time of .03 x 10^{-9} seconds, a pulse width of .97 x 10^{-9} seconds and an amplitude of 3.3 volts.

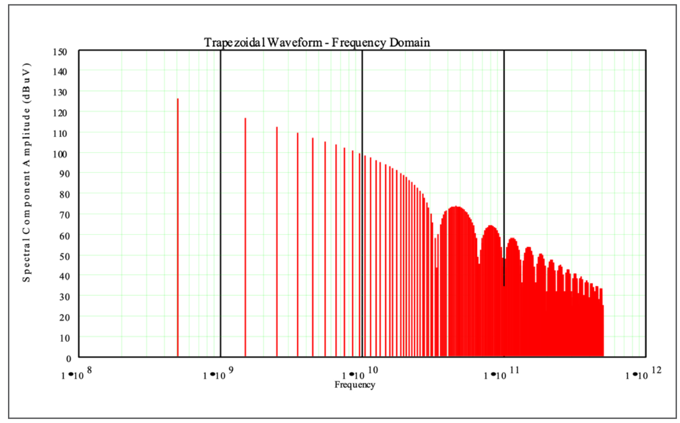


Figure 1: Frequencies resulting from a 500 MHz trapezoidal waveform

There are a couple of key things to note in *Figure 1*, including that the computed harmonics do not always rise to the envelope in *Figure 2*, but never exceed it. If you were to look at the signal (ideal) in both the time and frequency domains, it will look something like the following:

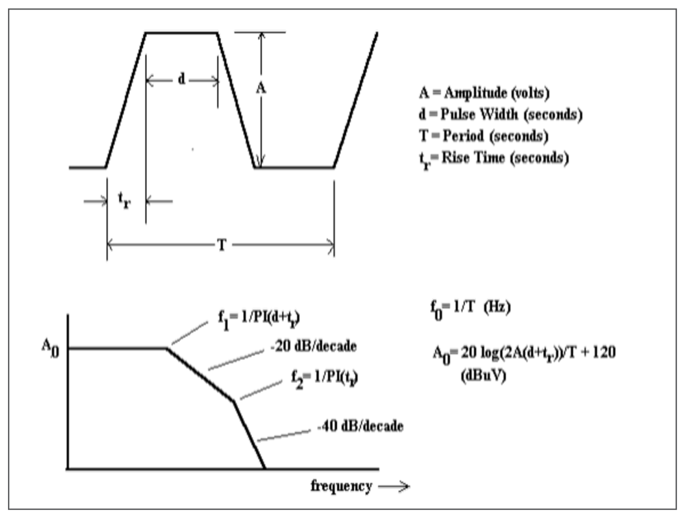


Figure 2: Trapezoidal waveform and envelope containing all harmonics

The fundamental of this 50% duty cycle signal actually falls above the first break point in frequency when the envelope starts falling at -20 dB/decade of frequency. Above f_2 the envelope falls off at -40 dB/decade of frequency. So, lowering the rise time of the signal moves this breakpoint to the left, decreasing the harmonics levels at higher frequencies faster. In reality, circuit designers are going to use the fastest products they can find, but the EMC engineer can always dream.

You may run into digital designers who say that 500 MHz isn't very high. Just remember, 470 MHz is the bottom of the UHF television broadcast band, so 500 MHz is very definitely RF. It may not be high to a digital circuit designer, but it definitely is RF and will certainly radiate and cause interference to licensed services.

Why is this preceding information important? It gives the EMC engineer a tool for computing the frequencies that may come from the product, at least as harmonics of intentionally generated digital signals. It also gives a tool for computing the amplitudes of these signals. The next step, at least for computing the radiated or conducted emissions, will be to compute the coupling factor or factors, as a function of frequency. Or, if the measurements have already been performed, then troubleshooting to bring them into compliance may be the next thing on the agenda.

Another means by which RF energy can be created by a product is due to transmission lines that are not properly terminated. The frequency of these emissions will not necessarily be harmonically related to the frequency of the signal being sent down the transmission line, but, will instead, be related to the propagation velocity of the wave down the transmission line and its length. This termination may be designed into the product at either end of the transmission line and each has its advantages and disadvantages. Troubleshooting these emissions can take more detective work.

There are a number of ways that RF energy created by a product through its normal operation can generate and radiate unintentional emissions that can cause interference or simply failure to pass emissions limits. This paper will not go into detail on each as this would be way beyond the scope of a single paper, but things to consider are current loops, exit points from PWBs for cables, bypassing (all filters are not created equal and installation methods are critical), component layout, trace routing, chassis and packaging design, and "grounding". Notice that I put quotation marks around grounding. Grounding in the EMC sense does not mean connection to earth ground. Ask yourself how this would be possible for a satellite in geosynchronous orbit around the earth. Obviously, it isn't, and satellites typically have to meet far more stringent EMC requirements than your computer on your desk.

WHAT IS A MODEL FOR INTERFERENCE?

There are three basic components in the interference model that must be considered.

There is a source. This may be a board, a complete device, or natural event. It generates the emission that is causing the problem.

There is a victim. This is the device (component, board, or full product) that suffers interference that causes whatever malfunction is being noted. This may be an unintended operation or a failure to operate on the part of the device suffering as a victim.

Finally, there is a path for the interfering emission to travel from the source to the victim. This may be a direct radiation path or a conducted path. It may fall under the control of the operator of the source, it may fall under the control of the operator of the victim, or a combination of both.

HOW DO I FIX AN EMC PROBLEM?

To quote a retired professor (Todd Hubing), "It depends." What is the problem? Did your product fail an EMC test? Is it causing harmful interference to another device or service? Fix your product. This is especially important if you only control the source (in the case of emissions) or the victim (in the case of immunity testing). If you control both the source and victim, you may be able to alter the path and leave the source and/or victim alone.

Let's assume that your product is failing an emissions test. This is not the best time to find out that you have an EMC problem as marketing probably wants to ship the product soon and you are being called the roadblock to shipping and are therefore the bad guy. Never mind that you have been telling the project team for a year that there are areas they need to address, and they have refused to make changes you've recommended. This is where a prime requirement to being an EMC engineer comes in—you must have a thick skin and stick to your guns. No data showing compliance, no shipment of product. Get to know the project lawyers well in advance, they likely will be on your side. You'll spend long hours in the lab finding and fixing the problem(s). Oh, and your fixes must be manufacturable and, ideally, cheap (or even free). Sometimes these are, and sometimes they aren't. Sometimes a product that passed in the lab last week or last month will have had a change made by a vendor as it was easier for them to make the part and your company's specification wasn't tight enough to prevent the change. Can you find this problem quickly and tell the program team how to fix it? Oh, and there are some problems that you will find repeatedly over a career as new designers come and go, creating job security for EMC engineers. So, from a personal point of view, these easy to find and fix problems aren't all bad. At least not after you've found and fixed them a few times over the years. It you are new to the game it will take a bit longer.

IMMUNITY

I haven't discussed immunity as a separate issue much in this paper. The good news (at least on the commercial side of the discussion) is that immunity isn't typically a major issue for designers and EMC engineers. Prior to immunity requirements being published for the first time about 30 years ago one major manufacturer only had internal specifications for electrostatic discharge and power line surges. Nothing else in their experience showed itself to be an issue. Some of the commercial immunity requirements are so low that the EMC engineer can tell the project designers 6 months in advance that he will run the test only because it is required, but not to worry as the product will pass. Or the company may have internal requirements for significantly higher test levels, in which case more attention must be paid to the test phenomena. ESD and surge testing, however, do not fall in the camp of serious concern. If a designer lives and works in an area where humidity levels are typically high, he probably doesn't have much experience or worry about ESD failures. If, however, he lives and works in an area like the front range of Colorado or Washington D.C. where humidity levels can be very low, he likely will be a firm believer in ESD. Likewise for electrical surge, if the designer lives in an area where lightning storms are common surge is an issue. If not, no worries. However, the product must be sold and used in areas where these are common problems.

Then there are the immunity or susceptibility matters that must be considered to avoid problems like the U.S.S. *Forrestal* in the late 1960s. Susceptibility can be a serious matter. Three V/m may be adequate for some commercial environments, but the flight deck of an aircraft carrier is not one of those environments. Do a Google search and look for the video and discussion of what went wrong on the *Forrestal* to see what I mean.

CONCLUSION

EMC is a matter deserving of serious consideration. It may only be a matter of whether a product can ship on time, or it may be a matter of life and death. Learn about it, ask questions of people who are considered experts in the subject (I'll give you my definition of "expert" some time), and read books and articles on the subject. Also, attend events where you can learn more about EMC by listening to papers, talking with vendors, and networking with "your fellow wizards". You'll find in many of those places that EMC folks (engineers and technicians) are EMC professionals first and employees of X, Y, or Z company second. They won't disclose company secrets, but they will help you fight a common enemy—EMC issues.

Listed below are a few places where you can learn more about EMC.

- *Noise Reduction Techniques In Electronic Systems, Second Edition*, Henry W. Ott, John Wiley & Sons, 1988

  This is a great book for learning more about EMC.

- *Fields and Waves in Communication Electronics*, Ramo, Whinnery and Van Duzer, John Wiley & Sons, 1965

  I thought this was a lousy textbook when I was in college (maybe some bias there), but it is a fantastic reference book that I highly recommend you have.

- *Introduction to Electromagnetic Compatibility, 2nd Edition*, Clayton R. Paul, John Wiley & Sons, 2006

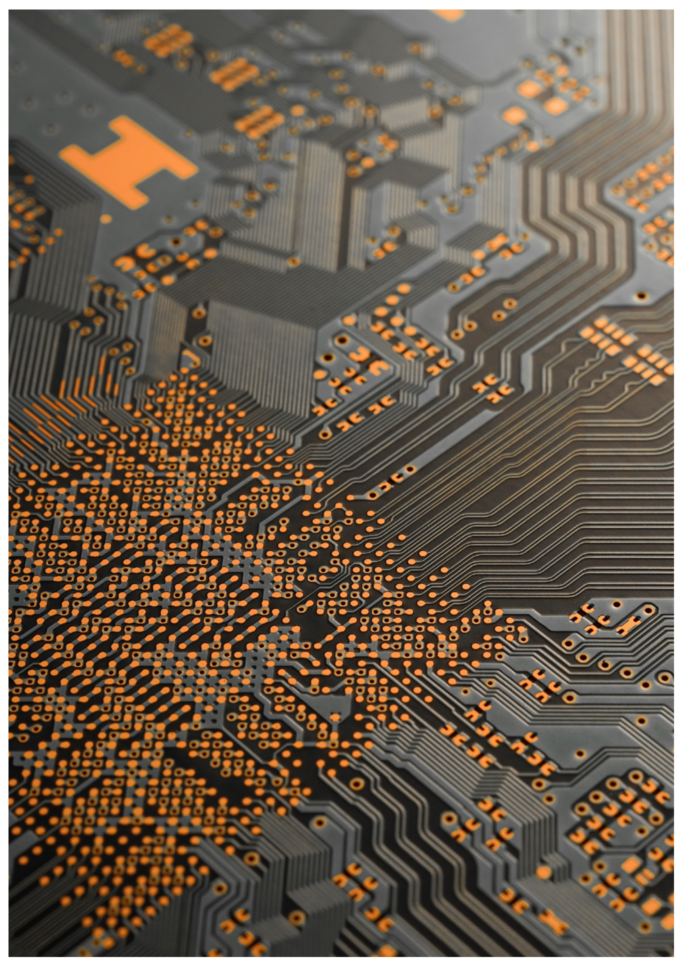
  Clayton has passed away, much to the sorrow of those of us who knew him, but if I was limited to a single book on EMC, this is the one I would have. Not a simple, easy to read, treatment on the subject, but complete and comprehensive. I highly recommend this book.

- *PCB Design for Real-World EMI Control*, Bruce Archambeault and James Drewniak, Kluwer Academic Publishers, 2002/2004

  The title says it all. It is limited to PCBs, but it is a great treatment on the subject, by two gentlemen who are well respected in the EMC world. Bruce is a past president of the IEEE EMC Society and has been around the block more than once.

There are plenty more books and papers that you can read and learn from. This is just a start, but for someone new to the EMC world this will be a great start.

Have fun and feel free to ask questions when you have some. I don't say "if" because after 44 years I still have many.



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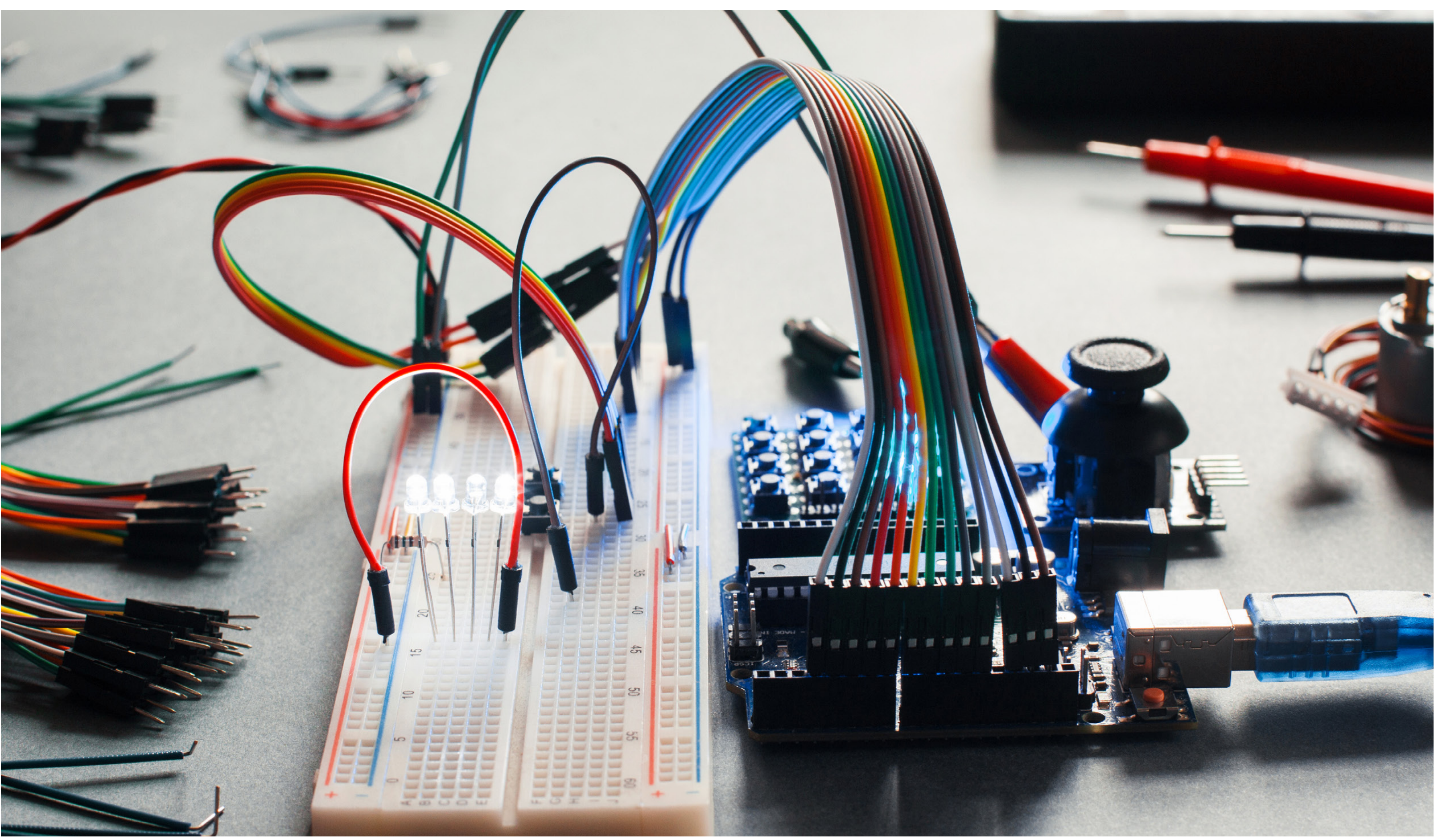

BASIC EMI CONCEPTS

Understanding EMC is all about two important concepts: (1) all currents flow in loops and (2) high frequency signals are propagated as electromagnetic waves in transmission lines and the field energy travels through the dielectric. The two concepts are related because they are intertwined together. Digital signals create the propagating field, which induces the convection current to flow in the copper traces/planes.

