JUNE 2023

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An Overview of

Aerospace Battery Compliance

PLUS

Line Impedance Stabilization is in its Seventieth Year and Still Going Strong

Inductors and Ferrites for Use in EMC

Recognized Components and Ethical Compliance Obligations

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CONTENTS

FCC Establishes Spectrum Management Principles for Transmitters, Receivers

The Policy Statement is based largely on proceedings held last year by the Commission

The U.S. Federal Communications Commission (FCC) has published a set of high-level principles that it says will guide its management of the electromagnetic spectrum in the future.

The FCC's Policy Statement, "Principles for Promoting Efficient Use of Spectrum and Opportunities for New Services," presents a framework designed to consider both transmitter and receiver components of wireless systems. The goal of the framework is reportedly to promote improved receiver performance as a key focal point in making more efficient use of the available spectrum and enabling new and advanced wireless technologies to be introduced to the market.

According to the FCC, the Policy Statement is based largely on proceedings held last year by the Commission, as well as research conducted by the FCC's Technological Advisory Council.

FDA Releases Latest Third-Party Review Performance Report

The U.S. Food and Drug Administration (FDA) has published its most recent data on the performance of accredited third parties conducting primary reviews of medical devices under the Agency's 510(k) process.

The FDA's "Third Party Review Organization Performance Report" summarizes the activity of third parties accredited by the FDA's Accredited Persons Program who completed at least five 510(k) submissions during the first six months of fiscal year 2023 (October 1, 2022, through March 31, 2023).

Created under the scope of the FDA Modernization Act of 1997, the FDA's Accredited Persons Program is intended to improve the efficiency and timeliness of medical device 510(k) reviews and help speed market access for medical devices.

During the 6-month evaluation period, the FDA accepted 35 submissions from FDA-accredited third parties, with 24 (69%) ultimately receiving final decisions from the FDA, with 11 decisions pending by the conclusion of the evaluation period. Unlike prior review periods, none of the submissions made during the review period were withdrawn by the device manufacturer for unspecified reasons.

For those submissions receiving a final FDA decision, 96% were achieved within 30 calendar days, with an average FDA total review time of just 23 days. Average review times in the lowest 25th percentile of submissions were as low as 19 calendar days, while the maximum review time reached as long as 70 days.

FCC Launches Space Bureau

Recognizing our future reliance on space-based infrastructures to support the deployment of advanced telecommunications capabilities in underserved areas, the U.S. Federal Communications Commission (FCC) has announced the formation of a new Space Bureau within the agency.

According to a press release, the Space Bureau will "lead policy and licensing matters related to satellite and space-based communications and activities."

Specifically, the Bureau will conduct policy analysis and rulemakings, authorize satellite and earth station systems for space-based services, and streamline regulatory processes to enable operators to meet customer needs more effectively.

Most important, the Space Bureau will help foster the efficient use of scarce spectrum and orbital resources and serve as a liaison with other federal agencies and foreign government officials on issues related to space policy and governance.

In its press release, the FCC also announced the formation of a new Office of International Affairs (OIA). The OIA will take the lead in engaging with representatives of regulatory authorities in other global jurisdictions around the world and help facilitate future rulemakings and policies on international telecommunications issues.

EU Commission Updates Regulation on Standby Energy Consumption of Electrical/Electronic Equipment

The Commission of the European Union (EU) has updated its ecodesign requirements applicable to electrical and electronic household and office equipment to address energy use in standby and off modes.

Published in the Official Journal of the European Union, Commission Regulation (EU) 2023/826 sets new, lower power consumption levels for electrical and electronic devices to reflect technological progress. The Regulation also expands the scope of products subject to these requirements, including motor-operated furniture such as standing desks and window blinds and curtains.

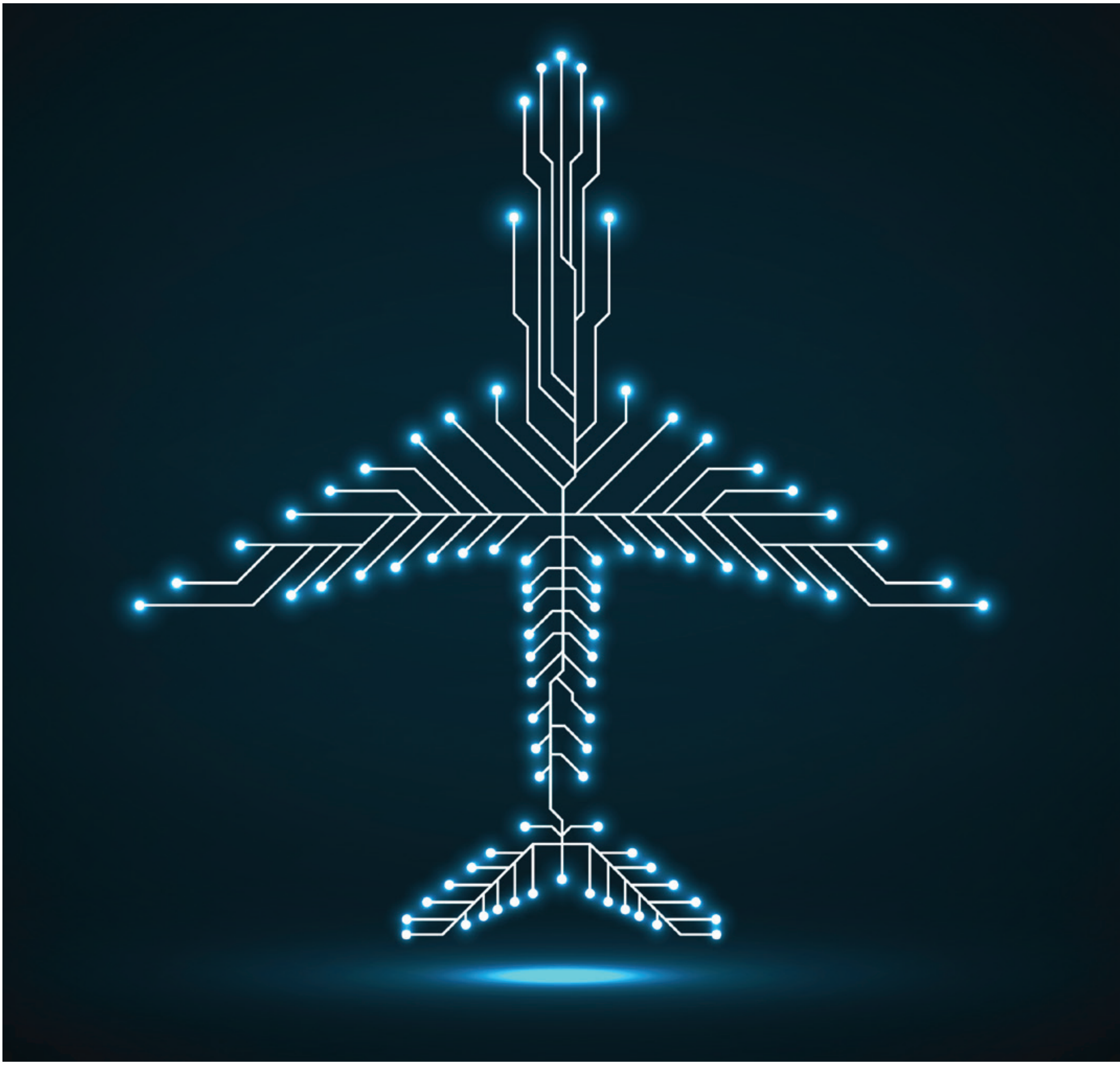
Here's a summary of the energy usage requirements presented in the new Regulation:

- From 2025 on, devices must not consume more than 0.5 Watts in standby or in off mode, or 0.8 Watts if they are in standby mode while displaying their status or other information;
- From 2027 on, devices must not consume more than 0.5 Watts in Standby, 0.3 Watts in off mode, or 0.8 Watts if they are in standby mode while displaying their status or other information; and
- From 2027 on, devices in network standby mode must not consume more than 2 to 7 Watts, depending on the product.

The Commission says that the updated energy consumption requirements will save an additional 4 terawatt-hour (TWh)/year of energy, with greenhouse gas emissions (GHG) emission reductions of 1.36 metric tons (MT) of carbon dioxide equivalent (CO2eq)/year by 2030.

AN OVERVIEW OF AEROSPACE BATTERY COMPLIANCE

Performance and Safety Requirements for Batteries Installed in Aircraft



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By John C. Copeland

Like everything else in our modern world, electrification is extending to aviation. Although much of this transformation involves the aircraft's onboard power generation capabilities such as generators, alternators, magnetos, and auxiliary turbines, battery energy storage systems are becoming increasingly more important. This ranges from small format batteries that provide keep-alive power for memory circuits in avionics to larger battery devices that provide the main source of power to propel the aircraft.

Given the nature of air travel, such batteries and their component cells must perform as designed and operate safely in their applications. In the United States, the Federal Aviation Administration (FAA) is the primary regulatory authority for aviation and is responsible for developing, implementing, and enforcing regulations to protect the public. This authority extends to the regulation of portable energy products that are considered a part of the aircraft itself.

The FAA produces a multitude of regulations and supporting guidance documents. As a point of fact, there are over fifty types of documents that are used for both internal and external purposes. General guidance on these document types can be found at https://www.faa.gov/guidance. Of interest to aerospace battery compliance, we will focus on two of these document types used to promulgate regulatory information to both FAA personnel and the public, as follows:

- *Advisory Circulars* (AC's) are used to uniformly "*…deliver advisory material to FAA customers, industry, the aviation community, and the public.*" All such ACs are maintained in a common database.
- *Technical Standard Orders* (TSO's) are intended to provide guidance of a technical nature to FAA personnel. However, the aviation industry as well as the general public make use of these documents to aid in compliance efforts and to foster a general understanding of the agency's efforts. Like the ACs, TSOs are maintained in a common database by the FAA.

Like many other regulatory agencies, the FAA will sometimes rely on the industry being regulated as a partner in establishing specific testing requirements. Although this may seem to some as a classic case of "the fox guarding the hen house," the truth is that the industry is incentivized to help develop a reasonable set of tests sufficient to support the stated intent of showing an acceptable level of both safety and performance. The industry knows that any safety failure has negative consequences for the entire industry, not just the company impacted, both in terms of governmental response as well as damage to the public's view of the industry itself. They also fully understand that if they fail to develop an acceptable test standard, the regulatory agency could take steps to develop one unilaterally without direct industry participation. Such an outcome would be considered less than ideal by most industry participants.

In the case of aviation, such standards development is commonly coordinated through the Radio Technical Commission for Aeronautics, now referred to simply as RTCA (https://www.rtca.org). RTCA is a non-profit organization founded in 1935 and is self-described on its website as "…the premier Public-Private Partnership venue for developing consensus among diverse, competing interests on critical aviation modernization issues in an increasingly global enterprise." (The RTCA test standards referenced here are copyrighted materials and can be purchased through RTCA.)

In the case of aviation battery regulations, several standards have been developed over time to address different chemistries. A summary of the regulatory references and their associated standards is given in Table 1.

The requirements for rechargeable lithium (typically lithium-ion) reflect some further nuanced specifications based upon their configuration and sample size. These requirements are detailed in Table 2.

In addition to the test requirements previously cited, the TSOs noted in Table 1 also refer to other RTCA standards for various design aspects (see Table 3).