CURRENTS FLOW IN LOOPS

These two concepts are closely related and coupled to one another. The problem we circuit designers miss is defining the return path back to the source. If you think about it, we don't even draw these return paths on the schematic diagram - just showing it as a series of various "ground" symbols.

So what is "high frequency"? Basically, anything higher than 50 to 100 kHz. For frequencies less than this, the return current will tend to follow the shortest path back to the source (path of least resistance). For frequencies above this, the return current tends to follow directly under the signal trace and back to the source (path of least impedance).

Where some board designs go wrong is when high *dV/dt* return signals, such as those from low frequency DC-DC switch mode converters or high di/dt return signals get comingled with I/O circuit return currents or sensitive analog return currents. We'll discuss PC board design in the next article. Just be aware of the importance of designing defined signal and power supply return paths. That's why the use of solid return planes under high frequency signals and then segregating digital, power, and analog circuitry (keeping them separate) on your board is so important.

HOW SIGNALS MOVE

At frequencies greater than DC, digital signals start to propagate as electromagnetic waves in transmission lines. As shown in *Figure 1*, a high frequency signal propagates along a microstrip transmission line (circuit trace over return plane, for example), and the wave front induces a conduction current in the copper trace and back along the return plane. Of course, this conduction current cannot flow through the PC board dielectric, but the charge at the wave front repels a like charge on the return plane, which "appears" as if current is flowing. This is the same principle for capacitors and Maxwell called this effect "displacement current".

The signal's wave front travels at some fraction of the speed of light, as determined by the dielectric constant of the material, while the conduction current is comprised of a high density of free electrons moving at about 1 cm/second. The actual physical mechanism of near light speed propagation is due to a "kink" in the E-field, which propagates along the molecules of copper. Refer to *References 1, 2,* and *3* for further details.

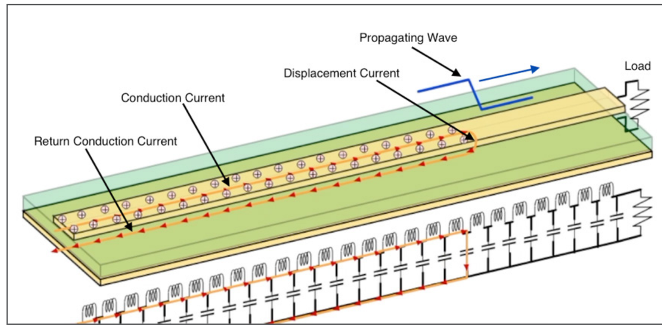

Figure 1 - A digital signal propagating along a microstrip with currents shown.

The important thing is that this combination of conduction and displacement current must have an uninterrupted path back to the source. If it is interrupted in any way, the propagating electromagnetic wave will "leak" all around inside the PC board dielectric layers and cause electromagnetic coupling and "common mode" currents to form, which then couple to other signals (cross-coupling) or to "antenna-like structures", such as I/O cables or slots/apertures in shielded enclosures.

Most of us were taught the "circuit theory" point of view and it is important when we visualize how return currents want to flow back to the source. However, we also need to consider the fact that the energy of the signal is not only the current flow, but an electromagnetic wave front moving through the dielectric, or a "field theory" point of view. Keeping these two concepts in mind just reinforces the importance of designing transmission lines (power and signal traces with return path directly adjacent), rather than just simple circuit trace routing.

It is very important to note that all power distribution networks (PDNs) and high frequency signal traces are transmission lines and the energy is transferred as electromagnetic waves at about half the speed of light in normal FR4-type board dielectrics. We'll show what happens when the return path or return plane is interrupted by a gap in the next article. More on PDN design may be found in *Reference 4, 5*, and *6*.

DIFFERENTIAL MODE VERSUS COMMON MODE CURRENTS

Referring to *Figure 2*, the differential mode current (in blue) is the digital signal itself (in this case, shown in a ribbon cable). As described above, the conduction current and associated return current flow simultaneously as the signal wave front moves along the transmission line formed by the microstrip and return plane.

The common mode current (in red) is a little more complex in that it may be generated in a number of ways. In the figure, the impedance of the return plane results in small voltage drops due to multiple simultaneous switching noise (SSN) by the ICs. These voltage drops induce common noise currents to flow all over the return (or reference) plane and hence, couple into the various signal traces.

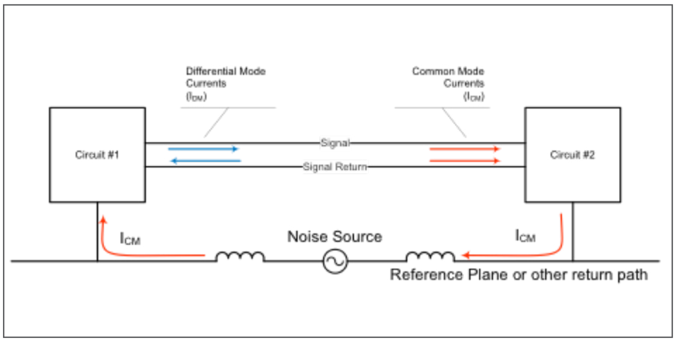

Figure 2 - An example of differential and common mode currents.

Besides SSN, common mode currents can also be created by gaps in return planes, poorly terminated cable shields, or unbalanced transmission line geometry. The problem is that these harmonic currents tend to escape out along the outside of shielded I/O or power cables and radiate. These currents can be very small, on the order of μA. It takes just 5 to 8 μA of current to fail the FCC class B test limit.

SUMMARY

To summarize product design for EMI compliance, a properly designed PC board with adjacent return planes to all signals and PDNs, properly bonded I/O cable shields, well bonded shielded enclosures with minimal slots or gaps, and common mode filtering on all I/O and power cables for unshielded products is generally required for best EMI performance. Paying attention to these factors early in the design greatly reduces the risk of EMC and EMI compliance failures.

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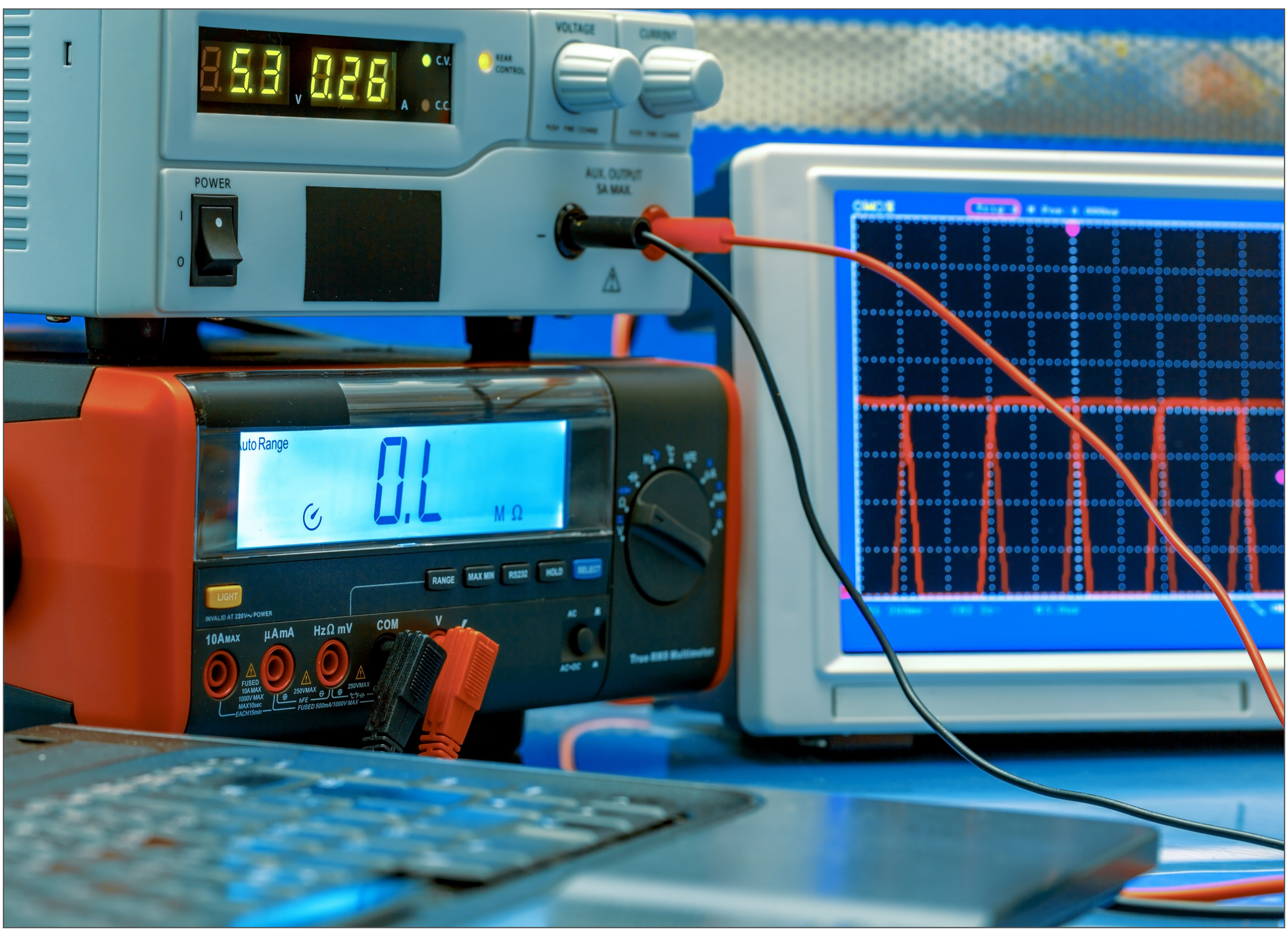

DESIGN FOR COMPLIANCE ESSENTIALS

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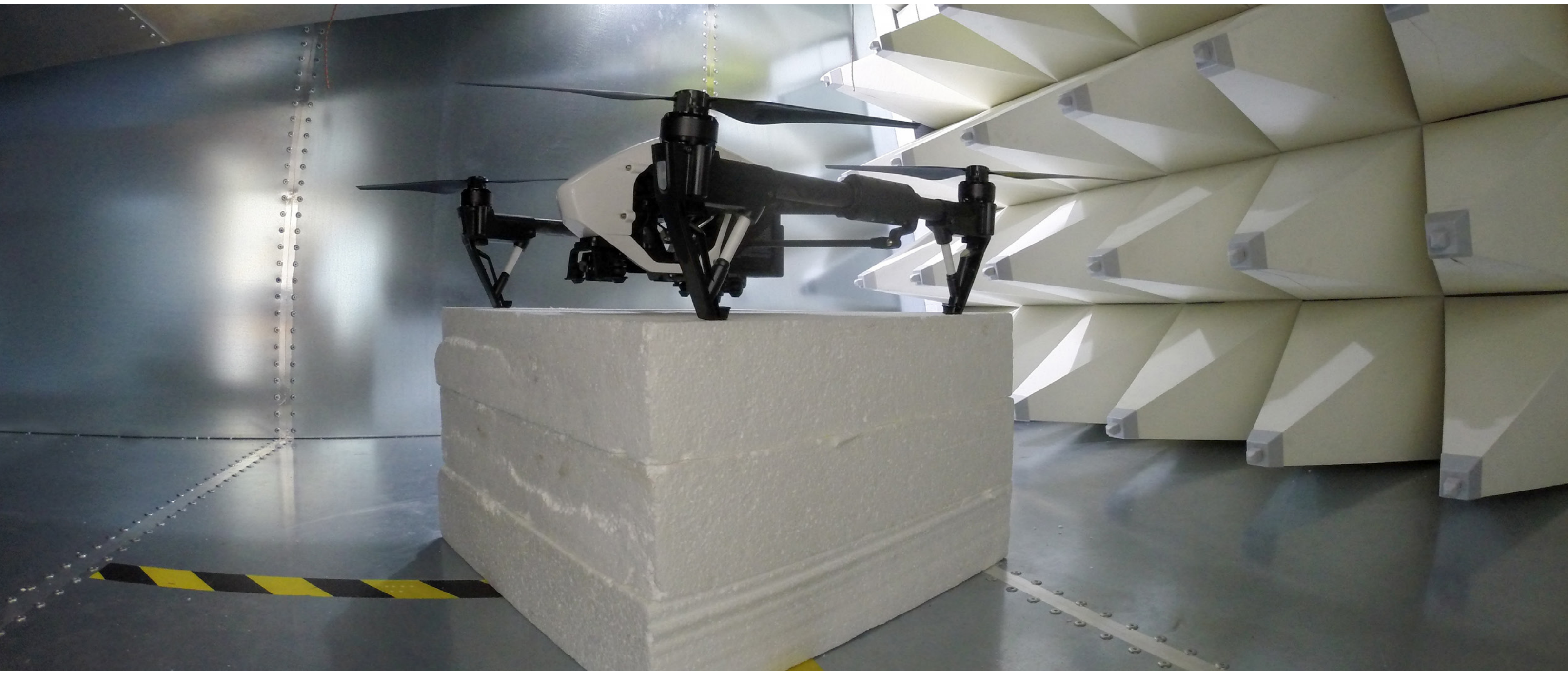
Introduction

While unrealistic to discuss all aspects of product design in a single article, I'll try to describe the most common design issues I find in the hundreds of client products I've had a chance to work on. These issues generally include PC board design, cables, shielding, and filtering. More detailed information may be found in the Reference section below.

As previously mentioned, the top three product failures I run into include (1) radiated emissions, (2) radiated susceptibility, and (3) electrostatic discharge. Other failures can include things like conducted emissions, electrically fast transient, conducted susceptibility, and electrical surge. Most of these last items are also the result of the same poor product designs, which cause the top three failures.

NOTE: I prefer to avoid the word "ground" in this article or in my consulting practice. The reason is that there are too many misinterpretations, which can also lead to EMC failures. It's much more clear to use power and power return, and signal and signal return - or just "return plane" or reference plane. Finally, cable shields or shielded enclosures are "bonded" together - not "grounded". The only exception is the so called "safety ground" or earth ground. But these have nothing at all to do with proper EMC design - just personal safety against electrical shock. I suppose the one exception would be the earth ground connection on a three-wire power line filter. Also, occasionally, there will be an earth ground on a PC board - especially for power supplies, but again, connecting a product or system to earth ground will not improve EMI, due to the very high inductance (length) of the wire.



DESIGN FOR COMPLIANCE ESSENTIALS

PC BOARD DESIGN

The single most important factor in achieving EMC/EMI compliance revolves around the printed circuit board design. It's important to note that not all information sources (books, magazine articles, or manufacturer's application notes) are correct when it comes to designing PC boards for EMC compliance - especially sources older than 10 years, or so. In addition, many "rules of thumb" are based on specific designs, which may not apply to future or leveraged designs. Some rules of thumb were just plain lucky to have worked.

PC boards must be designed from a physics point of view and the most important consideration is that high frequency signals, clocks, and power distribution networks (PDNs) must be designed as transmission lines. This means that the signal or energy transferred is propagated as an electromagnetic wave. PDNs are a special case, as they must carry both DC current and be able to supply energy for switching transients with minimal simultaneous switching noise (SSN). The characteristic impedance of PDNs is designed with very low impedance (0.1 to 1.0 Ohms, typically). Signal traces, on the other hand, are usually designed with a characteristic impedance of 50 to 100 Ohms.

The previous article introduced the concept of the circuit theory and field theory viewpoints. A successful PC board design accounts for both viewpoints. Circuit theory suggests that current flows in loops from source to load and back to the source. In many cases of product failure, the return path has not been well defined and in some cases, the path is broken. Breaks or gaps in the return path are major causes of radiated emissions, radiated susceptibility, and ESD failures.

Correspondingly, electric fields on PC boards exist between two pieces of metal, such as a microstrip over a return plane (or trace). If the return path is broken, the electric field will "latch on" to the next closest metal and will not likely be the return path you want. When the return path is undefined, then the electromagnetic field will "leak" throughout the dielectric and cause common mode currents to flow all over the board, as well as cause cross-coupling of clocks or other high speed signals to dozens of other circuit traces within that same dielectric.

Figure 1 shows a propagating wave within the dielectric between the signal trace and return plane (or trace). This shows both the conduction current flowing in the signal trace and back on the return plane (or trace) and the displacement current "through" the dielectric. The signal wave front travels at some fraction of the speed of light as determined by the dielectric constant. In air, signals travel at about 12 inches per nanosecond. In the typical FR4 dielectric, the speed is about half that at 6 inches per nanosecond. Refer to *Reference 1, 2*, and *3* for more information on the physics of signal propagation through PC boards.

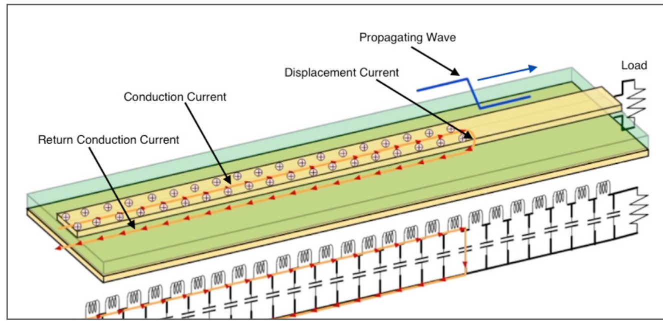


Figure 1 - A propagating wave along a microstrip with reference plane. Figure, courtesy Eric Bogatin.

In order to satisfy both the circuit and field theory viewpoints, we now see the importance of adjacent power and power return planes, as well as adjacent signal and signal return planes. PDN design also requires both bulk and decoupling "energy storage" capacitors. The bulk capacitors 4.7 to 10 µF, typ.) are usually placed near the power input connector and the decoupling capacitors (1 to 10 nF, typ) nearest the noisiest switching devices - and most importantly, with minimal trace length connecting these from the power pins to signal return plane. Ideally, all decoupling capacitors should be mounted right over (or close to) the connecting vias and multiple vias should be used for each capacitor to reduce series inductance.

Signal or power routed referenced to a single plane will always have a defined return path back to the source. *Figure 2* shows how the electromagnetic field stays within the dielectric on both sides of the return plane. The dielectric is not shown for clarity.

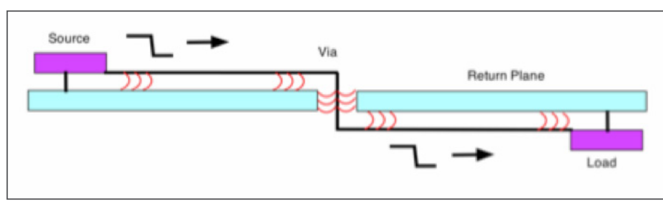


Figure 2 - A signal trace passing through a single reference plane.

On the other hand, referring to *Figure 3*, if a signal passes through two reference planes, things get a lot trickier. If the two planes are the same potential (for example, both are return planes), then simple connecting vias may be added adjacent to the signal via. These will form a nice defined return path back to the source.

If the two planes are differing potentials (for example, power and return), then stitching capacitors must be placed adjacent to the signal via. Lack of a defined return path will cause the electromagnetic wave to propagate throughout the dielectric, causing cross coupling to other signal vias and leakage and radiation out the board edges as shown.

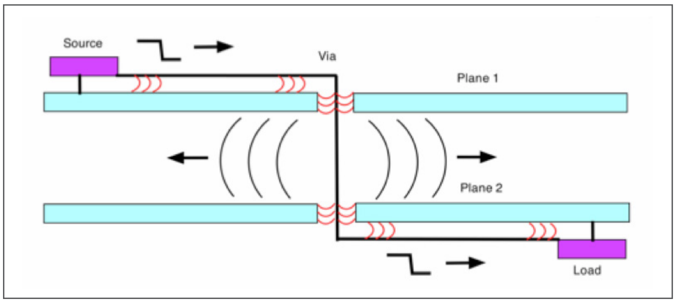


Figure 3 - A signal trace passing through two reference planes. If the reference planes are the same potential (signal or power returns, for example), then stitching vias next to the signal via should be sufficient. However, if the planes are different potentials (power and return, for example), then stitching capacitors must be installed very close to the signal via. Lack of a defined return path will cause the electromagnetic field to leak around the dielectric, as shown, and couple into other signal vias or radiate out board edges.

For example, let's take a look at a poor (but very typical) board stack-up that I see often. See *Figure 4*.

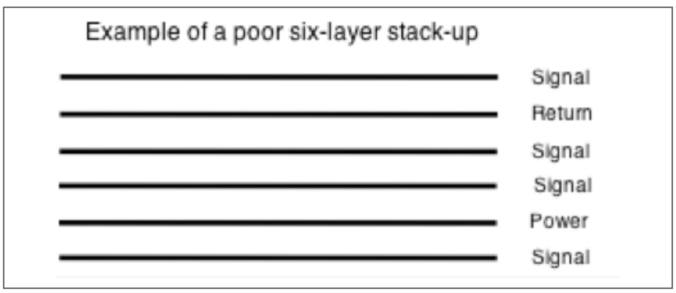


Figure 4 - A six-layer board stack-up with very poor EMI performance.

Notice the power and power return planes are three layers apart. Any PDN transients will tend to cross couple to the two signal layers in between. Similarly, only signal layers 1 and 3 have an adjacent return plane. Signal layers 4 and 6 are referenced to power, rather than signal return, therefore, the propagating wave return path will jump all over to whatever is the closest metal on the way back to the source, which is referenced to signal return. Again, this will tend to couple clock and other digital noise throughout the board.

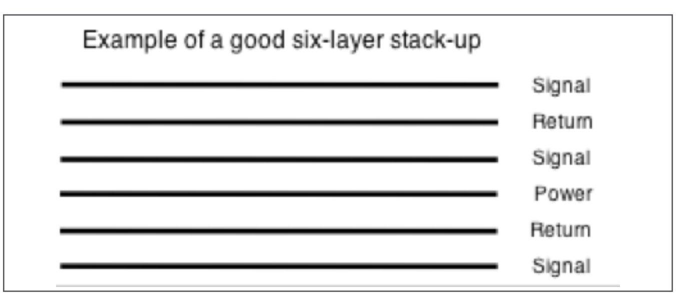


Figure 5 - A six-layer board stack-up with good EMI performance. Each signal layer has an adjacent return plane and the power and power return planes are adjacent.

A better design is shown in *Figure 5*. Here, we lose one signal layer, but we see the power and power return planes are adjacent, while each signal layer has an adjacent signal (or power) return plane. It's also a good idea to run multiple connecting vias between the two return planes in order to guarantee the lowest impedance path back to the source. The EMI performance will be significantly improved using this, or similar designs. In many cases, simply rearranging the stack-up is enough to pass emissions.

Note that when running signals between the top and bottom layers, you'll still need to include "stitching" vias between the return planes and stitching capacitors between the power and power return planes right at the point of signal penetration in order to minimize the return path. Ideally, these stitching vias should be located within 1 to 2 mm of each signal via.

Other Tips - Other design tips include placement of all power and I/O connectors along one edge of the board. This tends to reduce the high frequency voltage drop between connectors, thus minimizing cable radiation. Also, segregation of digital, analog, and RF circuits is a good idea, because this minimizes cross coupling between noisy and sensitive circuitry in the return plane.

Of course, high-speed clocks, or similar high-speed signals, should be run in as short and as direct a path as possible. These fast signals should not be run long board edges or pass near I/O or power connectors.

Gaps in Return Plane - I'd like to come back to the gap or slot in the return plane mentioned earlier and show an example of why it's bad news for EMI. When the return path is interrupted, the conduction current is forced around the slot, or otherwise finds the nearest (lowest impedance) path back to the source. The electromagnetic field is forced out and the field will "leak" all over the board. I have an article and good demonstration video of this and how it affects common mode currents and ultimately, EMI. See *Figure 6* and *Reference 4*.

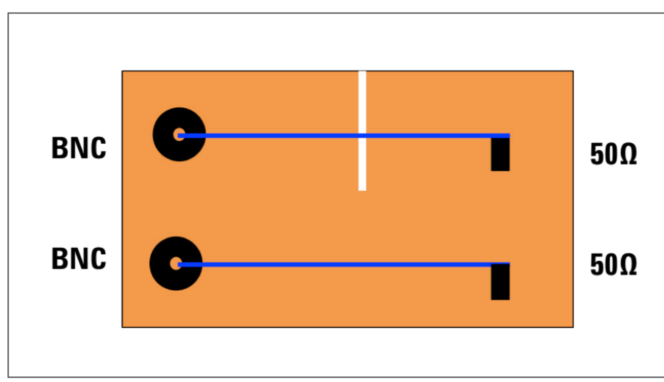


Figure 6 - shows a demonstration test board with transmission lines terminated in 50 Ohms. One transmission line has a gap in the return plane and the other doesn't. A harmonic comb generator (2 ns pulse) is connected to one of the two BNC connectors in turn and the harmonic currents in a wire taped to the return plane are measured with a current probe.

The difference between the gapped and un-gapped traces is shown in *Figure 7*. Note the harmonic currents are 10 to 15 dB higher for the gapped trace (in red). Failing to pay attention to the signal and power return paths is a major cause of radiated emissions failures.

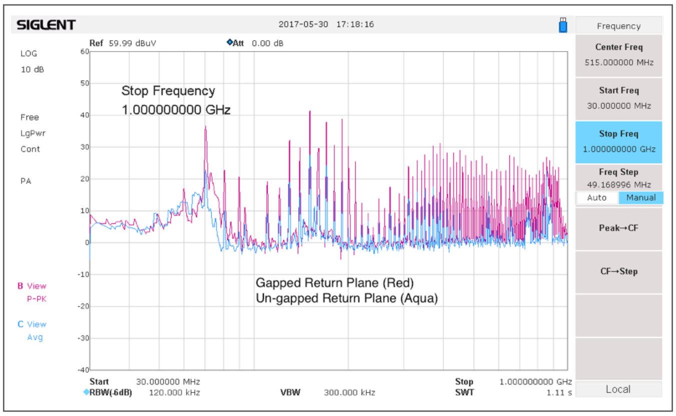


Figure 7 - The resulting common mode currents on an attached wire (to the return plane) as measured with a current probe. The trace in aqua is the un-gapped return path and the trace in red, the gapped return path. The difference is 10 to 15 dB higher for the gapped return path. These harmonic currents will tend to radiate and will likely cause radiated emissions failures.

SHIELDING

The two issues with shielded enclosures is getting all pieces well-bonded to each other and to allow power or I/O cable to penetrate it without causing leakage of common mode currents. Bonding between sheet metal may require EMI gaskets or other bonding techniques. Slots or apertures in shielded enclosures become issues when the longest dimension approaches a half wavelength.

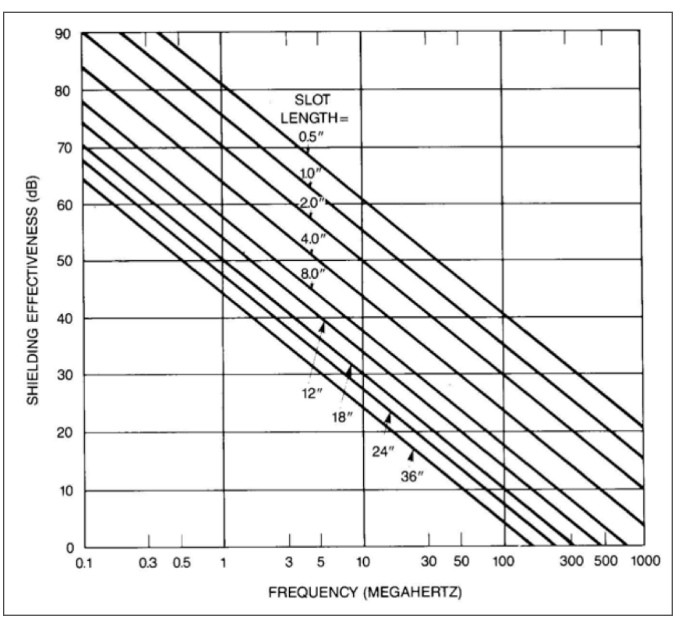


Figure 8 - A chart of attenuation versus slot length. Figure, courtesy Henry Ott.

Figure 8 shows a handy chart for determining the 20 dB attenuation of a given slot length. For example, if a product design requires at least a 20 dB shielding effectiveness, then the longest slot length can be just one-half inch. See *Reference 5* and *6* for more detail on shielding. Interference Technology also has a free downloadable 2017 EMI Shielding Guide with excellent information (*Reference 7*).

Figure 9 is a chart of wavelength versa half wave resonance at 1000 MHz. This is a handy tool for determining how efficient a cable or slot will act as an antenna.

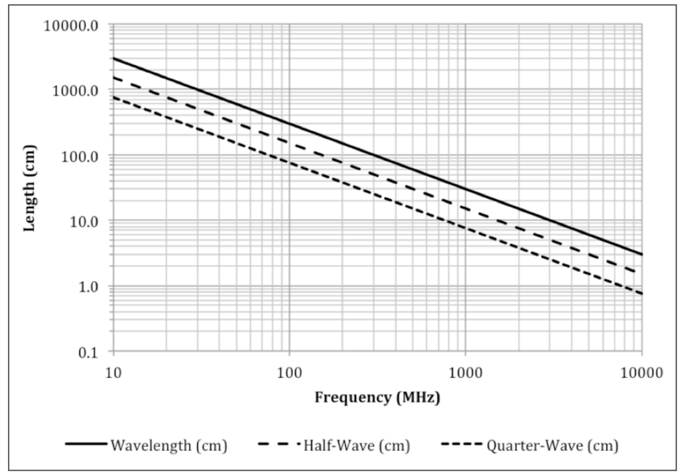


Figure 9 - A handy chart for determining resonant frequency versus cable or slot length in free space. Half-wavelength slots simulate dipole antennas and are particularly troublesome. Figure, courtesy Patrick André.

Cable Penetration - The number one issue I find when tracking down a radiated emissions problem is cable radiation. The reason cables radiate is that they penetrate a shielded enclosure without some sort of treatment - either bonding the cable shield to the metal enclosure or common mode filtering at the I/O or power connector (*Figure 10* and *11*). This occurs frequently, because most connectors today are attached directly to the circuit board and are then poked through holes in the shield. Once the cable is plugged in, it is "penetrating the shield" and EMI is the usual result.