Note also that certain types of battery-supported equipment have their own separate TSOs that may have battery requirements in addition to those noted so far. An example of this is TSO-C200a, titled "Airframe Low Frequency Underwater Locating Device (Acoustic) (Self-Powered)." These devices use non-rechargeable lithium batteries, but the TSO requires that the requirements given in RTCA/DO-227A be supplemented with selected tests from RTCA/DO-347, which is intended for rechargeable lithium batteries.

It should be clear that compliance with the stated requirements can be complex. The discussion in the preceding paragraphs does not cover every situation but rather attempts to depict those cases considered most typical to illustrate concepts common to the various regulatory requirements. Users of this information are cautioned to fully research their product's regulatory situation to ensure that the appropriate guidelines are being utilized.

As a general rule, the regulatory requirements should be confirmed early in the process with one's customer as well as the FAA or their Designated Engineering Representative (DER). From some perspectives,

Battery Chemistry	Advisory Circular	Technical Std Order	Referenced Test Standard
Rechargeable Lithium	AC 20-184	TSO-C179b	See Table 2
Non-Rechargeable Lithium	-----	TSO-C142b	RTCA/DO-227A
†Lithium Sulfur Dioxide	-----	TSO-C97	14 CFR § 37.209
Nickel Cadmium, Nickel Metal Hydride, Sealed Lead Acid	-----	TSO-C173A	RTCA/DO-293A

†Lithium Sulfur Dioxide is a specific type of non-rechargeable lithium batteries that have unique regulatory requirements.

Table 1: Linkage of battery chemistry to test standards

Battery Size	Configuration	Energy (Watt-Hours)	Referenced Test Standard
Coin and Button Cells	Single or Multi-Cell	Wh < 2	UL 1642, UL 2054, IEC 62133
Small/Medium*	Single Cell	2 ≤ Wh < 60	RTCA/DO-347
	Multi-Cell	2 ≤ Wh < 300	
Large	Single Cell	Wh ≥ 60	RTCA/DO-311A plus selected tests from RTCA/DO-347
	Multi-Cell	Wh ≥ 300	

**The terms "small" & "medium" are not differentiated in TSO-C179b but appear to generally reference the Energy Categories given in RTCA/DO-347. As noted above, they are treated the same for test purposes.*

Table 2: Rechargeable lithium test requirements

Design Aspect	Advisory Circular	Referenced Test Standard
Software	AC 20-115C	RTCA/DO-178C
Complex Hardware		RTCA/DO-254
Flammability	AC 20-152	

Table 3: Additional standards to consider

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Model Number	Frequency Range	Rated Power, Watts	P1dB Power, Watts	Gain dB
AMP2010	1.0-6.0GHz	50	25	47
AMP2010B	1.0-6.0GHz	75	50	48
AMP2070	1.0-6.0GHz	100	50	50
AMP2070A	1.0-6.0GHz	150	100	52
AMPP2070D-LC	1.0-6.0GHz	200	150	53
AMP2030-LC	1.0-6.0GHz	300	200	55
AMP2030B-LC	1.0-6.0GHz	400	250	56
AMP2030D-LC	1.0-6.0GHz	750	400	59
AMP2030-LC-1KW	1.0-6.0GHz	1000	600	60
AMP2030-LC-3KW	1.0-6.0GHz	3000	2500	65

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It is important to realize that the scope of the testing includes the entire tier structure of the device. This may include component cells, battery packs, or the supported device (the equipment under test, or EUT).

these discussions may be considered a negotiation as it is possible in some cases to modify requirements or have them waived altogether if the specific situation warrants. Any such changes will be recorded in a document known as a Quality Test Plan (QTP).

A QTP is a detailed document that describes the product but, more importantly, defines in detail how the tests are to be run. Development of this document is accomplished by the client with input from their test provider that might include equipment types and additional product-specific detail. The intent is to provide enough detail to reconstruct the test but not so much detail that the document becomes encumbered with information that does not significantly impact the conduct of the testing. It is not uncommon for such documents to be anywhere from 50-150 pages in length. The QTP will also form the basis for the final report.

It is important to realize that the scope of the testing includes the entire tier structure of the device. This may include component cells, battery packs, or the supported device (the equipment under test or EUT).

The testing itself may include:

- Electrical performance tests like capacity at temperature or high current discharge;
- Mechanical or environmental tests like vibration, drop, or thermal cycling. These are commonly specified as tests from the current revision of RTCA/DO-160, which covers environmental requirements for aviation electronics;
- Safety tests such as short-circuit or overcharge; and
- EUT-level tests such as thermal runaway containment.

Like the negotiation around the test requirements, there will need to be an agreement with the party responsible for conducting the testing. In some cases, the equipment vendor may have the expertise and equipment necessary to do the work in-house. For others without such internal resources, an external lab that has been accredited to the test standards involved may be selected. There also exists the possibility that a hybrid testing model will be used where both internal and external resources are being used to accomplish the needed testing.

Because of sensitivity around lithium battery safety due to widely publicized incidents both within the aviation industry as well as other non-aviation industries, it is not uncommon for customers further down the value chain to request the opportunity to witness some of the testing that is considered to represent greater risks. In some cases, the DER/FAA may also wish to witness certain tests. Such monitoring may be done onsite or remotely through commonly available meeting applications.

Unlike many other standards, the total number of samples required for RTCA rechargeable battery test regimes is relatively small (by its very nature, non-rechargeable battery testing requires larger sample sizes). This is achieved by specific samples being assigned to specific tests (very significant reuse), the sequential order of the testing being defined for each sample, and the number of replicates for any given test kept to a minimum. On balance, the testing takes longer than some other regimes since much of the testing is run in series instead of parallel.

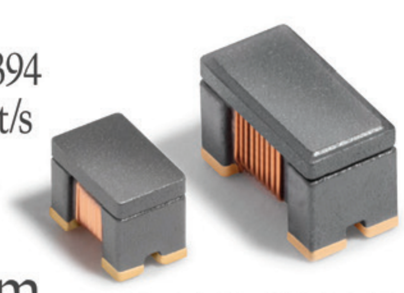
Conduct of the test regime requires that all samples be "conformed" prior to the start of any testing. This means that all test samples are verified to ensure that they are in the correct state for testing and are not damaged in a way that might negatively impact the test. The QTP is the reference for defining the correct pre-test state. Pre-test documentation will also include pictures. Execution of certain tests may require video of testing in progress in addition to the various parametric measurements called for in the test descriptions. Finally, post-test, the units are inspected with any anomalies being documented in writing and with pictures.

Formal report generation can be extensive due to the significant number of tests involved as well as the supplemental data and photo requirements. Having a report template developed at the beginning of the process can minimize the reporting effort required at the end of the test. It also helps identify key test aspects that must not be overlooked. Some labs will go a step further and develop lab-specific checklists or data sheets. These documents may be included in the QTP and/or report template.

Any negative findings will require some degree of analysis and corrective action once it has been established that the finding was attributable to the product itself and not the result of a test anomaly. Once the corrective actions have been implemented, a recovery test plan will be developed between the product manufacturer, their customer, and the FAA representative or their designate. It is possible that the implemented changes may require that other non-failed tests be repeated if there is a potential that the changes may have an impact on those test outcomes. Once again, a revision to the report will be generated that appends the existing report with the new data.

In conclusion:

- The method of compliance for aerospace battery applications in the United States is specified in the regulations and supporting guidance published by the FAA.
- The relevant FAA guidance document types include Advisory Circulars and Technical Standard Orders.
- Such regulations reference industry-developed test standards available from sources like RTCA, UL, and IEC.
- Common chemistries such as lithium-ion, NiCd, NiMH, SLA, and non-rechargeable lithium are included.
- The testing may include cells, battery packs, or the supported device (EUT).
- The process for complying with such standards is formally documented in a QTP that serves as an agreement with the manufacturer, their customers, and the FAA. It also provides the detailed test plan and reporting requirements for the test laboratory conducting the test program.
- The testing uses a minimum number of samples overall because it is sequential in nature. But this usually equates to a longer test duration than some other standards that utilize parallel testing.
- There are many nuances to FAA compliance, so it is imperative that the specific requirements for a given product are thoroughly researched and verified prior to beginning what is a rather extensive compliance effort.



LINE IMPEDANCE STABILIZATION IS IN ITS SEVENTIETH YEAR AND STILL GOING STRONG

What a Long, Strange Trip It's Been…

Ken Javor is a Senior Contributor to *In Compliance Magazine* and has worked in the EMC industry for over 40 years. Javor is an industry representative to the Tri-Service Working Groups that maintain MIL-STD-464 and MIL-STD-461. He can be reached at ken.javor@emccompliance.com.

By Ken Javor

INTRODUCTION[1]

Seventy years ago in May, the 5 microhenry line impedance stabilization network (LISN) made its debut in MIL-I-6181B.[2] Aside from the EMI receiver itself, the LISN is one of the oldest and most successful pieces of EMI test equipment in existence. And while EMI receivers have changed a great deal since 1953 (see images in last month's MIL-I-6181B anniversary article),[3] the 5 uH LISN is not only still with us, but almost unchanged and used in commercial aviation and the automotive industry, as well as military applications worldwide.[4] Other LISNs have come and gone, and others are with us still. The way we use LISNs has changed over time, not always for the better. But the LISN is here to stay in the world of EMI testing.

IN THE BEGINNING

Radio receivers used on WWII Army aircraft were quite susceptible to very low levels of noise on their primary (28 Vdc) power input. Further, unshielded antenna lead-ins (see Reference 3) were very susceptible to capacitive crosstalk from noisy 28 Vdc electrical power feeds.

The first EMI standards tried to control both these radio frequency interferences (RFI) coupling paths. Prior to 1953, JAN-I-225[5] used a pair of 4 uF bypass capacitors in shunt (8 uF total capacity between power feeder and ground plane) and a 10' length of power wire suspended not more than ¼" from the ground plane for what they called power supply stabilization (see Figure 1). Because these receivers tuned from

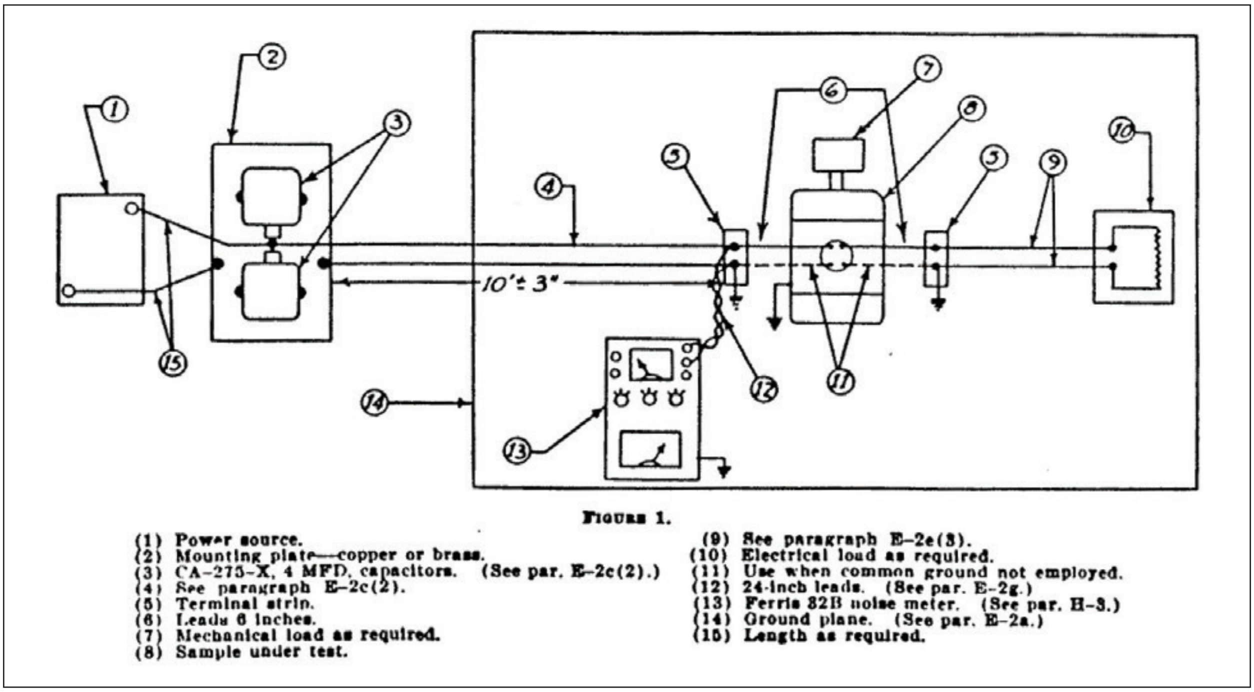


Figure 1: JAN-I-225 EMI test set-up, showing details of how line impedance stabilization was achieved without a "LISN in a box."