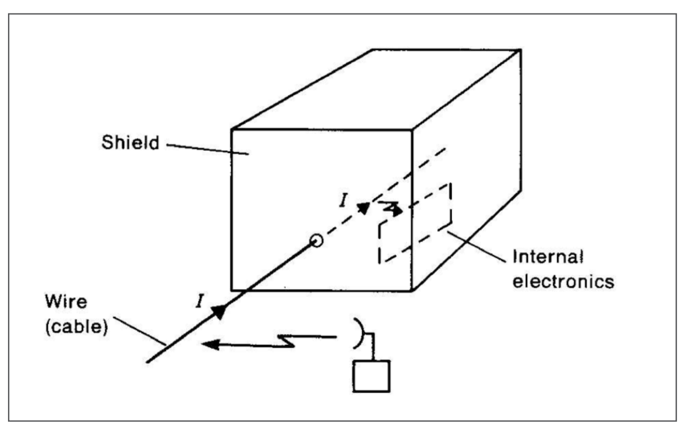


Figure 10 - Penetrating the shield with a cable defeats the shield. This example shows how external energy sources can induce noise currents in I/O cables, which can potentially disrupt internal circuitry. The reverse is also true, where internal noise currents can flow out the cable and cause emissions failures. Figure, courtesy Henry Ott.

There are four combinations or cases that must be considered: shielded or unshielded products, and shielded or unshielded cables. Power cables are usually unshielded for consumer/commercial products and so require power line filtering at the point of penetration or at the connector of the circuit board. Shielded cables must have the shield bonded (ideally in a 360 degree connection) to the product's shielded enclosure. If the product does not have a shielded enclosure, then filtering must be added at the point of penetration or at the I/O connector of the PC board. *Figure 11* shows the usual result when connectors simply poke through a shielded enclosure.

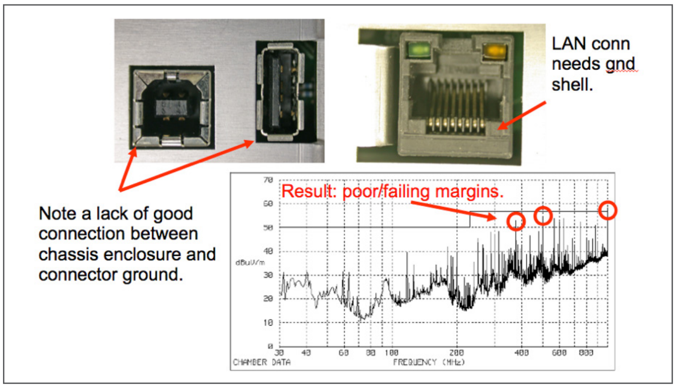


Figure 11 - Result of a penetrating cable through a shielded enclosure, because of un-bonded I/O connectors to the shielded enclosure.

Cable Shield Terminations - Another potential issue is if the I/O cable uses a "pigtail" connection to the connector shell. Ideally, cable shields should be terminated in a 360-degree bond for lowest impedance. Pigtails degrade the cable shield effectiveness by introducing a relatively high impedance. For example, a 1-inch pigtail connection has 12 Ohms impedance at 100 MHz and gets worse the higher you go in frequency. This is especially problematic for HDMI cables, because the HDMI working group (http://www.hdmi.org) originally failed to specify the method for terminating the cable shield to the connector. This may have been corrected in the latest edition of the standard released in 2017.

FILTERING

I won't go into very much detail here, because Interference Technology has an excellent EMI Filter Guide free for the downloading (see *Reference 8*). Suffice to say, filters, as well as transient protection, are important at power and I/O connectors. Typically, these will be common mode topologies, as shown in *Figure 12*. Most signal-level common mode chokes may be obtained in surface mount packaging. Power chokes are much larger to handle the current and may be obtained as either surface mount or through-hole mount, depending on the current rating. Many Ethernet connectors also have built-in common mode filtering.

Power supply input filters are generally designed to suppress both differential and common mode currents. A typical topology is shown in *Figure 13*. The "X" capacitor is designed to filter differential mode, while the CM choke and "Y" capacitors are designed to filter common mode. The resistor shown is usually 100 kOhm and the purpose is merely to bleed off the line voltage stored on the capacitors to a safe level.

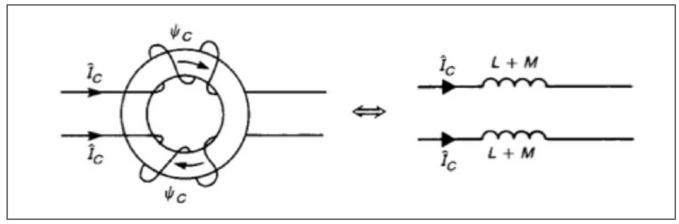


Figure 12 - A typical common mode filter used for I/O filtering. The two windings are wound in opposite directions and so tend to cancel the common mode currents.

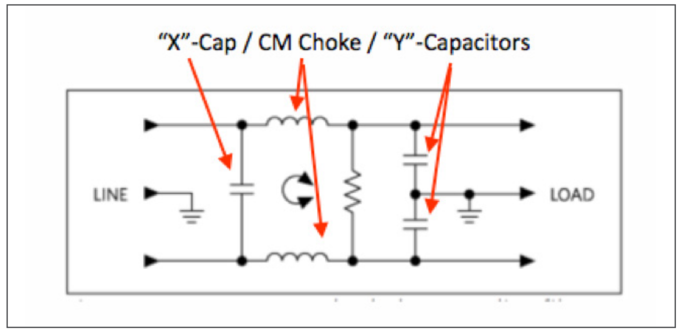


Figure 13 - A general purpose filter typically used for power supply input filtering.

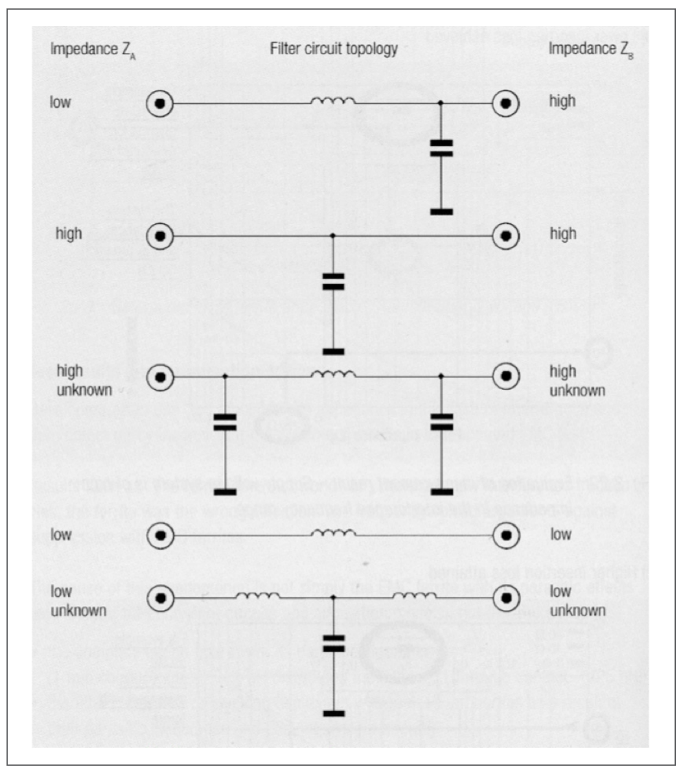


Figure 14 - Five common filter topologies, depending on the source and load impedances. Figure, courtesy Würth Electronik.

For general purpose filtering of signals, the handy chart of possible filter topologies may be found in *Reference 9* and is reproduced here in *Figure 14*. The appropriate topology depends on the source and load impedances. If these impedances are not known, then either the "PI" or "T" topology may be used (#3 or #5 on the chart, respectively).

Ferrite or inductive components should not be used in series with the power pins of ICs, as this will only reduce the ability of the local decoupling capacitors to supply required energy during simultaneous switching of the IC output stages with the resulting higher power supply noise. If used, they should be inserted "upstream" from the bulk capacitor.

Ferrite Chokes - One common filter element usually added to I/O cables is the ferrite choke. Ferrite chokes come in either the clamp-on types or solid cores meant to be assembled along with the cable assembly. Often, these are used as a last resort to reduce cable emissions or susceptibility.

Ferrite chokes have an associated impedance versus frequency characteristic, often peaking around 100 to 300 MHz. Some materials are designed to peak below 100 MHz for lower frequency applications. Maximum impedances can range from 25 to 1000 Ohms, depending on the ferrite material used and style of choke.

You may have noticed that clipping a ferrite choke onto a cable sometimes has no effect. This is usually due to the fact the choke has the same, or lower, effective impedance than the source and load impedances. The attenuation of a ferrite choke is easily calculated.

Attenuation (dB) = 20 * log((Zin + Zferrite + Zload) / (Zin + Zload))

For example, if we add a 100 Ohm ferrite choke to a power supply cable with system impedance of 10 Ohms (source and load), the attenuation would be:

Attenuation = 20 * log((10 + 100 + 10) / (10 + 10)) = 15.5 dB

Refer to *Reference 9* for much additional detail on ferrite chokes and general filter design.

TRANSIENT PROTECTION

In order to protect internal circuitry from electrical transients, such as ESD, electrically fast transient (EFT), or power line surge, due to lightning, transient protective devices should be installed at all power and I/O ports. These devices sense the transient and "clamp" the transient pulse to a specified clamp voltage.

Transient protectors in signal lines must generally have a very low parallel capacitance (0.2 to 1 pF, typical) to the return plane (or earth ground), depending on the data rate in order to maintain signal integrity. These silicon-based devices may be purchased in very small surface mount packaging.

Power line surge protection usually requires much larger transient protection devices and they can come in a variety of types. Gas discharge or metal oxide varistors are the most common, but larger silicon-based devices are also available. More information on the design of surge protection may be found in *Reference 9*.

SUMMARY

Most EMC/EMI failures are due to poor shielding, penetration of cables through shields, poor cable shield termination, poor filtering, and above all, poor PC board layout and stack-up. Paying attention to these common design faults will pay off with a lower risk of compliance failures and result in lower project costs and schedule slippage.

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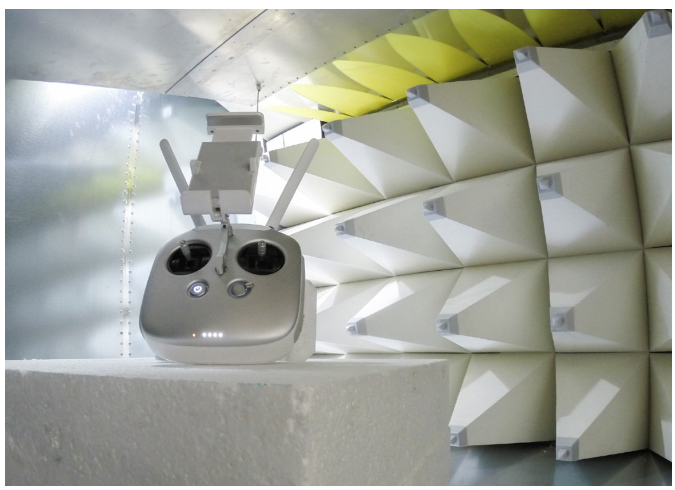
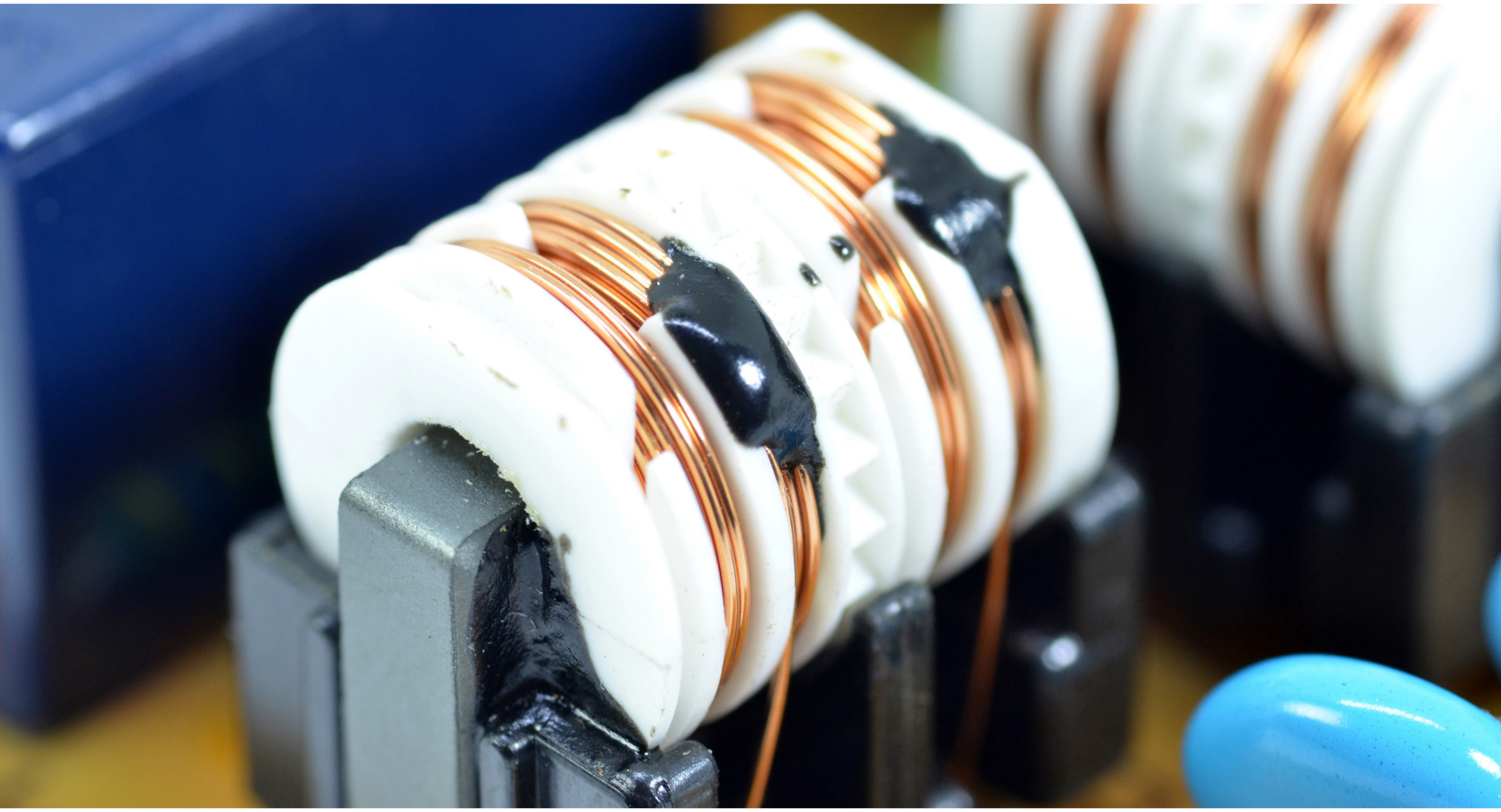


INPUT FILTERS — THE KEY TO SUCCESSFUL EMC VALIDATION

Ranjith Bramanpalli | Steffen Schulze
Würth Elektronik

Introduction

Input filters are today as ever a requisite factor for successful EMC validation of switching controllers, irrespective of the size of the AC component involved. Switching controllers create conducted EMC interferences due to AC components in their lines, independent of their individual topology and application. Certain component manufacturers have therefore optimized their power modules for a low line-bound and radiated emission of interferences. These types of modules' residual ripple generally exhibits a negligibly low value, meaning that an output filter can be dispensed within most applications. Since the input current at the step-down converter is pulsating, this may generate radio-frequency interferences in the application. Depending on the specific application, the hardware developer decides whether an input filter is necessary directly before the power module or in another position in the switch. The design process of input filters for optimized power modules and the measurement techniques that are used is discussed in this article.



INPUT FILTERS – THE KEY TO SUCCESSFUL EMC VALIDATION

As a starting point it is useful to illustrate how differential mode noises develop in the first place. Differential mode noises are interference signals in a system with a symmetrical current back and forth between the source and the load in the lines of a switching controller.

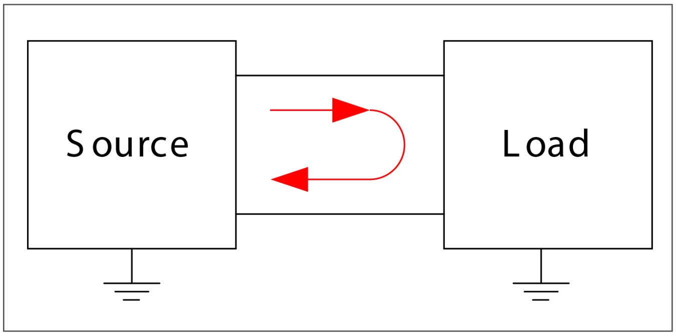


Figure 1 – Symmetrical system

In the input circuit, the clock frequency of the power module includes an AC component superimposed over the useful current and is similar in its configuration to the current through the storage inductance of the power module. The input current flows into the input capacitor Cin. Real capacitors possess a resistive component, the ESR, and an inductive component, the ESL as shown in *Figure 2*.

Due to the ESR of the input capacitor and the impedances of the lines of the power module, the AC component produces an undesirable voltage drop.

In this form, the noise voltage shows up as a differential-mode signal. The amplitude of the interference voltage occurring at the input capacitor is essentially dependent on the ESR of the capacitor used. Electrolytic capacitors have a relatively high ESR, the value of which can range between just a few milliohms up to several ohms. As a consequence, the interference voltage can vary between a few millivolts up to several volts. Ceramic capacitors, on the other hand, have a very small ESR of just a few milliohms and thus result in a noise voltage of a few millivolts. In addition, the circuit-board design of the power module exerts a great effect on the interference voltage.

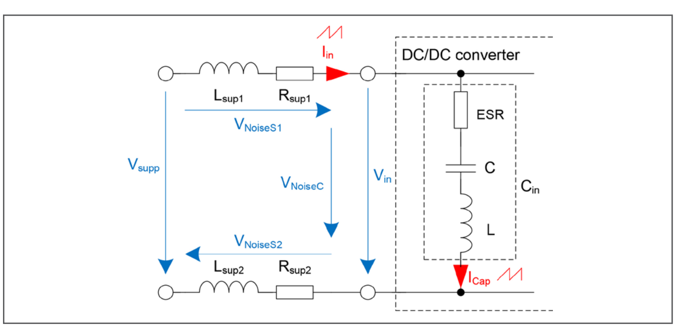


Figure 2 – Development of the noise voltage

To reduce differential mode noises, at least one simple LC filter must be fitted at the input of the converter as a measure to minimize the AC component in the line. In high-impedance systems, such an input filter can theoretically produce a voltage attenuation of 40 dB/decade in the stopband. In practice, a lower degree of attenuation is achieved since the terminating impedances are low-ohm in their nature and also because the components themselves exhibit losses. In dimensioning the LC filter a corner frequency f_c is selected that is below the switching frequency f_{sw} of the power module. If the factor is one tenth, theoretically an insertion loss of 40 dB is achieved at the switching frequency at which the highest spectral amplitude occurs.

$$f_C = \frac{f_{SW}}{10} \qquad (1)$$

The corner frequency of an LC filter is generally:

$$f_C = \frac{1}{2\pi \cdot \sqrt{L_f \cdot C_f}} \qquad (2)$$

As an example for the calculation of the filter, an inductance of 10 μH is selected and *Equation (2)* is transformed to:

$$C_f = \frac{1}{(2\pi \cdot 0.1 \cdot f_{sw})^2 \cdot L_f} \qquad (3)$$

In arranging the filter components, as shown in *Figure 3,* the filter capacitor can be positioned on the side of the voltage source or on the input side of the power module. The decisive factor for the attenuation of the pulsating current drawn from the voltage source is the inductance of the filter inductor.

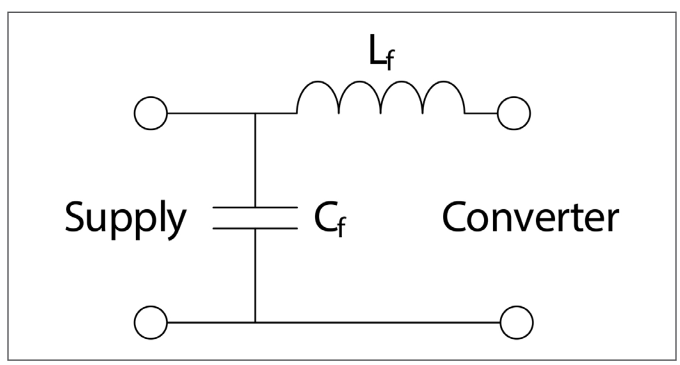


Figure 3 – Arrangement of the components of the input filter

When the quality of the filter resonance is too high, oscillations may occur in the event of changes in the input voltage that must be regulated. The stability criterion that applies here is that the output impedance of the input filter $Z_{out,filter}$ within a broad frequency spectrum has to be lower than the input impedance of the power module $Z_{in,converter}$:

$$|Z_{out,filter}| < |Z_{in,converter}| \qquad (4)$$

In addition, the corner frequency f_c of the input filter should lie far below the crossover frequency f_{co} of the power module.

$$f_{c,filter} \ll f_{co,converter} \quad (5)$$

Figure 4 shows how this is done by placing an attenuating branch parallel to the power module input.

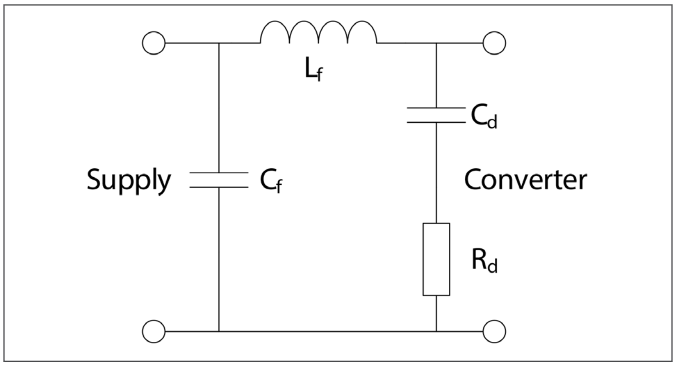


Figure 4 – Attenuation of the input filter

The attenuator reduces the quality of the input filter and consequently its output impedance at the resonance frequency. *Equation (6)* can be applied to calculate the attenuation resistance Rd for a filter quality of Qf=1:

$$R_d = \sqrt{\frac{L_f}{C_f}} \quad (6)$$

A value that has established itself in practice as an indicator of the capacity of the attenuation capacitor C_d is the five-to-ten-fold measure of the filter-capacitor capacitance:

$$(5 \cdot C_f) < C_d < (10 \cdot C_f) \quad (7)$$

As an alternative, the filter can be attenuated by selecting an electrolytic capacitor that is switched parallel to the filter output instead of the attenuator. As a rule, the value of the ESR of the electrolyte capacitor is sufficient to attenuate the filter.

SELECTING THE LC FILTER COMPONENTS

Both capacitors and coils show capacitive as well as inductive properties in reality. Filter inductors have their highest filter effect at their self-resonant frequency (SRF). In coils, the SRF is strongly dependent on the inductance and the capacitive coupling between the winding turns. In capacitors, the SRF is strongly dependent on the capacitance and the length of their terminations. When selecting the filter components, it is hence advisable to make sure that the SRF is at the upper end of the frequency range in which the RFI voltage is at its maximum or, respectively, in which the filter is to be active.

The decisive factor for the reduction of the differential-mode noise is the filter inductor, since this is the component that counteracts the rapid rise and drop in the current in the input circuit. *Figure 5* shows the impedance curves of three rod core chokes based on an example of the Würth Electronics WE-SD product family.

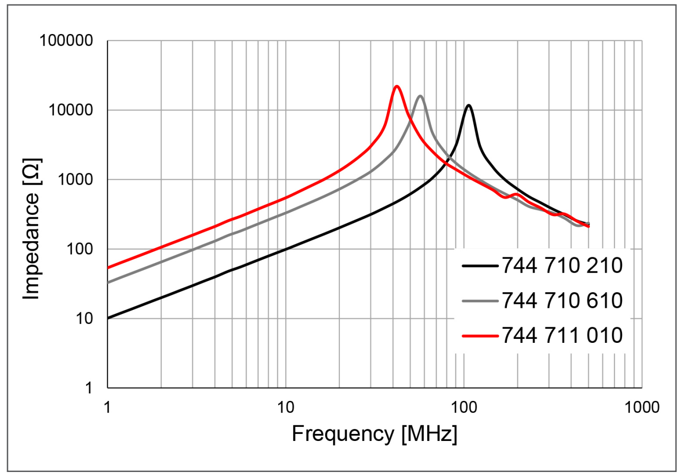


Figure 5 – Example of Impedance of one manufacturer's SD rod core chokes

The higher the inductance, the smaller the SRF. It is recommend-ed to select an inductor with an inductance whose numeric value is lower than the capacitance of the filter capacitor. In practice, a filter inductance with a maximum value of 10 µH is selected, since – depending on the design – such an inductance has a self-resonant frequency of approximately 30 MHz.

Exceeding the rated current of the filter inductor may result in damage to the wire winding. Taking the efficiency of the switching controller as a basis, it is possible to calculate the effective input current of the power module using *Equation (8)*.

$$I_{in} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot \eta} \quad (8)$$

For safety reasons, a larger value should be selected as the rated current of the filter coil.

The filter capacitor may take the form of a liquid electrolyte capacitor, a polymer capacitor, or even a ceramic capacitor. The only aspect that must be considered is that the filter quality at the corner frequency is sufficiently low.

Further measures must be considered when dimensioning a Π filter. In the optimal case, an input filter should be placed as close as possible to the input of the power module. For the case that the in-put filter is placed further away due to geometric circumstances, the traces may act as an antenna between the input filter and the power module at higher frequencies. The trace inductance can, however, also be used together with a ceramic capacitor to establish an additional LC filter with a higher cut-off frequency (see *Figure 6*). Due to its negligibly low ESR, a ceramic capacitor can swiftly short-circuit high-frequency voltages to ground with low impedance.

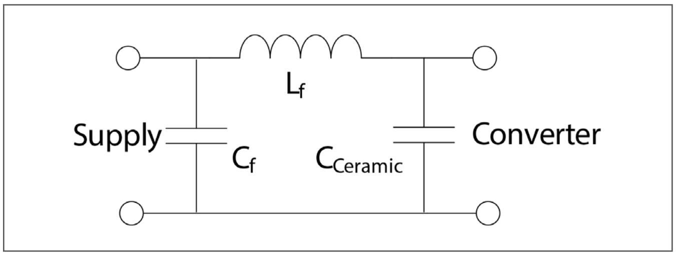


Figure 6 – Π input filter

The SRF of the capacitor should roughly lie within the spectrum of the switching frequency of the power module. To illustrate this point, *Figure 7* shows impedance curves of Würth Elektronik WCAP-CSGP ceramic capacitors in the 0805 size.

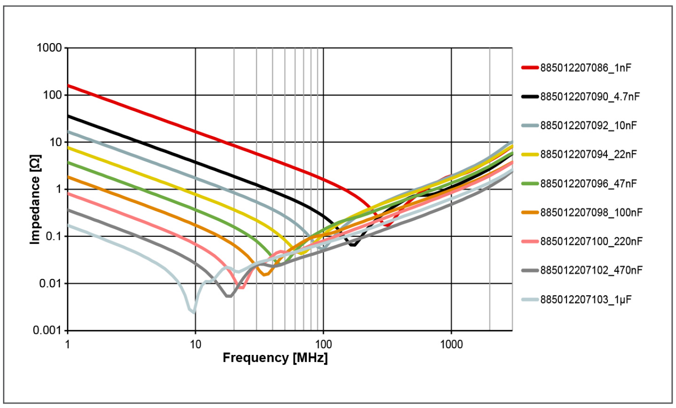


Figure 7 – Impedance of ceramic capacitors

Of the components shown in *Figure 7,* at a clock frequency of 2 MHz, for example, a capacitor with 1 µF would be suitable (resonant frequency marked in red). Even a 100 nF ceramic capacitor (resonant frequency marked in blue), which is used as a blocking capacitor in numerous electronic circuits, would be a suitable candidate at these values; it should be mentioned, however, that com-pared with the 1 µF version the 100 nF capacitor has an ESR higher by a factor of nine.

DIMENSIONING AN OUTPUT FILTER

Some power modules on the market, such as Würth Elektronik MagI³C power modules, exhibit a negligibly low residual ripple at the output, which is why an output filter is not absolutely necessary. For the case that components supplied by the switching controller decouple interference signals via interfaces (e.g. sensor switches, analog switching circuits), it may be necessary to include an output filter to filter the output voltage.

The circuit schematic shown in *Figure 6* images an output filter as an option comparable to that shown here in *Figure 8.* It is not generally possible to make a definitive statement on the necessity for and effectiveness of such an output filter, since this must be dimensioned individually for each specific application. It may be possible to use an output filter to reduce the residual ripple of the power module to an absolute minimum, or otherwise to suppress undesirable subharmonic oscillations. The filter can be dimensioned as already described. Attenuation of the filter resonance is not necessary in this case.

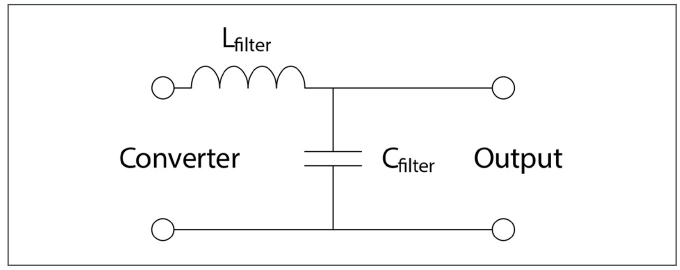


Figure 8 – Output filter

MEASURING THE NOISE VOLTAGE

The noise voltage is measured according to the basic standard IEC CISPR 16-2-1, which describes the types of the interference variables to be measured, the equipment to be used for the various interfaces, and the measurement set-up for table-top and floor-standing devices. The interferences are evaluated in the frequency range from 9 kHz to 30 MHz. The measuring devices include besides the EMI receiver a variety of line impedance stabilizing networks (LISNs), voltage probes, current clamps and capacitive couplers. In a measurement set-up for table-top devices, as shown in *Figure 9,* the test object (DUT, "device under test") is positioned on a non-conductive table standing on a ground reference plane. The table should be 40 cm in height. In the case that a vertical ground reference plane is also present, the table should be at least 80 cm in height. The LISN must be connected to the ground plane ensuring good conductivity. The DUT itself and any attached cables are to be arranged so that they are 40 cm distant from the ground plane.