0.15 to 20 MHz, JAN-I-225 conducted and radiated emission measurements covered that same range. The resonant frequency of the 10' wiring and 8 uF capacity occurred below the test frequency range, so that the impedance looking back into the capacitors through 10' of wiring was inductive in character.

JAN-I-225 was superseded in 1953 by MIL-I-6181B, which included both required impedance (Figure 2) and construction drawings (Figure 3) for the 5 uH LISN. These same drawings, with two minor tweaks, appeared in RTCA/DO-160 for commercial aircraft avionics, up to 1989.[6] After that, they required the extended impedance control as in DEF STAN 59-411, but don't include the construction details of DEF STAN 59-411. The two tweaks already appeared in MIL-I-6181C[7] which replaced MIL-I-6181B in 1957: a 1 kΩ bleeder resistor from the EMI port center conductor to case and the removal of the 1 Ω resistor in series with the input side 1 uF filter capacitor.

The upper frequency of the controlled impedance bounced around some over the years. MIL-I-6181B has it at 25 MHz, as does MIL-I-6181D[8] (1959), but the intervening "C" in 1957 pushed it out to 100 MHz. It had settled down to 30 MHz in most specifications and standards, as that was the upper limit for conducted emissions and radiated emissions with the rod antenna. But in the past few decades, various specifications have pushed the upper end as far up as 400 MHz for rf conducted susceptibility, and the automotive world (CISPR 25[9]) has pushed it to 100 MHz for conducted emissions.

It would surely be gratifying for the originator of the 5 uH LISN to know that

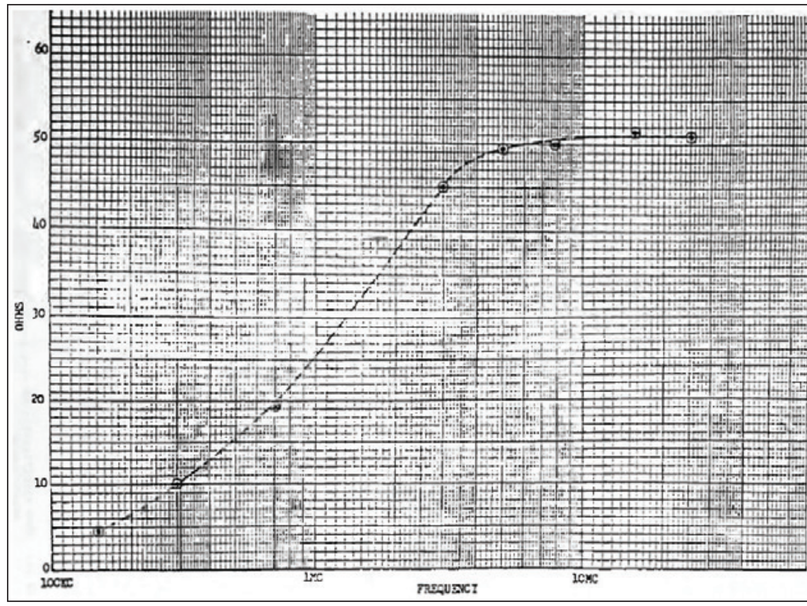
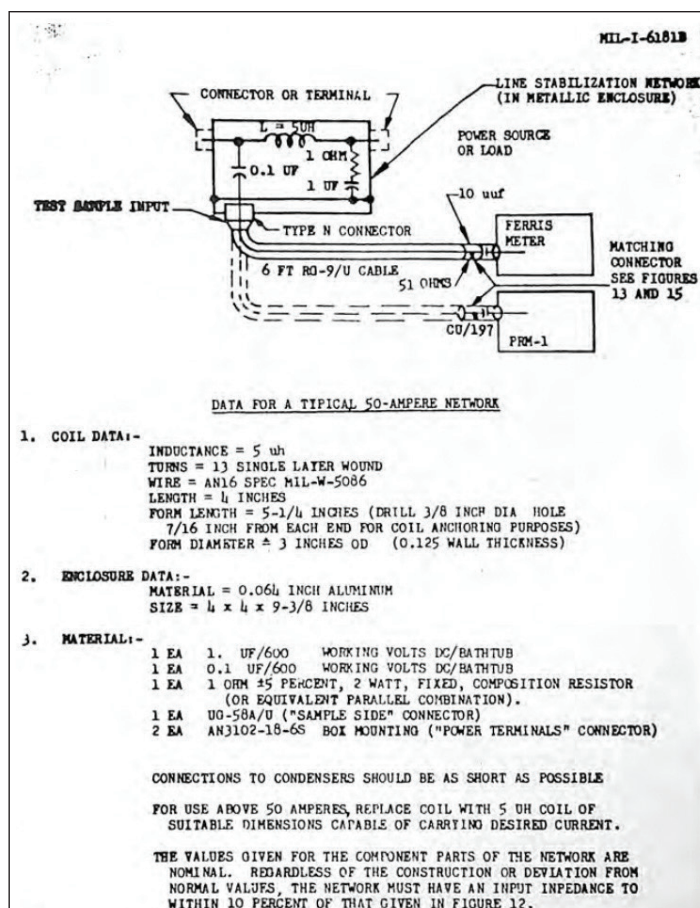


Figure 2: MIL-I-6181B 5 uH LISN impedance plot



DATA FOR A TIPICAL 50-AMPERE NETWORK

1. COIL DATA:-
INDUCTANCE = 5 uh
TURNS = 13 SINGLE LAYER WOUND
WIRE = AN16 SPEC MIL-W-5086
LENGTH = 4 INCHES
FORM LENGTH = 5-1/4 INCHES (DRILL 3/8 INCH DIA HOLE 7/16 INCH FROM EACH END FOR COIL ANCHORING PURPOSES)
FORM DIAMETER ≐ 3 INCHES OD (0.125 WALL THICKNESS)

2. ENCLOSURE DATA:-
MATERIAL = 0.064 INCH ALUMINUM
SIZE = 4 x 4 x 9-3/8 INCHES

3. MATERIAL:-
1 EA 1. UF/600 WORKING VOLTS DC/BATHTUB
1 EA 0.1 UF/600 WORKING VOLTS DC/BATHTUB
1 EA 1 OHM ±5 PERCENT, 2 WATT, FIXED, COMPOSITION RESISTOR (OR EQUIVALENT PARALLEL COMBINATION).
1 EA UG-58A/U ("SAMPLE SIDE" CONNECTOR)
2 EA AN3102-18-6S BOX MOUNTING ("POWER TERMINALS" CONNECTOR)

CONNECTIONS TO CONDENSERS SHOULD BE AS SHORT AS POSSIBLE

FOR USE ABOVE 50 AMPERES, REPLACE COIL WITH 5 UH COIL OF SUITABLE DIMENSIONS CAPABLE OF CARRYING DESIRED CURRENT.

THE VALUES GIVEN FOR THE COMPONENT PARTS OF THE NETWORK ARE NOMINAL. REGARDLESS OF THE CONSTRUCTION OR DEVIATION FROM NORMAL VALUES, THE NETWORK MUST HAVE AN INPUT INPEDANCE TO WITHIN 10 PERCENT OF THAT GIVEN IN FIGURE 12.

Figure 3: LISN construction details in MIL-I-6181B

his work has gained this much success and acceptance worldwide. Who was this person, and how did the 5 uH LISN come about in the first place? We are indebted to A. T. Parker (1915 – 2000), for the following historical snippet. In 1960, Parker founded Solar Electronics, a designer and supplier of EMI test equipment. Previously he had worked at the Stoddart Aircraft Radio Company, which was the company that produced the first commercial 5 uH LISN. In Parker's own words:

> *"Early in WW2, an aircraft propulsion engineer named Alan Watton working for the Air Corp was concerned about the r.f., being conducted along wiring in a military aircraft of the Douglas DC-3 type. He devised the first Line Impedance Stabilization Network which simulated the impedance of the d.c. power leads in the aircraft. It used a five microhenry choke and a means for coupling voltages developed across this inductance to a 50-ohm receiver over the frequency range 150 KHz to 25 MHz."*[10]

This is all that Parker has to say about its inception, but there are additional facts and deductions that apply.

The DC-3 (military version C-47 "Skytrain") was all aluminum. Aluminum aircraft return current on structure, except where inductance causes excessive voltage drop. No such problem occurs with dc power. Electrical power was from engine-mounted generators. Engine centerlines were about three meters from the aircraft centerline. Thus, using a nominal value, such as one microhenry per meter for a wire suspended above a ground plane, 5 uH seems a reasonable value if the measurement was taken in the cockpit-mounted breaker boxes, which act as the point of distribution for electrical power in the aircraft.