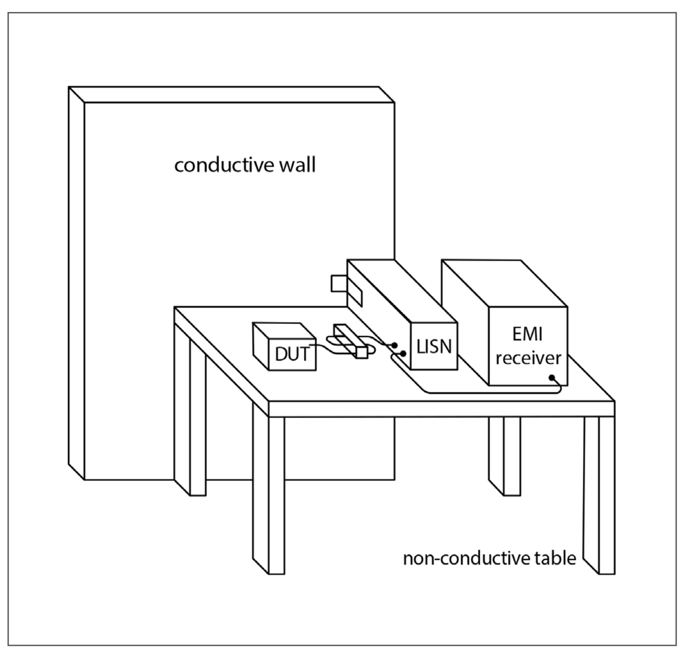


Figure 9 – Test set-up for measuring conducted interferences on power-supply lines

The length of the cable between the DUT and the LISN should not exceed 80 cm. The EMI receiver evaluates the asymmetric noise voltage that is decoupled at the LISN for the separate leads of the cable.

MEASURING THE RADIATED NOISE

The method for measuring the radiated noise above 30 MHz is described in the IEC CISPR16-2-3 basic standard. The measurement environment is generally in the form of an anechoic room with a conductive floor or, at a smaller scale, an anechoic chamber. Here, too, the DUT is positioned on a non-conductive table (for portable or table-top devices, see *Figure 10,* or on the floor. To enable the DUT to revolve on its own axis in its default state during the measurement, it is placed on a turntable. In larger anechoic rooms, the receiving antenna is placed at a distance of 10 m from the DUT and adjusted in its height during the measurement to find the maxi-mum electric field strength at each measurement frequency (peak spectrum). In addition, the orientation of the antenna is altered (horizontal and vertical polarization). In smaller anechoic chambers, the distance between antenna and DUT should be 3 m; since the antenna height needs to be fixed, the height scan is omitted and he floor between the antenna and the DUT must be covered with absorbing material.

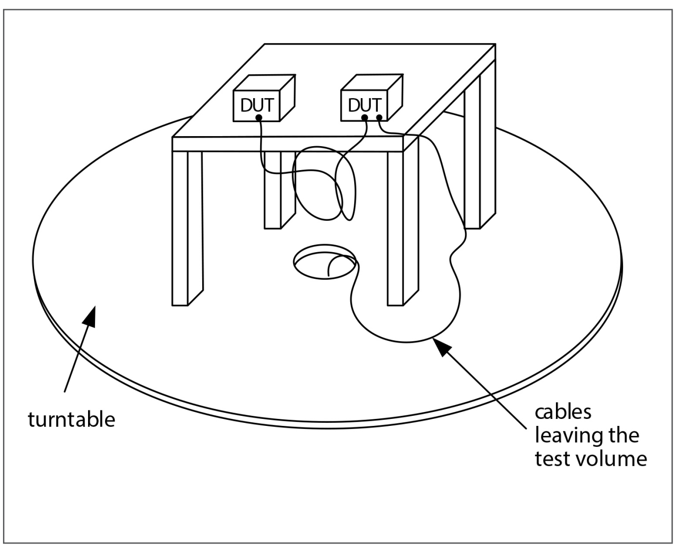


Figure 10 – Test set-up for measuring the radiated noise in anechoic rooms or chambers

CASE STUDY – MEASURED NOISE VOLTAGE

The following section describes the measurement of the noise volt-age using a Würth Elektronik MagI³C power module evaluation board fitted with a Variable Step Down Regulator Module (171 020 601) as an example.

Already during the preliminary phase it is possible to measure the AC component at the power module's input using an oscilloscope. By running an analysis within the time domain, the anticipated interference spectrum can be estimated at the start of the work on the design of the filter.

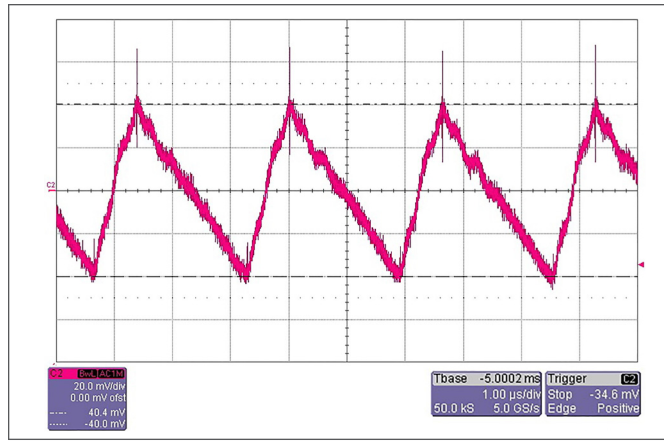


Figure 11 – Time-domain signal with a broadband spectral content

Figure 11 shows an AC component of 80 mV, measured at an in-put voltage of the power module of 7.5 V, an average input current of 1.2 A, and an average load current of 2 A. Switching controllers have the property to show up as a negative differential resistance from the viewpoint of the power supply. The input current rises with decreasing input voltage. For this reason, the noise voltage is measured under "worst case" conditions – minimum input voltage, maximum current.

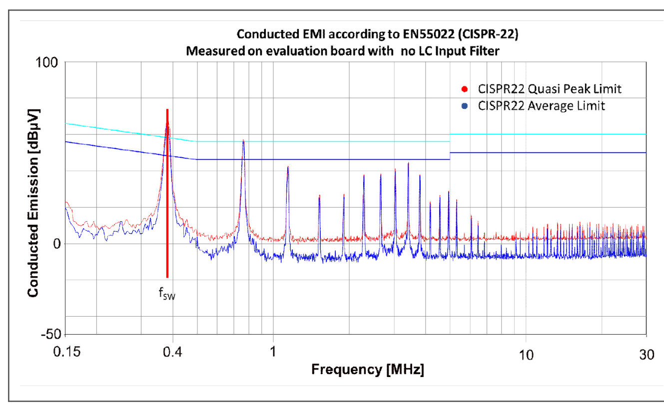


Figure 12 – Noise voltage without an input filter

The decisive factor in the analysis of this type of noise emission, however, remains the measurement of noise voltage as can be per-formed in an EMC laboratory. *Figure 12* shows the result of a noise voltage measurement without an input filter.

This power module operates at a clock frequency of 370 kHz. In the interference spectrum, the highest amplitude (red peak: 68 dBµV) can be measured at this frequency. The amplitude density of the noise voltage drops at a rate of approx. 40 dB/decade, meaning that no significant interference level can be seen above the 15th harmonic. Nevertheless, it is only above the 9th harmonic that the interference level is more than 10 dB below the limit for the average detector (dark blue line).

Equation (3) can now be used to calculate a suitable LC input filter. Due to the relatively low switching frequency, an inductor with a low SRF and an inductance of 4.7 µH is selected and the filter capacitance is calculated.

$$C_f = \frac{1}{(2\pi \cdot 0.1 \cdot f_{sw})^2 \cdot L_f} \quad (9)$$

The selected filter capacitor is the one with a little higher capacitance of 10 µF. The maximum input current is calculated using *Equation (8)*.

This calculation requires the efficiency of the evaluation board, which is determined by measurement and in this case has a value of 91%.

$$I_{in} = \frac{5\,V \cdot 2\,A}{6\,V \cdot 0.91} = 1.83\,A \quad (10)$$

On the basis of the calculations of the filter inductance and input current, it is now possible to select an appropriate inductor. Picked for the purpose is an unshielded inductor from the Würth Elektronik PD2 series, size 5820. *Figure 13* shows the result of the noise voltage measurement with the matched filter.

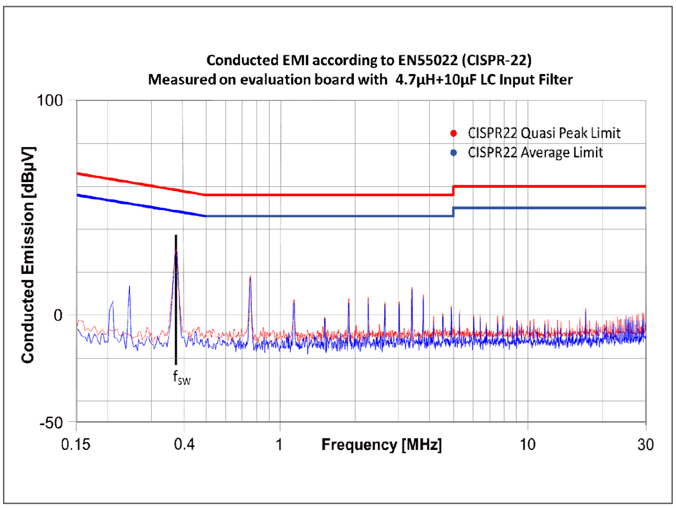


Figure 13 – Noise voltage with an input filter

The interference level measured at the 370 kHz switching frequency has a value of 30 dBµV. The levels of all harmonics are lower than 20 dBµV and are thus sufficiently attenuated. The average level at 370 kHz corresponds to the peak level and is 18 dB lower than the average limit of 47 dBµV. In measuring such conducted interferences in the practical context, a signal-to-noise ratio of this dimension is entirely sufficient in order to confirm the conformity of this measurement.

The purpose of the measurement of the noise voltage is to demonstrate the usefulness of an analysis of the interference potential in the time domain; though an analysis in the frequency domain is still indispensable.

Finally, the equations can be used to calculate an attenuating resistance.

$$R_d = \sqrt{\frac{4.7\,\mu H}{10\,\mu F}} = 0.686\,\Omega \quad (11)$$

The higher the value of the attenuation resistance, the higher the attenuation of the filter resonance. In this case, the next higher resistance of the E12 series of 1 Ω can be selected.

A value of 47 µF is selected for the attenuation capacitor. This may be, for example, a Würth Elektronik eiCap ceramic capacitor of the WCAP-CSGP series.

MEASURING ACCORDING TO IEC CISPR 22

The above measurements were performed according to the IEC CISPR16-2-1 standard, as described in Section 8. The use of a LISN enabled the asymmetric voltage to be decoupled and equated to the asymmetric (common-mode) voltage, which was then compared to the limit, taken from the IEC CISPR 22 standard for devices for private and commercial use (Class B). For power-supply components – and this includes all types of switching controllers – there is no directly applicable EMC standard. The entire application in which the switching controller is used must be assigned to a specific category of devices and then tested according to the corresponding standard applicable for the product or product family. In this case, the product-family standard IEC CISPR 22 for IT installations was taken only with reference to the limits, which are also given in the IEC 61000-6-3 generic standard. The generic standards can be used in cases for which there is no specific standard for the device in question.

SUMMARY

Irrespective of the size of the AC component involved, an input filter is today as ever a requisite factor for a successful EMC validation of a switching controller. Simple-to-apply equations can be used to calculate such an input filter on an individual basis. Taking the impedances of the filter and the switching controller into account in the equations, this enables oscillations to be avoided and also ensures the control stability of the switching controller itself. A targeted selection of the filter components lays the foundations for an optimal design of the filter. Equipped with an appropriate degree of technical skill in EMC testing methods, the hardware developer can design his switch purposefully and, wherever necessary, make any adjustments to the filter himself.

COMMON COMMERCIAL EMC STANDARDS

►COMMERCIAL STANDARDS

The following are some of the most common commercial EMC standards. Most standards have a fee associated and most on the list are linked back to the source where they're available. If you're purchasing the printed version of this guide, then refer to the Standards Organizations in the References section for standards purchase information. Note that many Euro Norm (EN) versions of IEC standards may be purchased at a considerable discount from the Estonian Centre for Standardization, https://www.evs.ee.

FCC

(https://www.ecfr.gov)

Electronic Code of Federal Regulations (e-CFR)
CFR 47 - Part 15 (Radio Frequency Devices)

ANSI

(http://webstore.ansi.org)

Document Number	Title
C63.4	Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz

IEC

(https://webstore.iec.ch)

Document Number	Title
IEC 61000-3-2	Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
IEC 61000-3-3	Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection
IEC 61000-4-2	Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
IEC 61000-4-3	Electromagnetic compatibility (EMC) - Part 4-3 : Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
IEC 61000-4-4	Electromagnetic compatibility (EMC) - Part 4-4 : Testing and measurement techniques - Electrical fast transient/burst immunity test
IEC 61000-4-5	Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
IEC 61000-4-6	Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields
IEC 61000-4-7	Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

IEC 61000-4-8	Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test
IEC 61000-4-9	Electromagnetic compatibility (EMC) - Part 4-9: Testing and measurement techniques - Impulse magnetic field immunity test
IEC 61000-4-10	Electromagnetic compatibility (EMC) - Part 4-10: Testing and measurement techniques - Damped oscillatory magnetic field immunity test
IEC 61000-4-11	Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests
IEC 61000-4-12	Electromagnetic compatibility (EMC) - Part 4-12: Testing and measurement techniques - Ring wave immunity test
IEC 61000-6-1	Electromagnetic compatibility (EMC) - Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments
IEC 61000-6-2	Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity standard for industrial environments
IEC 61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments
IEC 61000-6-4	Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
IEC 61000-6-5	Electromagnetic compatibility (EMC) - Part 6-5: Generic standards - Immunity for power station and substation environments
IEC 61000-6-7	Electromagnetic compatibility (EMC) - Part 6-7: Generic standards - Immunity requirements for equipment intended to perform functions in a safety-related system (functional safety) in industrial locations
IEC 61326-1	Electrical equipment for measurement, control and laboratory use – EMC requirements – Part 1: General requirements
IEC 61326-2-1	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-1: Particular requirements - Test configurations, operational conditions and performance criteria for sensitive test and measurement equipment for EMC unprotected applications
IEC 61326-2-2	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-2: Particular requirements - Test configurations, operational conditions and performance criteria for portable test, measuring and monitoring equipment used in low-voltage distribution systems
IEC 61326-2-3	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-3: Particular requirements - Test configuration, operational conditions and performance criteria for transducers with integrated or remote signal conditioning
IEC 61326-2-4	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-4: Particular requirements - Test configurations, operational conditions and performance criteria for insulation monitoring devices according to IEC 61557-8 and for equipment for insulation fault location according to IEC 61557-9
IEC 61326-2-5	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-5: Particular requirements - Test configurations, operational conditions and performance criteria for field devices with field bus interfaces according to IEC 61784-1

IEC 61326-2-6	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-6: Particular requirements - In vitro diagnostic (IVD) medical equipment
IEC 61326-3-1	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 3-1: Immunity requirements for safety-related systems and for equipment intended to perform safety-related functions (functional safety) - General industrial applications
IEC 61326-3-2	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 3-2: Immunity requirements for safety-related systems and for equipment intended to perform safety-related functions (functional safety) - Industrial applications with specified electromagnetic environment
IEC 61340-3-1	Electrostatics - Part 3-1: Methods for simulation of electrostatic effects - Human body model (HBM) electrostatic discharge test waveforms

CISPR

(https://webstore.iec.ch)