This point is critical. People often assume that a LISN represents the impedance the test sample sees as installed in the platform. But this is not the case.[11]

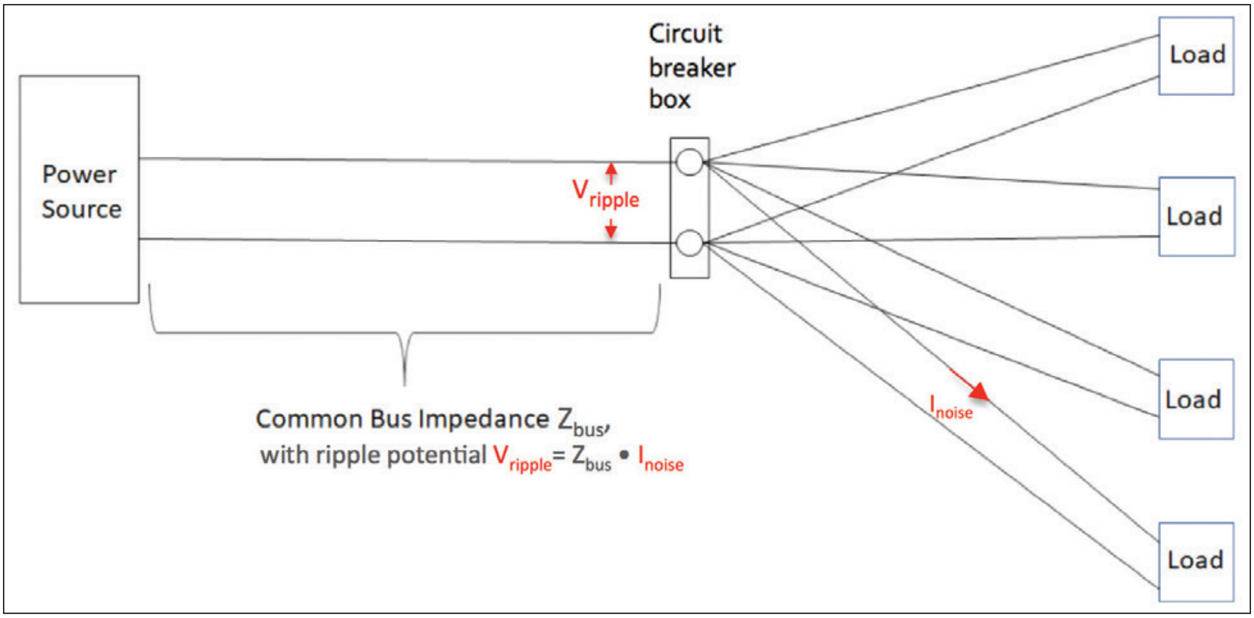


Figure 4: A LISN simulates the common bus impedance, not power source-to-load impedance.

As shown in Figure 4, a LISN simulates the common bus impedance seen by all loads, so that noise currents drawn by a culprit load, acting through the common bus impedance, generates a noise potential inflicted on all other victim loads.

It is specifically this property of a LISN that allowed it to be used in MIL-I-6181B through "D" (the last revision prior to MIL-STD-461) in mirror image roles when measuring conducted emissions (Figure 5) and conducted susceptibility (Figure 6).

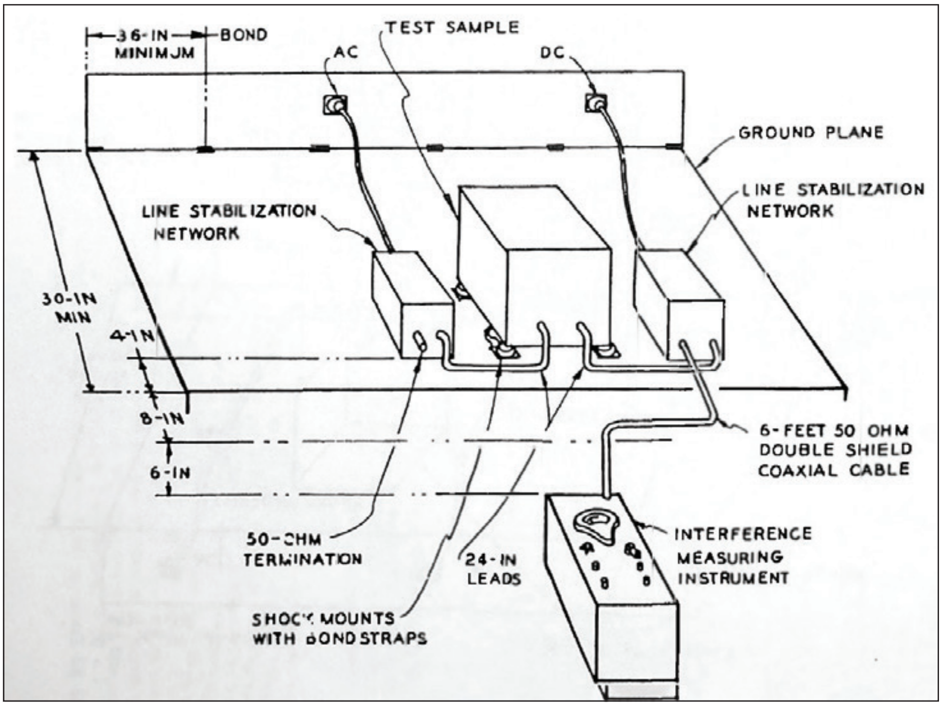


Figure 5: MIL-I-6181B conducted emission set-up (figure actually copied from MIL-I-6181C, because easier to see what is going on for instructional purposes).

AS TIME GOES BY

In all versions of MIL-I-6181B-D, a LISN is inserted in each power feeder, ac or dc. The return is always through the ground plane. But Navy ships never return current on structure, and Navy EMI specification

MIL-I-16910A[12] reflected that practice, inserting a 5 uH LISN in both feeder and return.

When all the Service- and platform-specific EMI specifications released prior to 1967 were superseded by the Tri-Service EMI standards MIL-STD-461[13] and MIL-STD-462,[14] it was the Navy practice of inserting line impedance stabilization in each power conductor that was adopted for Tri-Service use. That is, instead of running return current back through the ground plane, it is returned through a wire and LISN instead.

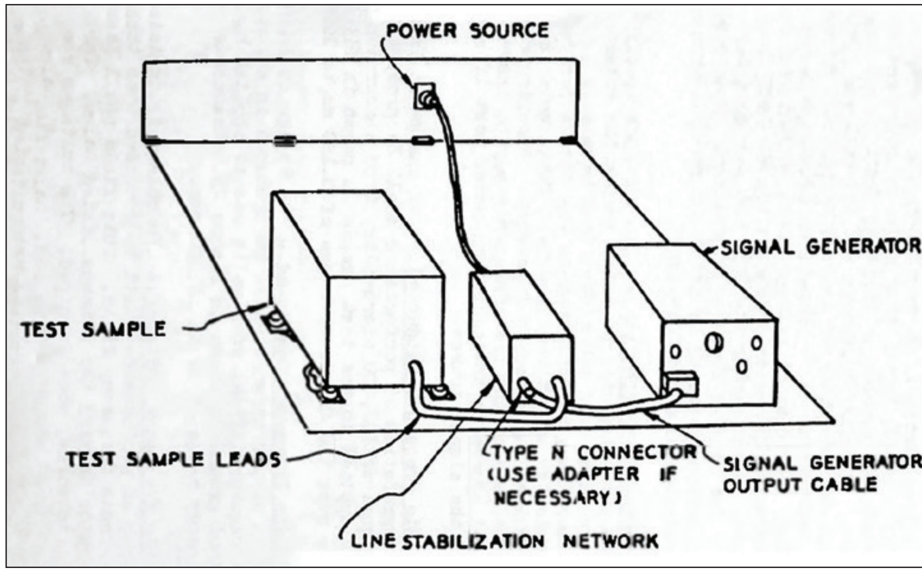


Figure 6: MIL-I-6181B conducted susceptibility set-up (figure actually copied from MIL-I-6181C, because easier to see what is going on for instructional purposes).

This has several problematical consequences that reverberate down to the present day. But before delving into that issue, we should note that MIL-STD-461 and MIL-STD-462 1967 releases followed a new practice introduced in MIL-STD-826,[15] replacing the 5 uH LISN with a 10-microfarad feed-through capacitor. This then became the standard practice for a quarter-century, until MIL-STD-461D[16] and MIL-STD-462D[17] reinstated rf potential instead of current control. This necessitated a LISN again, albeit now a 50 uH LISN in lieu of the original 5 uH LISN, for reasons related further on.

We return once again to Mr. Parker for the rationale behind current measurements in lieu of measuring rf potential across a LISN.[18] This is follow-on to the material quoted earlier from Reference 10.

> *"So the Line Impedance Stabilization Network (LISN) was born. It was a pretty good simulation of that particular aircraft and the electrical systems it included. But then someone arbitrarily decided to use this artificial impedance to represent* ***any*** *power line.*
>
> *"At any rate, this impedance suddenly began appearing in specifications which demanded its use in each ungrounded power line for determining the conducted EMI (then known as RFI) voltage generated by any kind of a gadget. The resulting test data, it was argued, allowed the government to directly compare measured RFI/EMI voltages from different test samples and different test laboratories.*
>
> *"No one was concerned about the fact that filtering devised for suppressing the test sample was based on this artificial impedance in order to pass the requirements, but that the same filter might have no relation to reality when used with the test sample in its normal power line connection.*
>
> *"Not until 1947, that is. At that time, this same Alan Watton, a propulsion engineer having no connection with the RFI/EMI business, decided to rectify the comedy of errors which had misapplied his original brainchild. He was in a position to place a small R and D contract with Stoddart for the development of two probes; a current measuring probe and a voltage measuring probe. Obviously, he felt that one needed to know at least two parameters for a true understanding of conducted interference...*[19]
>
> *"As it turned out, Stoddart was successful in developing a current probe based on Alan Watton's suggestions regarding the toroidal transformer approach which is still the primary basis used today. However, the development of the voltage measurement probe suffered for lack of sensitivity. Watton's hope had been to provide a high impedance voltage probe with better sensitivity than was then available for measurement receivers designed for rod antennas and 50-ohm inputs. Since this effort failed and Watton's funds (and probably his interest in the subject) faded out of the picture, the program came to a halt.*
>
> *"This meant that the RFI/EMI engineer could either measure EMI voltage across an artificial impedance which varied with frequency, or he could measure EMI current flowing through a circuit of unknown r.f. impedance. Either way, the whole story is not known. In spite of the unknown impedance, the military specifications began picking up the idea of measuring EMI current instead of voltage…"*

One may infer that what Watton was after was a Thévenin-like model of the test sample: "open circuit" output rf potential and short-circuit rf current. By this means, one could then predict noise potentials and currents into any arbitrary power source impedance. This interpretation is bolstered by material in the appendix of MIL-STD-462D:

> *"The (LISN) impedance is standardized to represent expected impedances in actual installations and to ensure consistent results between different test agencies. Previous versions of MIL-STD-462 used 10 microfarad feedthrough capacitors on the power leads. The intent of these devices was to determine the current generator portion of a Norton current source model. If the impedance of the interference source were also known, the interference potential of the source could be analytically determined for particular circumstances in the installation. A requirement was never established for measuring the impedance portion of the source model. More importantly, concerns arose over the test configuration influencing the design of power-line filtering. Optimized filters are designed based on knowledge of both source and load impedances.*

Significantly different filter designs will result for the 10-microfarad capacitor loading versus the impedance loading shown in Figure 7 of the main body." (Author's note: Figure 7 in MIL-STD-462D shows the impedance of the 50 uH LISN.)

The concern over designing an EMI filter for a specific (but different) source impedance is of the same type that Watton was concerned about a half-century earlier.

The more things change, the more they stay the same!

Completing our "as time goes by theme," it is worth noting why MIL-STD-462D went with a 50 uH LISN instead of the 5 uH LISN. In fact, the original proposal for MIL-STD-462D going in was the 5 uH LISN. The same section of the MIL-STD-462D appendix says,

"A specific 50 microhenry LISN was selected to maintain a standardized control on the impedance as low as 10 kHz."