Document Number	Title
CISPR 11	Industrial, scientific and medical (ISM) radio-frequency equipment - Electromagnetic disturbance characteristics - Limits and methods of measurement
CISPR 12	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers
CISPR 13	Sound and television broadcast receivers and associated equipment - Radio disturbance characteristics - Limits and methods of measurement
CISPR 14-1	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
CISPR 14-2	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 2: Immunity - Product family standard
CISPR 15	Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment
CISPR 16-1-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus
CISPR 16-1-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-2: Radio disturbance and immunity measuring apparatus - Coupling devices for conducted disturbance measurements
CISPR 16-1-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-3: Radio disturbance and immunity measuring apparatus - Ancillary equipment - Disturbance power
CISPR 16-1-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-4: Radio disturbance and immunity measuring apparatus - Antennas and test sites for radiated disturbance measurements
CISPR 16-1-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-5: Radio disturbance and immunity measuring apparatus - Antenna calibration sites and reference test sites for 5 MHz to 18 GHz
CISPR 16-1-6	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-6: Radio disturbance and immunity measuring apparatus - EMC antenna calibration
CISPR 16-2-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-1: Methods of measurement of disturbances and immunity - Conducted disturbance measurements

CISPR 16-2-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-2: Methods of measurement of disturbances and immunity - Measurement of disturbance power
CISPR 16-2-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-3: Methods of measurement of disturbances and immunity - Radiated disturbance measurements
CISPR 16-2-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-4: Methods of measurement of disturbances and immunity - Immunity measurements
CISPR TR 16-2-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-5: In situ measurements for disturbing emissions produced by physically large equipment
CISPR TR 16-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 3: CISPR technical reports
CISPR TR 16-4-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-1: Uncertainties, statistics and limit modelling - Uncertainties in standardized EMC tests
CISPR 16-4-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-2: Uncertainties, statistics and limit modelling - Measurement instrumentation uncertainty
CISPR TR 16-4-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-3: Uncertainties, statistics and limit modelling - Statistical considerations in the determination of EMC compliance of mass-produced products
CISPR TR 16-4-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-4: Uncertainties, statistics and limit modelling - Statistics of complaints and a model for the calculation of limits for the protection of radio services
CISPR TR 16-4-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-5: Uncertainties, statistics and limit modelling - Conditions for the use of alternative test methods
CISPR 17	Methods of measurement of the suppression characteristics of passive EMC filtering devices
CISPR TR 18-1	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 1: Description of phenomena
CISPR TR 18-2	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 2: Methods of measurement and procedure for determining limits
CISPR TR 18-3	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 3: Code of practice for minimizing the generation of radio noise
CISPR 20	Sound and television broadcast receivers and associated equipment - Immunity characteristics - Limits and methods of measurement
CISPR 22	Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement (Withdrawn and replaced by CISPR 32:2015)
CISPR 24	Information technology equipment - Immunity characteristics - Limits and methods of measurement (Withdrawn and replaced by CISPR 35:2016)
CISPR 25	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers
CISPR 32	Electromagnetic compatibility of multimedia equipment – Emission requirements
CISPR 35	Electromagnetic compatibility of multimedia equipment - Immunity requirements

OTHER RELEVANT STANDARDS

(https://webstore.iec.ch)

Document Number	Title
IEC 60601-1	General requirements for basic safety and essential performance
IEC TR 60601-4-2	Electromagnetic immunity performance
IEC TR 60601-4-3	Considerations of unaddressed safety aspects in the third edition of IEC 60601-1
IEC TR 62354	General testing procedures for medical electrical equipment
ISO 14708-1	Active implantable medical devices

EMC STANDARDS ORGANIZATIONS

American National Standards Institute
www.ansi.org

ANSI Accredited C63
www.c63.org

Asia Pacific Laboratory Accreditation Cooperation (APLAC)
https://www.apac-accreditation.org/

BSMI (Taiwan)
http://www.bsmi.gov.tw/wSite/mp?mp=95

Canadian Standards Association (CSA)
www.csa.ca

CISPR
http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1298,25

CNCA (China)
http://english.cnca.gov.cn

Electromagnetic Compatibility Industry Association UK
http://www.emcia.org

FDA Center for Devices & Radiological Health (CDRH)
https://www.fda.gov/MedicalDevices/default.htm

Federal Communications Commission (FCC)
www.fcc.gov

Federal Standards
https://quicksearch.dla.mil/qsSearch.aspx

Gosstandart (Russia)
https://gosstandart.gov.by/en/

IEC
http://www.iec.ch/index.htm

IEEE Standards Association
https://standards.ieee.org/

IEEE EMC Society Standards Development Committee (SDCOM)
https://standards.ieee.org/develop/index.html

Industry Canada (Certifications and Standards)
http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf06165.html

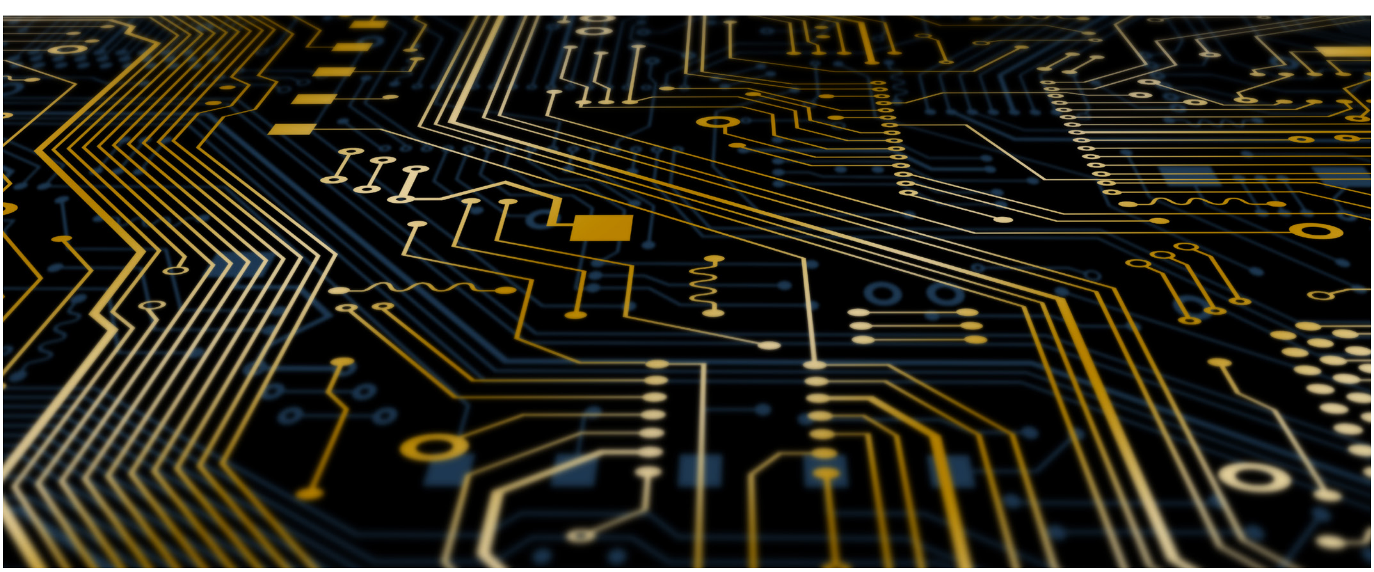
ISO (International Organization for Standards)
http://www.iso.org/iso/home.html

RTCA
https://www.rtca.org

SAE EMC Standards Committee
www.sae.org

SAE EMC Standards
http://www.sae.org/servlets/works/committeeHome.do?comtID=TEVEES17

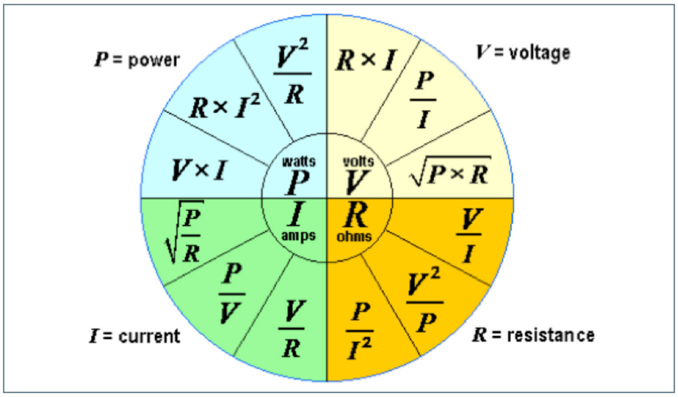
VCCI (Japan, Voluntary Control Council for Interference)
http://www.vcci.jp/vcci_e/



EQUATIONS, TOOLS, & CALCULATORS

COMMON EMC-RELATED EQUATIONS

OHMS LAW



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

BANDWIDTH VERSUS RISE TIME

$$BW\,(GHz) = \frac{0.35}{RT\,(nsec)}$$

Empirically derived and applies for a square wave, with rise time measured at 10 and 90%. Example, for a rise time of 1 nsec, the bandwidth is 350 MHz.

BANDWIDTH VERSUS CLOCK FREQUENCY

$$BW_{Clock}(GHz) = 5\,X\,F_{Clock}(GHz)$$

Assuming the rise time of a clock is 7% of the period, we can approximate the bandwidth as shown.

Example, for a clock frequency of 100 MHz, the bandwidth is 500 MHz. That is, the highest significant sine-wave frequency component in a clock wave is the fifth harmonic.

PERIOD VERSUS FREQUENCY

$$F_{Clock}(GHz) = \frac{1}{T_{Clock}\,(nsec)}$$

PARTIAL SELF-INDUCTANCE OF A ROUND WIRE (1MM)

25 nH/inch or 1 nH/mm
Example, a 1.5 mm long via has a partial self-inductance of about 1.5 nH.

IMPEDANCE OF A WIRE

$$Z_{Wire}\,(Ohms) = 2\pi\,f\,(GHz)L(nH)$$

Example, a 1-inch wire (25 nH) has an impedance of 16 Ohms at 100 MHz.

SPEED OF SIGNALS

In air: 12 inches/nsec

In most PC board dielectrics: 6 inches/nsec

VSWR AND RETURN LOSS

VSWR given forward/reverse power $VSWR = \dfrac{1+\sqrt{P_{rev}/P_{fwd}}}{1-\sqrt{P_{rev}/P_{fwd}}}$

VSWR given reflection coefficient (ρ) $VSWR = \left|\dfrac{1+\rho}{1-\rho}\right|$

Reflection coefficient (ρ), given Z_1,Z_2 Ohms $\rho = \left|\dfrac{Z_1 - Z_2}{Z_1 + Z_2}\right|$

Reflection coefficient (ρ), given fwd/rev power $\rho = \sqrt{\dfrac{P_{rev}}{P_{fwd}}}$

RETURN LOSS, GIVEN FORWARD/REVERSE POWER

$$RL(dB) = -10\log(\frac{P_{OUT}}{P_{IN}})$$

EQUATIONS, TOOLS, & CALCULATORS

RETURN LOSS, GIVEN VSWR

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

Return Loss, given reflection coefficient (ρ)

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

E-FIELD FROM DIFFERENTIAL-MODE CURRENT

$$|E_{D,max}| = 2.63 * 10^{-14}\frac{|I_D|f^2Ls}{d}$$

ID = differential-mode current in loop (A)

f = frequency (Hz)

L = length of loop (m)

s = spacing of loop (m)

d = measurement distance (3 m or 10 m, typ.)

(Assumption that the loop is electrically small and measured over a reflecting surface)

E-FIELD FROM COMMON-MODE CURRENT

$$|E_{C,max}| = 1.257 * 10^{-6}\frac{|I_C|fL}{d}$$

IC = common-mode current in wire (A)

f = frequency (Hz)

L = length of wire (m)

d = measurement distance (3 m or 10 m, typ.) (Assumption that the wire is electrically short)

TEMPERATURE CONVERSIONS

Celsius to Fahrenheit: °C = 5/9(°F - 32)
Fahrenheit to Celsius: °F = 9/5(°C) + 32

ANTENNA (FAR FIELD) RELATIONSHIPS

Gain, dBi to numeric $Gain_{numeric} = 10^{dBi/10}$

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

Gain,dBi-to-Antenna Factor $AF = 20\log(MHz) - dBi - 29.79$

Antenna Factor-to-gain indBi $dBi = 20\log(MHz) - AF - 29.79$

Field Strength given watts, numeric gain, distance in meters

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

Field Strength given watts, dBi gain, distance in meters

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

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

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

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

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

PC BOARD EQUATIONS

1 oz. copper = 1.4 mils = 0.036 mm

0.5 oz. copper = 0.7 mils = 0.018 mm

Convert mils to mm: multiply by 0.0254 mm/mil

Convert mm to mils: multiply by 39.4 mil/mm

Signal velocity in free space: approx. 12 in/ns

Signal velocity in FR-4: approx. 6 in/ns

EQUATIONS, TOOLS, & CALCULATORS

WORKING WITH DB

The decibel is always a ratio

Power Gain = Pout/Pin

Power Gain(dB) = 10log(Pout / Pin)

Voltage Gain(dB) = 20log(Vout/Vin)

Current Gain(dB) = 20log(Iout/Iin)

We commonly work with:

dBm (referenced to 1 mW)

dBµV (referenced to 1 µV)

dBµA (referenced to 1 µA)

Power Ratios

3 dB = double (or half) the power

10 dB = 10X (or /10) the power

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

DBM, DBµV, DBµA (CONVERSION)

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

Note: For current relationships, substitute A for V

FIELD STRENGTH EQUATIONS

dBµV/m to V/m:	$V/m = 10^{(((dB\mu V/m)-120)/20)}$
V/m to dBµV/m:	dBµV/m = 20log(V/m) + 120
dBµV/m to dBµA/m:	dBµA/m = dBµV/m - 51.5
dBµA/m to dBµV/m:	dBµV/m = dBµA/m + 51.5
dBµA/m to dBpT:	dBpT = dBµA/m + 2
dBpT to dBµA/m:	dBµA/m = dBpT - 2
µT to A/m:	A/m = µT/1.25
A/m to µT:	µT = 1.25 * A/m

DBM TO DBUV CHART

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

A common formula for converting default spectrum analyzer amplitudes (dBm) to the limits as shown in the emissions standards (dBµV):

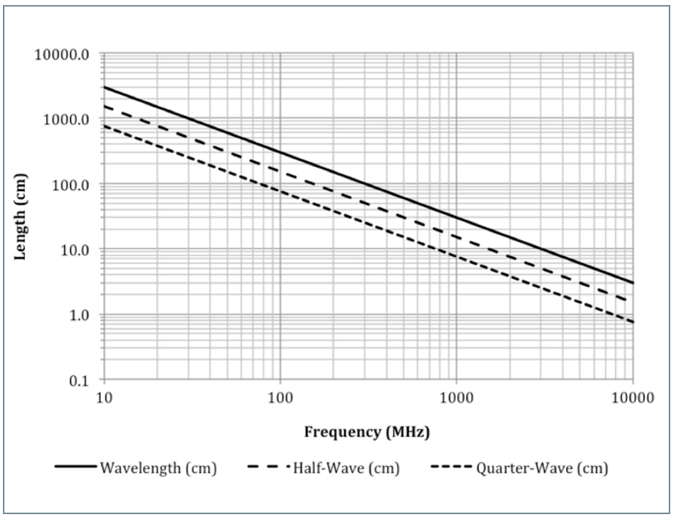
dBm to dBµV, use: dBµV = dBm + 107

EQUATIONS, TOOLS, & CALCULATORS

WAVELENGTH EQUATIONS (FREE SPACE)

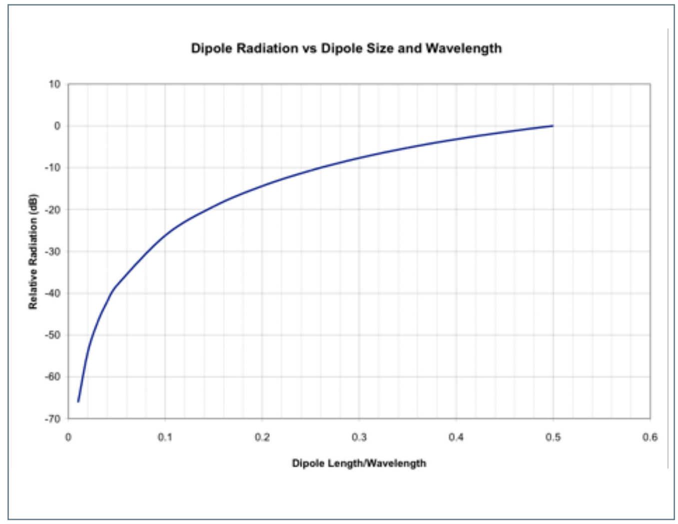
Wavelength(m) = 300/f(MHz)
Half wavelength(ft.) = 468/f(MHz)

RESONANCE OF STRUCTURES



Use this handy chart for determining the resonant frequency versus cable or slot length in free space. Half-wavelength slots or cables simulate dipole antennas and are particularly troublesome. Image Source: Patrick André.

DIPOLE RADIATION VERSUS LENGTH



Use this chart to for determining the relative radiation versus size in wavelength. Image Source: Bruce Archambeault.

For example, a wire or slot whose length is 0.2 wavelength at a particular frequency, would radiate about 15 dB down from the equivalent half-wavelength wire or slot.

LINKEDIN GROUPS

Electromagnetic Compatibility Forum

Electromagnetics and Spectrum Engineering Group

EMC - Electromagnetic Compatibility

EMC Experts

EMC Troubleshooters

ESD Experts

Signal & Power Integrity Community

EMI/EMC Testing

iNARTE

IEEE

COMMON SYMBOLS

A	Amperes, unit of electrical current
AC	Alternating Current
AM	Amplitude modulated
dBm	dB with reference to 1 mW
dBµA	dB with reference to 1 µA
dBµV	dB with reference to 1 µV
DC	Direct Current
E	"E" is the electric field component of an electromagnetic field.
E/H	Ratio of the electric field (E) to the magnetic field (H), in the far-field this is the characteristic impedance of free space, approximately 377 Ω
EM	Electromagnetic
EMC	Electromagnetic compatibility
EMI	Electromagnetic Interference
FM	Frequency modulated
GHz	Gigahertz, one billion Hertz (1,000,000,000 Hertz)
H	"H" is the magnetic field component of an electromagnetic field.
Hz	Hertz, unit of measurement for frequency
I	Electric current
kHz	Kilohertz, one thousand Hertz (1,000 Hertz)
λ	Lambda, symbol for wavelength
MHz	Megahertz, one million Hertz (1,000,000 Hertz)
mil	Unit of length, one thousandth of an inch
mW	Milliwatt (0.001 Watt)
mW/cm^2	Milliwatts per square centimeter, a unit for power density
Pd	Power density, unit of measurement of power per unit area (W/m^2 or mW/cm^2)
R	Resistance
RF	Radio Frequency
RFI	Radio Frequency Interference
V	Volts, unit of electric voltage potential
V/m	Volts per meter, unit of electric field strength
W/m^2	Watts per square meter, a unit for power density, one W/m^2 equals 0.1 mw/cm^2
Ω	Ohms, unit of resistance

Ref: ANSI/IEEE 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms, 1984.

ACRONYMS

AF	(Antenna Factor) - The ratio of the received field strength to the voltage at the terminals of a receiving antenna. Units are 1/m.
ALC	(Absorber-Lined Chamber) - A shielded room with RF-absorbing material on the walls and ceiling. In many cases, the floor is reflective.
AM	(Amplitude Modulation) - A technique for putting information on a sinusoidal carrier signal by varying the amplitude of the carrier.
BCI	(Bulk Current Injection) - An EMC test where common-mode currents are coupled onto the power and communications cables of an EUT.
CE	(Conducted Emissions) - The RF energy generated by electronic equipment, which is conducted on power cables.
CE Marking	The marking signifying a product meets the required European Directives.
CENELEC	French acronym for the “European Committee for Electrotechnical Standardization”.
CI	(Conducted Immunity) - A measure of the immunity to RF energy coupled onto cables and wires of an electronic product.
CISPR	French acronym for “International Special Committee on Radio Interference”.
Conducted	Energy transmitted via cables or PC board connections.
Coupling Path	A structure or medium that transmits energy from a noise source to a victim circuit or system.
CS	(Conducted Susceptibility) - RF energy or electrical noise coupled onto I/O cables and power wiring that can disrupt electronic equipment.
CW	(Continuous Wave) - A sinusoidal waveform with a constant amplitude and frequency.
EMC	(Electromagnetic Compatibility) - The ability of a product to coexist in its intended electromagnetic environment without causing or suffering disruption or damage.
EMI	(Electromagnetic Interference) - When electromagnetic energy is transmitted from an electronic device to a victim circuit or system via radiated or conducted paths (or both) and which causes circuit upset in the victim.
EMP	(Electromagnetic Pulse) - Strong electromagnetic transients such as those created by lightning or nuclear blasts.
ESD	(Electrostatic Discharge) - A sudden surge in current (positive or negative) due to an electric spark or secondary discharge causing circuit disruption or component damage. Typically characterized by rise times less than 1 ns and total pulse widths on the order of microseconds.
ESL	(Equivalent Series Inductance) - Generally refers to the parasitic series inductance of a capacitor or inductor. It could also include the extra series inductance of any connecting traces or vias on a PC board.
ESR	(Equivalent Series Resistance) - Generally refers to the parasitic series resistance of a capacitor or inductor.
EU	European Union.
EUT	(Equipment Under Test) - The device being evaluated.
Far Field	When you get far enough from a radiating source the radiated field can be considered planar (or plane waves).
FCC	U.S. Federal Communications Commission.
FM	(Frequency Modulation) - A technique for putting information on a sinusoidal “carrier” signal by varying the frequency of the carrier.
IEC	International Electrotechnical Commission
ISM	(Industrial, Scientific and Medical equipment) - A class of electronic equipment including industrial controllers, test & measurement equipment, medical products and other scientific equipment.
ITE	(Information Technology Equipment) - A class of electronic devices covering a broad range of equipment including computers, printers and external peripherals; also includes, telecommunications equipment, and multi-media devices.

ACRONYMS

LISN	(Line Impedance Stabilization Network) - Used to match the 50-Ohm impedance of measuring receivers to the power line.
MLCC	(Multi-Layer Ceramic Capacitor) - A surface mount capacitor type often used as decoupling or energy storage capacitors in a power distribution network.
Near Field	When you are close enough to a radiating source that its field is considered spherical rather than planar.
Noise Source	A source that generates an electromagnetic perturbation or disruption to other circuits or systems.
OATS	(Open Area Test Site) - An outdoor EMC test site free of reflecting objects except a ground plane.
PDN	(Power Distribution Network) - The wiring and circuit traces from the power source to the electronic circuitry. This includes the parasitic components (R, L, C) of the circuit board, traces, bypass capacitance and any series inductances.
PLT	(Power Line Transient) - A sudden positive or negative surge in the voltage on a power supply input (DC source or AC line).
PI	(Power Integrity) - Refers to the quality of the energy transfer along the power supply circuitry from the voltage regulator module (VRM) to the die of the ICs. High switching noise or oscillations mean a low PI.
Radiated	Energy transmitted through the air via antenna or loops.
RE	(Radiated Emissions) - The energy generated by a circuit or equipment, which is radiated directly from the circuits, chassis and/or cables of equipment.
RFI	Radio Frequency Interference) - The disruption of an electronic device or system due to electromagnetic emissions at radio frequencies (usually a few kHz to a few GHz). Also EMI.
RI	Radiated Immunity) - The ability of circuits or systems to be immune from radiated energy coupled to the chassis, circuit boards and/or cables. Also Radiated Susceptibility (RS).
RF	(Radio Frequency) - A frequency at which electromagnetic radiation of energy is useful for communications.
RS	(Radiated Susceptibility) - The ability of equipment or circuits to withstand or reject nearby radiated RF sources. Also Radiated Immunity (RI).
SSCG	Spread Spectrum Clock Generation) - This technique takes the energy from a CW clock signal and spreads it out wider, which results in a lower effective amplitude for the fundamental and high-order harmonics. Used to achieve improved radiated or conducted emission margin to the limits.
SI	(Signal Integrity) - A set of measures of the quality of an electrical signal.
SSN	(Simultaneous Switching Noise) - Fast pulses that occur on the power bus due to switching transient currents drawn by the digital circuitry.
TEM	(Transverse Electromagnetic) - An electromagnetic plane wave where the electric and magnetic fields are perpendicular to each other everywhere and both fields are perpendicular to the direction of propagation. TEM cells are often used to generate TEM waves for radiated emissions (RE) or radiated immunity (RI) testing.
Victim	An electronic device, component or system that receives an electromagnetic disturbance, which causes circuit upset.
VRM	(Voltage Regulator Module) - A linear or switch-mode voltage regulator. Generally, there will be several of these mounted to a PC board in order to supply different levels of required voltages.
VSWR	(Voltage Standing Wave Ratio) - A measure of how well the load is impedance matched to its transmission line. This is calculated by dividing the voltage at the peak of a standing wave by the voltage at the null in the standing wave. A good match is less than 1.2:1.
XTALK	(Crosstalk) - A measure of the electromagnetic coupling from one circuit to another. This is a common problem between one circuit trace and another.

RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

ITEM 2021
(Interference Technology Engineer's Master)
ITEM is an exhaustive guide full of invaluable EMC directories, standards, formulas, calculators, lists, and "how-to" articles, compiled in easy-to-find formats.
https://learn.interferencetechnology.com/item-2021/

2020 Europe EMC Guide
This guide features technical articles, reference materials, a company directory, and a products and services list for more than 10 countries.
https://learn.interferencetechnology.com/2020-europe-emc-guide/

2020 EMC Fundamentals Guide
The Fundamentals Guide keeps your project running smoothly by better understanding how to address EMI and EMC in the early design phases.
https://learn.interferencetechnology.com/2020-emc-fundamentals-guide/

2019 Components & Materials Guide
This guide is updated with the most critical changes in standards, upcoming events, new product distributors, and more as they relate to EMI shielding and filtering.
https://learn.interferencetechnology.com/2019-components-and-materials-guide/

André and Wyatt,
EMI Troubleshooting Cookbook for Product Designers
SciTech Publishing, 2014. Includes chapters on product design and EMC theory & measurement. A major part of the content includes how to troubleshoot and mitigate all common EMC test failures.

Archambeault,
PCB Design for Real-World EMI Control
Kluwer Academic Publishers, 2002.

Armstrong,
EMC Design Techniques For Electronic Engineers
Armstrong/Nutwood Publications, 2010. A comprehensive treatment of EMC theory and practical product design and measurement applications.

Armstrong,
EMC For Printed Circuit Boards - Basic and Advanced Design and Layout Techniques
Armstrong/Nutwood Publications, 2010. A comprehensive treatment of PC board layout for EMC compliance.

ARRL,
The RFI Handbook
(3rd edition), 2010. Good practical book on radio frequency interference with mitigation techniques. Some EMC theory.

Bogatin,
Signal & Power Integrity - Simplified
Prentice-Hall, 2009 (2nd Edition). Great coverage of signal and power integrity from a fields viewpoint.

Brander, et al,
Trilogy of Magnetics - Design Guide for EMI Filter Design, SMPS & RF Circuits
Würth Electronik, 2010. A comprehensive compilation of valuable design information and examples of filter, switch-mode power supply, and RF circuit design.

Goedbloed,
Electromagnetic Compatibility
Prentice-Hall, 1990. Good general text on EMC with practical experiments. May be out of print.

Kimmel and Gerke,
Electromagnetic Compatibility in Medical Equipment
IEEE Press, 1995. Good general product design information.

Mardiguian,
Controlling Radiated Emissions by Design
Springer, 2016. Good content on product design for compliance.

Kunkel,
Shielding of Electromagnetic Waves, Theory and Practice
Springer. 2019. Provides efficient ways for design engineers to apply electromagnetic theory in shielding of electrical and electronic equipment.

Hall, Hall, and McCall,
High-Speed Digital System Design - A Handbook of Interconnect Theory and Design Practices
Wiley, 2000.

Joffe and Lock,
Grounds For Grounding
Wiley, 2010. This huge book includes way more topics on product design than the title suggests. Covers all aspects of grounding and shielding for products, systems, and facilities.

RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

Johnson and Graham,
High-Speed Digital Design - A Handbook of Black Magic
Prentice-Hall, 1993. Practical coverage of high speed digital signals and measurement.

Johnson and Graham,
High-Speed Signal Propagation - Advanced Black Magic
Prentice-Hall, 2003. Practical coverage of high speed digital signals and measurement.

Ott,
Electromagnetic Compatibility Engineering
Wiley, 2009. The “bible” on EMC measurement, theory, and product design.

Paul,
Introduction to Electromagnetic Compatibility
Wiley, 2006 (2nd Edition). The one source to go to for an upper-level course on EMC theory.

Mardiguian,
EMI Troubleshooting Techniques
McGraw-Hill, 2000. Good coverage of EMI troubleshooting.

Montrose,
EMC Made Simple
Montrose Compliance Services, 2014. The content includes several important areas of EMC theory and product design, troubleshooting, and measurement.

Morrison,
Digital Circuit Boards - Mach 1 GHz
Wiley, 2012. Important concepts of designing high frequency circuit boards from a fields viewpoint.

Morrison,
Grounding And Shielding - Circuits and Interference
Wiley, 2016 (6th Edition). The classic text on grounding and shielding with up to date content on how RF energy flows through circuit boards.

Sandler,
Power Integrity - Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems
McGraw-Hill, 2014. The latest information on measurement and design of power distribution networks and how the network affects stability and EMC.

Slattery and Skinner,
Platform Interference in Wireless Systems - Models, Measurement, and Mitigation
Newnes Press, 2008. The first publication to publicize the issue of self-interference to on-board wireless systems.

Smith,
High Frequency Measurements and Noise in Electronic Circuits
Springer, 1993. A classic book on high frequency measurements, probing techniques, and EMC troubleshooting measurements.

Smith and Bogatin,
Principles of Power Integrity for PDN Design - Simplified
Prentice-Hall, 2017. Getting the power distribution network (PDN) design right is the key to reducing EMI.

Williams,
EMC For Product Designers
Newnes, 2017. Completely updated text on product design for EMC compliance.

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Electromagnetic Compatibility - Methods, Analysis, Circuits, and Measurement
CRC Press, 2017 (3rd Edition). A comprehensive text, encompassing both commercial and military EMC.

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Spectrum and Network Measurements
(2nd edition), SciTech Publishing, 2014. The best text around explaining the theory and usage of spectrum and network analyzers.

Wyatt and Jost,
Electromagnetic Compatibility (EMC) Pocket Guide
SciTech Publishing, 2013. A handy pocket-sized reference guide to EMC.

Wyatt and Gruber,
Radio Frequency (RFI) Pocket Guide
SciTech Publishing, 2015. A handy pocket-sized reference guide to radio frequency interference.

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