The low frequency end of the 5 uH LISN is 150 kHz. The desire to begin making rf potential measurements well below 150 kHz nixed the selection of the 5 uH LISN. In turn, the reason for wanting to make rf potential measurements down to audio frequencies was based on the previous quarter-century of making CE03 measurements down to audio frequencies. They wanted the break between CE101 and CE102 to be roughly the same as between CE01 and CE03. None of which is to say that the 50 uH LISN is a better simulation of most vehicle electrical bus impedances…

SIMPLE THINGS BECOME COMPLICATED[20]

From MIL-STD-826 (1964) forward, the practice of placing an impedance stabilizing device in each ungrounded power lead (both feeder and return) resulted in at best questionably useful data. When a single device is used, the measured rf potential or current is simply that in the loop comprised of LISN, power feeder, load (test sample), and ground plane. Using two such devices result in measuring vector sums of differential mode (dm) and common mode (cm) currents/potentials.

Figures 7a and 7b show differential and common mode current paths when current returns above structure on a dedicated ground wire – i.e., isolated from chassis ground within the test sample. Inspection of Figures 7a and 7b indicates that, when there is an above ground current return path, differential and common mode currents sum in the feeder, but subtract in the return, as indicated in Figure 7c. Figure 7d shows how all current, regardless of the current-generating mechanism, is constrained to flow in the same path in the original structure return 5 uH LISN configuration.

This means that with above ground current return, as shown in Figure 7c, measured single line currents or rf potentials look similar but not identical. The traces are identical for feeder and return when one or the other mode dominates, but where they are of similar amplitude and add on the feeder and subtract on the return, they differ. Separation of cm and dm modes to assist filter design has been a topic of interest since the late 1970s.[21,22,23]

It is of note that in most standards, if there is any question as to how power current will return (structure or dedicated wire), the default test method is to use a pair of LISNs and measure the vector sums and differences of common and differential mode signals on each LISN separately. It is not obvious why this is the go-to default. Particularly for radiated emissions, this technique decreases the radiation efficiency of the differential mode

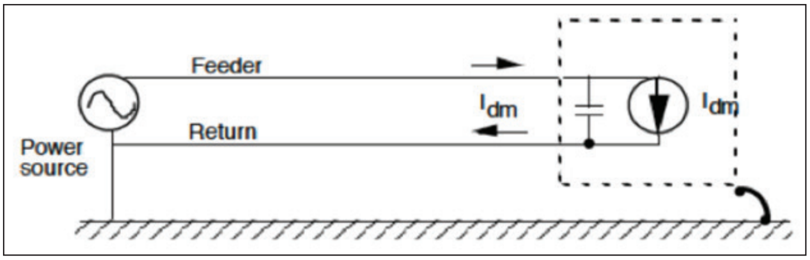


Figure 7a: Differential mode current path

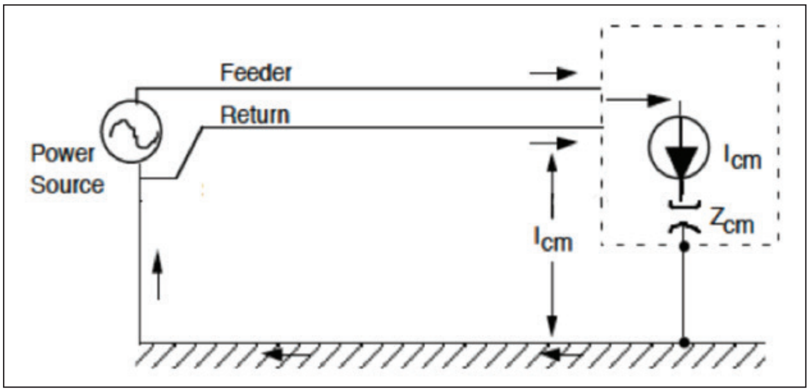


Figure 7b: Common mode current path

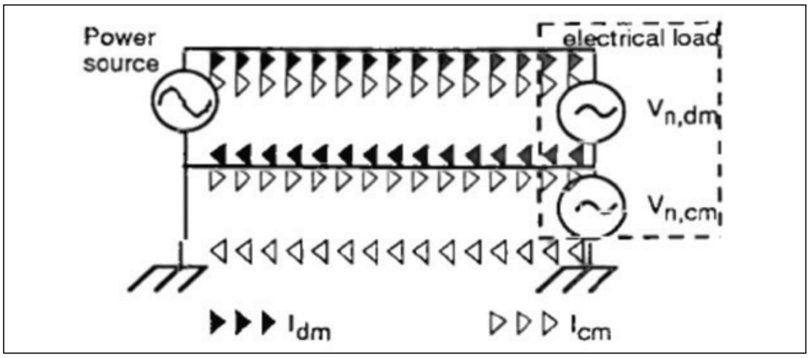


Figure 7c: CM & DM currents adding and subtracting in feeder and return

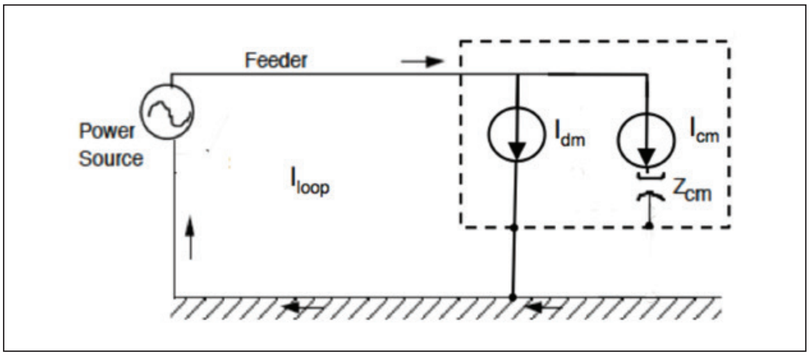


Figure 7d: All noise currents flow in the same path when structure is the return path.

component of the composite noise (especially if, as is common, the wire pair is twisted). Figure 7d makes it clear that using a single LISN keeps the radiation efficiency of each mode identical.

When we know that current will be returned on a dedicated wire, not on structure, a better technique than controlling emissions on each individual lead is controlling emissions by mode. Separating modes may be done directly off the LISN (References 20 – 22) or using current probes. Regardless, if we control emissions via mode, not line, we can then assign limits based on what the modes actually affect:

- Differential mode noise currents cause ripple, and
- Common mode currents cause radiated emissions

Therefore, when the feeder and return wires are twisted or held tightly together throughout the vehicle, it is reasonable to relax the differential mode limit compared to the common mode limit. Even if no radios operate in the conducted emission frequency range, it may be worthwhile to control common mode emissions to limit crosstalk to adjacently placed cables that might carry potentially susceptible low level signals.[24]

A concrete and illuminating example of the problem of LISN misuse may be found in a report by the author dating to the late 1990s.[25] This report showed that the (now obsolete) FCC Class B 48 dBuV conducted emission limit was in fact 20 dB too stringent for differential mode noise but was precisely correct for common mode noise. The problem arose because the original work done to establish the 48 dBuV limit was performed using a single 5 uH LISN, but the FCC test method was based on a pair of (50 uH) LISNs.[26] It was not the disparity in the LISN impedance but the mode separation inherent in a pair of LISNs that demonstrated the disparity.

Another modern confusion is using long power leads between the LISN and test sample. Such values range from one meter (for conducted emissions) in MIL-STD-462 (1967 – 1993), 2 – 2.5 meters in MIL-STD-462D and follow-on versions of MIL-STD-461, one meter in RTCA/DO-160, and 1.5 meters in CISPR 25. By way of contrast, the specified length in MIL-I-6181B was 24 inches.

Consider the ramifications with respect to measurement uncertainty. First, MIL-I-6181B conducted emission limits stopped at 20 MHz. The electrical length of a 24" long wire at 20 MHz is a twenty-fifth wavelength. VSWR will be negligible, and therefore the LISN does in fact control the power source impedance seen by the test sample. MIL-STD-462D and follow-on MIL-STD-461 versions using a 2.5-meter-long power lead and 10 MHz upper CE102 limit frequency come in at less than a tenth-wavelength, so the LISN controls the power source impedance.

But look at specifications such as RTCA/DO-160 and DEF STAN 59-411, with 400 MHz LISNs and 100 MHz conducted emission control. A one-meter-long power lead is a third wavelength at 100 MHz. And for CISPR 25, using a two-meter-long power wire, the LISN is over a half-wavelength from the test sample. All the work and expense that went into the extended frequency range LISN is wasted when the parasitics controlled within the LISN is simply migrated to the LISN – test sample interconnection.[27]

CONCLUSION

Alan Watton bequeathed us a great gift some seventy years ago. It is up to us to use it wisely, and well. To echo Parker about the comedy of errors, and intentionally misquote Gall's Law, "A complex system that works poorly is invariably found to have evolved from a simple system that worked well."

ACKNOWLEDGMENTS

The author wishes to thank the reviewers for their time and effort in making this article useful. Any errors of omission or commission are the author's own.

ENDNOTES

1. Visit http://www.emccompliance.com to find all specifications, standards, and other sundry documents cited herein that are not copyrighted by others.
2. MIL-I-6181B, Interference Limits, Tests and Design Requirements, Aircraft Electrical and Electronic Equipment, 29 May 1953
3. Javor, K. "Seventy Years of Electromagnetic Interference Control in Planes, Trains and Automobiles (and Ships and Spaceships, as well)," *In Compliance Magazine*, May 2023.
4. Ministry of Defence Standard 59-411 and the older 59-41 all use a modification of the 5 uH LISN.

The modification extends the frequency range of controlled impedance down to 1 kHz and up to 400 MHz. It is less than obvious why the LISN impedance needs to be controlled to 400 MHz when it is placed several meters from the test sample. The mismatch between power wire transmission line characteristic impedance and the 50 Ω LISN is always going to generate reflections, no matter how well the LISN impedance is controlled. If it is desired to have true impedance control, the LISN needs to be within a tenth-wavelength of the test sample power input. A 10 uF feedthrough capacitor would function admirably so used, at a tenth the cost of the 400 Hz LISN.

5. JAN-I-225, Interference Measurement, Radio, Methods Of, 150 Kilocycles to 20 Megacycles (For Components and Complete Assemblies), 14 June 1945
6. RTCA/DO-160 original through C revision: Environmental Conditions and Test Procedures for Airborne Equipment
7. MIL-I-6181C, Interference Control Requirements, Aeronautical Equipment, 06 June 1957
8. MIL-I-6181D, Interference Control Requirements, Aircraft Equipment, 25 November 1959
9. CISPR 25 all editions, various titles. "Limits and methods of measurement of radio disturbance characteristics for the protection of receivers used on board vehicles" is the 1995 title.
10. Parker, A. T. "A Brief History of EMI Specifications," presented at the 1992 IEEE EMC Symposium. The Army Air Corp to which Parker refers was the forerunner of the US Air Force. The Army Air Corp became the United States Air Force in 1947.
11. Some exceptions that prove the rule are many spacecraft line impedance simulation networks that appear to be designed to include the dedicated wiring to the test sample itself. See the line impedance simulation section of older print Solar catalogs (they no longer supply spacecraft LISNs, so the on-line catalog is of no value here). Pay special attention to the series resistance value. Values above a few tens of milliohms mean they are simulating the entire power distribution network, not the main bus. As Mr. Parker said in his catalogs, in his gentlemanly way, "Spacecraft designers do not always agree on the characteristics of the d.c. power source aboard the

vehicle. The inductance in series with the load, the resistance across the inductor, and the series resistance in each leg of the unit are variables specified by different spacecraft engineers."

12. MIL-I-16910A, Interference Measurement, Radio, Methods and Limits: 14 Kilocycles to 1000 Megacycles, 30 August 1954
13. MIL-STD-461, Electromagnetic Interference Characteristics, Requirements, Electrical for Equipment, 31 July 1967
14. MIL-STD-462, Electromagnetic Interference Characteristics, Measurement of, 31 July 1967
15. MIL-STE-826, Electromagnetic Interference Test Requirements and Test Methods, 20 January 1964
16. MIL-STD-461D, Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility, 31 January 1993
17. MIL-STD-462D, Measurement of Electromagnetic Interference Characteristics, 31 January 1993
18. Solar Electronics Application Note AN622001, "Using the Type 6220-1A Transformer for the Measurement of Low Frequency EMI Currents." The application note used to be included in Solar Electronics catalogs. The excerpted portion is still found on their website under "Audio Isolation Transformers" under "History." https://www.solar-emc.com/6220-1B.html
19. Author's comment about the 1947 date cited in this paragraph. 1947 seems too early. That is before MIL-I-6181, which used JAN-I-225, which didn't include the 5 uH LISN. The date 1957 fits better, because MIL-I-6181C released in that year for the first time includes an alternate conducted emission test method and limit based on the use of a current probe, for cases when line current exceeds the 50 ampere LISN maximum current rating. But there is no way to know for certain if this was a typo, or bad memory or some other explanation.
20. For much more on the topic of conducted emission mode separation, see the expanded version of this article on the author's website, and other articles by this author and those listed as references on this topic.
21. A. A. Toppeto, "Test Method to Differentiate Common Mode and Differential Mode Noise," Proc. 3rd Symposium on Electromagnetic Compatibility, Rotterdam pp. 497-502, May 1979.
22. M. J. Nave, "A Novel Differential Mode Rejection Network," IEEE International Symposium on Electromagnetic Compatibility, Denver, May 1989.
23. LISN UP Application Note, Fischer Custom Communications, 2005.
24. Two spacecraft specifications follow this approach, where it is known that no current of any sort returns on structure. These spacecraft don't operate radios in the bands where conducted emissions are controlled; the imposition of a common mode limit is based purely on controlling crosstalk. The resulting common mode limit is sufficient to the task and represents a large relaxation relative to typical radiated emission limits that protect against radio frequency interference.
    - GSFC-STD-7000B, General Environmental Verification Standard (GEVS) for Goddard Space Flight Center Flight Programs and Projects, 29 April 2021
    - GP 11461, Gateway Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 06 November 2019
25. Javor, Ken. "Investigation Into the Susceptibility of Radio Receivers to Power-Line Conducted Noise" EMC Compliance, 1998. Technical committee presentation and demonstration at 1998 IEEE EMC Symposium, Denver
26. CBEMA/ESC5/77-29, Limits and Methods of Measurement of Electromagnetic Emanations from Electronic Data Processing and Office Equipment, 20 May 1977
27. MIL-STD-462 (1967) had a unique approach to this conundrum. It specified one-meter-long wires for conducted tests, and two-meter-long wires for radiated. The only problem with that approach was not enough people followed directions; opting for one or the other length for both conducted and radiated measurements. The end result was that when the "D" revisions came along, they "dumbed down" the standard to one length optimized for radiated and reduced the conducted frequency range accordingly. Hence the 10 MHz upper limit for conducted emission control, unique amongst conducted emission limits. The goal for standardized test results outweighed the desire to control conducted emissions out to the traditional 30 MHz.

INDUCTORS AND FERRITES FOR USE IN EMC

Choosing the Right Magnetic Materials to Filter EMI

Patrick G. André has worked in the EMC field since 1983. His emphasis is on EMC issues specific to the military and aerospace environment, and he works with the RTCA as a member of SC-135 committee. André is an iNARTE Certified Engineer and was honored as an iNARTE Certified Master Design Engineer. He is also a senior member of the IEEE EMC Society, the author of several publications, and the coauthor of EMI Troubleshooting Cookbook for Product Designers. André can be reached at pat@andreconsulting.com.

By Patrick G. André

Solutions to electromagnetic interference (EMI) problems can be complex in many cases. But when you come back from the lab with unsuccessful radiated emission results, it can be frustrating to hear, "Didn't you try adding a ferrite?" When used wisely in a good design, ferrites can work very well, but there is a reason they are sometimes called "prayer beads" – we throw them on cables and pray they work.

Let us start with the basics, highly simplified. Common passive components are resistors, capacitors, and inductors. One simple way to differentiate them is that in a resistor, both the current and voltage can change instantaneously. However, in a capacitor, voltage cannot change instantaneously. And in an inductor, current cannot change instantaneously.

All three of these aspects (resistance, capacitance, and inductance) are present in any conductor. Conductive materials, in our case wires, are not perfect metals and have resistance. They have a capacitance to other conductors based on the area each conductor has and their separation. And when carrying a current, they have inductance due to the magnetic field generated by the current in the wire. Knowing that each of these three characteristics exists and cannot be eliminated can be used to the advantage of the circuit design. If we must live with inductance, we might as well wisely put it to use.

The amount of inductance in a wire can be increased by making loops in the wires through which the current can flow. Coiling the wire has the effect of concentrating the magnetic field, or flux, through the middle of the coil and inducing some back electromotive force on the opposite side of the coil.

To increase this effect, a magnetic material having a permeability greater than 1 is placed inside the coil. If the material is ring-shaped, a toroid, and the wire is wrapped around this core material, the inductance can significantly increase, and the residual and uncontrolled magnetic fields reduced. Being able to control these magnetic fields is important since these fields can create currents in other conductors. If those conductors are sensitive circuits with minimal currents in them, having uncontrolled magnetic fields can induce unwanted signals, which is a source of susceptibility.

CHOOSING THE MATERIALS TO USE

One aspect of magnetic materials that makes them desirable is permeability. To explain permeability using simple terms, permeability can be thought of as the ease of the material to conduct magnetic fields. The higher the permeability, the easier it is for magnetic fields to flow through it. This is not how much total field or flux it can contain. A copper wire may be more conductive than an iron wire. But if it is too small a gauge, it will not be able to handle as much current. So if the core is too small, even if it has a high permeability, it can only contain so much magnetic field before it becomes saturated.

This factor becomes an important parameter for inductors and ferrites that might have an initial amount of current flowing in the wire. If the equipment operates with a current of 4 amperes DC, the inductor or ferrite on the power line will see a continuous magnetic field based on that current. If you have an inductor rated for 5 amperes maximum current with the given number of turns wound on the core, you may find the core has limitations on how well it will perform. The issue is that the rating may be based on when the material begins to be saturated and cannot handle additional field.

Figure 1 on page 28 depicts a figure commonly known as a B-H curve.[1] The horizontal axis represents the magnetic field strength induced on the core, which is based on the number of turns on the core and the current in the wire. The axis may also be called a magnetizing force. The vertical axis represents the resulting magnetic field density induced inside the material or flux density. The areas at the top and bottom of the curve where the curve begins to flatten out represent the point at which the material begins to saturate and lose its ability to handle any more magnetic flux. This is due to the internal crystalline structure containing the magnetic dipoles all being aligned by the induced magnetic field. Once the dipoles all are aligned, the core is saturated and no additional magnetization is available from the material.

The black diagonal line represents the area in which the core will operate if no DC bias is induced on the core. Notice that the line is more vertical than the green line above and a bit to the right. The green line is the area where the core operates if a DC current is induced on the core. Notice that the green line is less vertical than the black line. For the same change in the field strength inside the core, the change in flux is 2000 Gauss for the black line and only 500 Gauss for the green line. If the DC bias is increased, the induced flux continues to decrease.

Figure 1 illustrates the reduction in the effectiveness of the core due to the bias current. The more current and resulting field strength on the core, the more the core will lose its ability to operate as an inductor. Though shown as simple lines, the actual curves for these two lines would have an open-eye shape similar to the B-H curve, and the green line will flatten with a higher induced magnetic field.

Remember that a core that is wound as a common mode inductor will have both the line current to the load and the return current wound in the same direction but with the current flowing in opposite directions. The result is the total line current through the core will be zero or near zero. As a result, the core will be operating near the center of the B-H curve (the area of the black line), and the effectiveness of the material maximized for common mode currents. Common mode currents will flow in the same direction through the core,

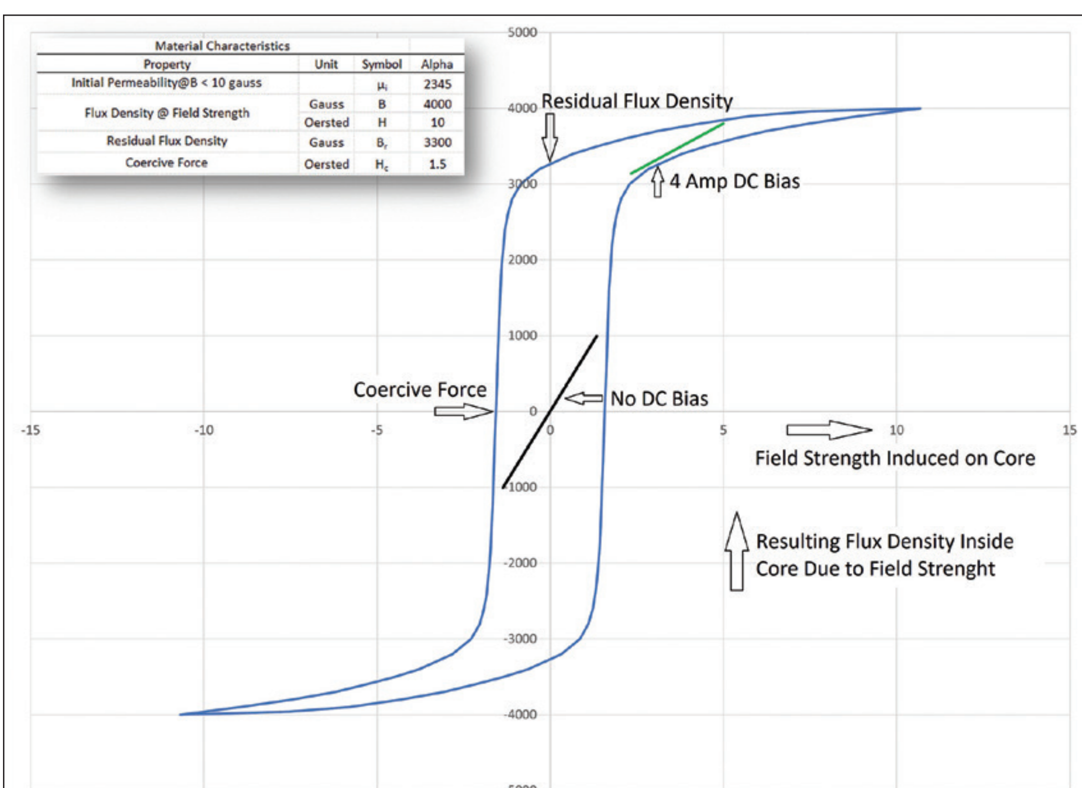


Figure 1: B-H curve characteristics

and thus experience a much higher impedance than the differential current. This is what makes common mode inductors so effective.

For this curve, there are two more important parameters to understand. First is at the top, the residual flux density, also called remanence. This is the flux density that remains in the material if the core is driven to saturation, in this case, +10 Oersted or more. If the current returns to 0 amperes, the core is magnetized, which is the remanence of the core. To demagnetize the core will require a negative field strength and thus a current in the opposite direction. The required field strength to demagnetize the core back to zero Gauss is called the coercive force, or the coercivity of the material, and is shown on the horizontal axis to the left of the curve.

The term "soft ferrites" refers to these last two parameters. The lower the remanence of the core, and the lower the coercive force needed to demagnetize the core, the softer the ferrite. For permanent magnets, this B-H curve can become very wide and, in some cases, have very sharp corners, making the curve look block-shaped. The softer the ferrite, the more it turns into a lazy S shape, with lower residual flux density. Toroids made from powdered iron will have very low residual flux compared to saturation. In comparison, hard ferrites or hard magnetic materials can be used as a permanent magnet. Once driven to saturation, the remanence of the material is what creates the magnet.

These values become important in the performance of the inductor. When harder core materials are used, the result is greater losses in the core. Also, if the core is too conductive, eddy currents can be created inside the core, and both can result in inefficiencies and excessive heating. So, for use in switching power supplies and the like, the choice of core materials becomes very important, which is why powdered iron and soft ferrites are used. Note that, up to a point, ferrites will maintain their inductance with increasing current in the core better than powdered iron. Once saturation occurs, ferrites radically lose their inductive characteristics, whereas powdered iron degrades much more gradually but continues to be useful.

Molypermalloy powder cores, known as MPP, have been used for decades because of their higher permeability over powdered iron, along with very low core losses and other positive characteristics. However, with higher-speed switching power supplies, MPP cores can have a frequency limitation and may not be the best choice. For this reason, ferrite cores are being considered for highest-speed switch mode power supplies.

Ferrites are typically composed of manganese and zinc or nickel and zinc, mixed with iron. Manganese-zinc ferrites will have higher permeability than nickel-zinc but will have a limited frequency range. In general, the lower the permeability of a material, the higher the frequency range in which it will work. This should be carefully noted when choosing a ferrite as an EMI filter. If there is a radiated emissions issue above 100 MHz, a nickel-zinc core will be the best choice for a filter. And there are other aspects to consider when choosing these cores. Magnesium zinc ferrites are now being developed that have similar characteristics in high frequency material but avoid the use of nickel.

In Figure 2, a ferrite's permeability is plotted over the frequency range.[2] As is common with ferrite manufacturers, two lines are given for the permeability: 1) μ' representing the real or initial permeability, and 2) μ" for the imaginary or lossy component of the core. For the lower frequency manganese-zinc cores, the initial permeability μ' is higher but may drop more quickly and be ineffective as an inductor above a few megahertz. However, the lossy aspect of the core might provide benefits at higher frequencies. The range where μ" becomes significant is a loss range and can be thought of as resistive but not inductive. Since it is not an inductive component in this frequency range, it is not useful as a transformer or purely as an inductor. When plotted on an impedance analyzer capable of showing phase angle, the inductive portion will appear at 90 degrees

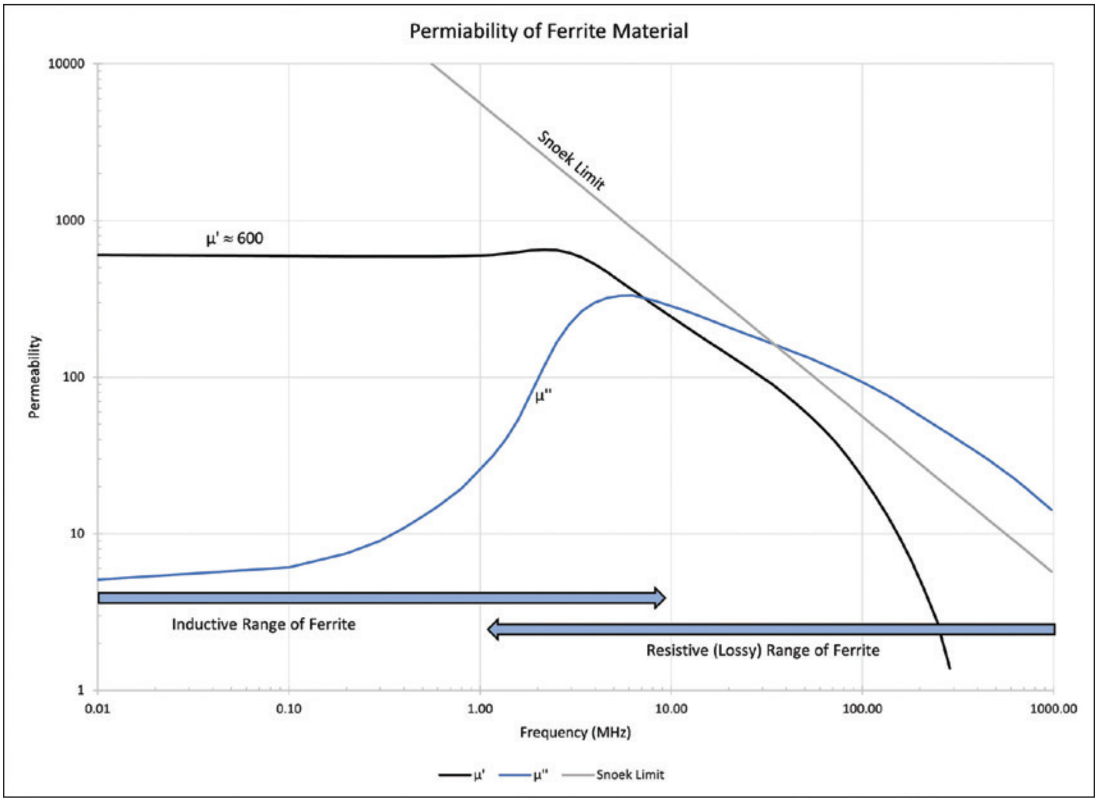


Figure 2: Permeability of a ferrite material over frequency

(voltage leading current), while the phase of the μ" portion will be near 0 degrees.

A material of this nature may be useful as a power transformer in the flat region of the permeability, μ,' about 1 MHz in this case. In this region, the loss factors are still low. As an inductor, a higher frequency can be used up to the point where μ' starts to roll off but before the loss factor μ" becomes dominant, about 5 MHz. Above this range, the material may be best used as a suppression device, where the loss factor μ" dominates but has not rolled off too much, about 100 MHz.

Notice the line called the Snoek Limit, also known as Snoek's Law. Dr. Jacob L. Snoek found these characteristics in ferrites in his research published in 1947. The general limit for ferrites is simplified as a line with the formula 5600/(frequency in MHz). Plots depicting the real permeabilities of ferrites with this limit show that the μ' line may approach this limit but does not cross it. The loss factors tend to cross the limit but with little margin. With this in mind, ferrites that have high permeability at high frequency do not exist at this time. Materials that exceed the Snoek Limit are being created but are not commercially available to our knowledge.

HOW TO CHOOSE

The following questions address the key aspects that should be considered when choosing a core for EMI purposes.

Where is the core being used? Power lines or signal line? Internal or external to the unit? Inductors, by nature, create magnetic fields. The fields are not completely captured in the core material and some "leakage inductance" will exist. If the type of core used is gapped, such as an E core, bobbin, or other types of structures, the fact there are two or more pieces to the core means that some type of gap exists. Gaps will bloom uncontrolled magnetic fields.

All these magnetic fields can cross-coupled into other electronics and cause cross-coupled energy to be generated in other wires, circuits, or structures. Each of these can be the cause of emissions or susceptibility.

If the filter is mounted in the chassis wall of the equipment or located outside of the chassis, and assuming the chassis is a solid metal, the control of these fields becomes less critical due to the location of the filter.

Note that most signal lines will have much lower currents than power lines. When this is the case, the size and nature of the inductor used also changes. Ferrites used as common mode inductors may be beneficial on signal lines to assure the intended differential signals remain differential and do not "leak" a return current by some uncontrolled path. These uncontrolled returns are often the source of radiated emissions.

Will it be a power line filter, common mode filter, transformer, or other use?

If an inductor is needed and the core is placed on individual current carrying lines, the use of ferrites may be less desirable. This is because the current can saturate the material. If the core is placed on an AC power line and does go into saturation at the peak of the current, the core will be driven in and out of saturation two times each cycle (120 times a second on a 60 Hz line). This effect has been seen to create emissions more than decrease them.

Thus, choosing the right material for differential mode power line inductors is important. Powdered iron, MPP, and other such materials are designed to handle these types of currents in a more controlled manner.

Common mode filters using ferrites work best when the sum of all currents in all wires passing through the core is zero or very close to zero. In the case where the power and power return lines are not balanced and a return path may exist in other signal lines, which can occur in some DC equipment configurations, the imbalance can limit the effectiveness of the core.

What frequency range will the material need to operate?

When very high-frequency materials are needed, ferrites are often the best material to consider, especially those containing nickel or magnesium. Most manganese materials may work well up to a few megahertz but have limited use above that. Very high permeability materials tend not to have high-frequency effectiveness.

This can often be noticed in the value of permeability. If the material has a permeability of less than about 1500 or 2000, the likelihood is that the material will work well at high frequencies. If the permeability is over 5000, it likely will not work.

How much impedance will be needed?

Remember that most inductors and common mode chokes will have a maximum impedance typically less than 1-5 kΩ or so. If you need 10 kΩ or more to have adequate impedance to a signal, inductors alone may not be helpful. In these cases, a small amount of capacitance, if it can be used, may provide more benefit than a great deal of inductance.

Remember that creating high values of inductance will often require many turns on a core. Having a large number of turns will have two effects. First, there may be a chance of saturation of the core, as stated earlier. Second, the number of windings on the core will begin to become increasingly capacitive with each other. This leakage capacitance will reduce the high-frequency effectiveness of the core. The capacitance effectively bypasses the inductors from input to output. Impedance graphs of inductors with many windings will increase to some maximum before dropping when the leakage capacitance becomes dominant.

SUMMARY

Not all inductors are created equal. It is important to know how these materials work, the frequency range within which they work, and what benefits can be obtained from their use. Know when to use differential mode inductors and what materials will be best to use for the current demand on that line. Location, core structure, number of windings, and many other aspects are all important factors to consider in choosing the magnetic to use.

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ENDNOTES

1. This curve and material characteristics are invented by the author, and no commercially available material is known to have these properties. The curve is based on actual ferrite materials and similar performance might be expected of such a material.
2. As with the B-H curve, these characteristics are adapted from real materials, and though similar, these values are not from a commercially available product.

RECOGNIZED COMPONENTS AND ETHICAL COMPLIANCE OBLIGATIONS

Understanding and Fulfilling Conditions of Acceptability

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By James L. Bender, P.E.

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INTRODUCTION

Third-party safety certification evaluations are offered by many independent national and international independent, third-party safety testing laboratories. Within North America and the focus of this paper, accredited laboratories are referred to as "Nationally Recognized Test Laboratories (NRTL)" [1].

Selection of a particular third-party independent safety laboratory is by choice. Selection is often based on a variety of business factors including, but not limited to, the test laboratory's brand recognition, technical capabilities, subject matter expertise in particular product evaluation categories, responsiveness, quality of work, costs, regional location and other factors outside the scope of this paper.

Third-party safety certifications provide an important element in a product development cycle, providing independent and non-biased safety evaluation of products, while benefiting many "softer" ethical balances.

The majority of third-party safety certification product evaluations focus on construction and testing requirements against nationally and/or internationally recognized safety standards. These evaluations focus either on the complete end-product, with the end certification being a "Listed or Certified" product, or component/subassembly evaluation known as a Recognized Component or Certified Component approval.

COMPONENTS/SUBASSEMBLIES (RECOGNIZED COMPONENTS)

A recognized component certification is still evaluated against applicable safety standards. It's important to differentiate that the evaluation and testing approach tends to be more limited. Many of a component's safety features are based on the intended end-product application where such differences and limitations introduce subtle but important ethical obligations and considerations.

For Recognized Components, an often overlooked end-product design consideration is what's known as "Conditions of Acceptability" (COA). These are specific end-product application integration, test or other restrictions published in the component/subassembly's certification test report as issued by the certification laboratory.

Virtually all Recognized Components carry one form or another COAs which must be satisfied in the design of the end-product. Although a responsibility of the third-party safety certification laboratory performing the end-product Listing investigation, the end-product original equipment manufacturer (OEM) is also responsible to assure safety critical component/subassembly level COAs are satisfied in their end-product. This is an obligation to help contribute towards a safe end-product. Like the name implies, it's a condition of acceptability for safe use of the end-product.

RECOGNIZED COMPONENT CONDITIONS OF ACCEPTABILITY – KEY CONSIDERATIONS AND DIFFERENCES

End-product developers and OEMs introducing a product to market, especially those new to the field of compliance are often unaware of differences between

Identically functioning components/subassemblies may carry a totally different set of COAs for a variety of reasons, some good, some not so good, potentially impacting ethical considerations and outcomes.

Listing (end-product) and Recognized Component (component and/or subassembly) certifications. Recognized Components certification reports are exclusively assigned COAs, not found in Listing reports. They are identified and documented in their Recognized Component certification report to cover application specifics that must be included in the end-product's Listing investigation. This report is accessible to the component/subassembly "Applicant" and generally available upon request from the component/subcomponent supplier, although the certification report and its COAs may be considered proprietary by the component owning entity.

The responsibilities for identifying and obtaining component level COAs lies between the end-product OEM and Recognized Component supplier. Ability to obtain these important COAs can be accomplished through normal business relationships including considering the use of defining contractual specification obligations in procurement agreements between the end-product OEM and Recognized Component supplier.

Depending on the component specifics, application and particular safety standard, a Recognized Component's COAs may also be published in a third-party certification safety laboratory's Recognized Component certification directory, but this is not always the case nor a requirement. The information is also internally available to the third-party end-product Listing certification laboratory if the Recognized Component was certified by the same laboratory performing the end-product Listing investigation.

ETHICAL CONSIDERATIONS – WHY IMPORTANT?

First and foremost, unlike end-product certification Listings, Recognized Component certifications can vary significantly depending on the desired certification approach desired by the Recognized Component manufacturer and as determined with its certification laboratory. Recognized Component certifications are, by design, not intended to cover all application considerations like an end-product Listing encompasses. The actual safety evaluation program (construction and testing elements) can vary significantly since the components themselves are not considered "complete" or "ready to use" like the Listed end-products utilizing use these components and subassemblies.

A component/subassembly manufacturer and selected third-party certification laboratory have a great deal of flexibilities defining and implementing the Recognized Component construction and testing program elements since its tailored toward integration with other products and operating environments.

Identically functioning components/subassemblies may carry a totally different set of COAs for a variety of reasons, some good, some not so good, potentially impacting ethical considerations and outcomes:

Good reasons:

- Safety critical application needs of anticipated Listed end-product are limited, with little to no risk;
- Primary protective safety features are not primarily provided by the recognized component/subassembly vs. elsewhere in the Listed end-product being investigated;
- Supplier cost savings producing lower cost component/subassembly requiring limited safety features as defined in the intended end-products;
- Knowing the end-product will be evaluated in the design and certification process that accounts for the component/subassembly COAs.

Not so good reasons:

- Component/Subassembly manufacturer seeks a Recognized Component certification mark, knowingly accepting many complicated COAs to reduce their own testing obligations of the Recognized Component. Essentially, passing Recognized Component testing obligations from the Recognized Component supplier to the Listed end-product, potentially adding safety risks to the end-product;

- Component/Subassembly manufacturer is only interested in displaying a Recognition Mark on their component and supporting marketing information/ data sheet to satisfy "compliance", while knowing the certification is at minimum levels;
- Component/Subassembly manufacturer seeks a recognition component evaluation plan that requires the least path of compliance testing by the use of many COAs being passed on to the end-product Listing. This creates significant construction and testing evaluation obligations that must be fulfilled for the Listed end-product OEM.

ETHICAL IMPORTANCE OF COAs – AN EXAMPLE COMPONENT/SUBASSEMBLY POWER SUPPLY

Virtually all recognized component power supplies have COAs ranging from simple considerations to more onerous ones, which depends on the technology, application and the power supply vendor's integrity itself.

There are "ethical" elements to consider since some suppliers of component power supplies try to substitute COAs in their recognized component power supply certification as a cost-reduced approach to minimize and/or eliminate basic safety certification obligations and/or features. This is sometimes achieved by passing these component manufacturers' obligations to the end-product OEM, increasing both safety certification construction and testing obligations. In many cases, a power supply can and should provide primary

At the end of the day, all COAs must be satisfied in the end-product. In absence of a third-party safety test lab performing this deliverable, the obligation to satisfy the requirement falls on the OEM.

safety protection for the end-product since it is the workhorse of voltage conversion and power transfer capable of providing isolated (and safe) current levels and voltages within the OEM end-product by limiting risk of electrical shock and/or fire hazards.

This clearly simplifies construction and testing obligations of the power supply component itself not to mention cost if such features are not included in the recognized component power supply, transferring this obligation to the unsuspecting end-product manufacturer.

One might argue if this is a deliberate opportunity to cut corners by marketing a very limited safety featured recognized component certified power supply to pass on many of the inherent safety features to an unaware OEM building their end-product.

This may be an ethical compromise since the recognized component power supply is marketed as certified by a third- party, independent safety laboratory, particularly in absence of any differentiation between Listed and being a Recognized Component.

There is no obvious right or wrong answer here since COAs are used to address application integration compliance needs. Determining "goodness" of this approach is beyond scope of this publication but should be considered an owned responsibility of the Recognized Component supplier.

Example: Tying a computing product Recognized Component power supply COAs to ethical obligations

Let's conclude with a simple, high-level walk-through of a partially framed/enclosed switch mode power supply typically used in computing equipment. For illustration purposes, the power supply includes a battery for certain power failure back- up conditions.

The Recognized Component power supply and OEM end-product computing device are covered by IEC 62368-1, Audio/Video, Information and Communication Technology Equipment – Part 1: Safety Requirements (Edition 3)

For this hypothetical example, four simple COAs (or "Application Considerations as noted earlier) are provided in the power supply's Recognized Component certification report as follows:

- DC outputs of power supply have not been evaluated for short circuit protection.
- Power supply tested to a maximum internal ambient temperature rating of 30°C as measured in the power supply, meaning the power supply cannot exceed 30°C air temperature in its immediate surrounding area where installed in the end-product.
- Open frame rear panels containing AC receptable connector not evaluated as an enclosure.
- A lithium battery is provided for back-up circuits and has not been evaluated.

Both compliance and ethical obligations for the third-party NRTL performing the end-product Listing investigation is well defined, being a required action. Critical recognized component COAs must be verified as a part of the end-product certification evaluation.

The "ethical" question comes into play regarding confirmation of the power supply's COAs compliance for this particular computing product if the *OEM elects not to certify their end-product through a third-party NRTL*, or, self-certifies the safety of the computer to various norms and directives in countries that permit these practices.

At the end of the day, all COAs must be satisfied in the end-product. In absence of a third-party safety test lab performing this deliverable, the obligation to satisfy the requirement falls on the OEM. Failure to effectively validate that COAs are being satisfied in the end-product creates compliance gaps that may raise question regarding the overall ethical commitment of the end-product OEM. This is due to the selection of a Recognized Component power supply NOT BEING COMPLETE without COA compliance verification in the OEM's end-product.

The OEM end-product developer may not always be aware of the component/subassembly COA requirement since its often a subtle requirement, particularly when selecting and qualifying recognized components/subassembly that potentially ignore these important obligations, often occurring in situations where the OEM's end-product is not certified by a third-party NRTL.

CLOSING ON POWER SUPPLY COAs – WHY IMPORTANT FROM BOTH A COMPLIANCE AND ETHICAL PERSPECTIVE?

Let's walk through each of the Recognized Component's power supply COAs to conclude why compliance of each are critical to the safety of the OEM end-product computer and why failure to comply may lead to both a safety issue and ethical infraction:

- COA #1: DC outputs of the power supply have not been evaluated for short circuit protection
  - Failure to meet: Computer end-product loads fail due to non-limiting shorted power supply output, creating electrical shock risk (if isolation system compromised) or fire condition due to overheating.
- COA #2: Power supply tested to a maximum ambient surrounding temperature ambient rating of 30°C
  - Failure to meet: Most computing products are rated to 40°C ambient. With power supply rated to 30°C surrounding ambient temperature, and, in absence of suitably certified temperature derating curves or other end-product certification testing considerations, a possible fire risk may occur if exceeding the power supply's rated ambient temperature rating as integrated into the computer.
- COA #3: Open frame rear panel containing AC power receptable not evaluated as an enclosure
  - Failure to meet: If the OEM end-product computer employs the rear panel of the power supply as a part of the overall computer's enclosure, additional fire or shock hazard risks could be created due to an ineffective power supply panel enclosure.
- COA# 4: The lithium battery and back-up circuits have not been evaluated
  - Failure to meet: Depending on the selected non-rechargeable lithium battery, most recognized component lithium batteries have stringent end-product protective requirements including use of series diodes and/or limiting current resistors. These components help to minimize risk of rupture and/or fire due to charging and/or short circuit reverse polarity requirements. Without such verification, risks may not be mitigated.

CONCLUSIONS

Takeaways from this paper underscore importance from a product safety design and ethical obligation to understand, identify, and implement a Recognized Component's accompanying "Conditions of Acceptability or "Application Considerations" as published in its certification report.

When developing an end-product that integrates Recognized Components, awareness for these important design and ethical compliance obligations should be addressed early in the development process. It should be carefully reviewed between the Recognized Component supplier, the end-product OEM and where end-product Listing is applicable, your third-party certification laboratory of choice, typically being a NRTL if North American based.

These obligations should not be arbitrarily assigned or assumed to any one entity since ownership starts with the OEM developing a product that effectively executes components/subassemblies whose safety critical COAs are carefully evaluated, effectively implemented and verified in the end-product.

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SMITH CHART AND INPUT IMPEDANCE TO TRANSMISSION LINE

Part 3: Input Impedance to the Line

By Bogdan Adamczyk

This is the last of the three articles devoted to the topic of a Smith Chart. The previous two articles, [1,2], introduced the concept of normalized load impedance leading to the resistance and reactance circles, which in turn were used to locate the normalized load impedance on the Smith Chart. This article explains how to use a Smith Chart to determine the input impedance to transmission line at a given distance from the source or the load.

Recall the two typical circuit models of a transmission line [1]. In Model 1, shown in Figure 1, the source is located at $z = 0$, and the load is located at $z = L$.

In Model 2, shown in Figure 2, the load is located at $d = 0$, and the source is located at $d = L$.

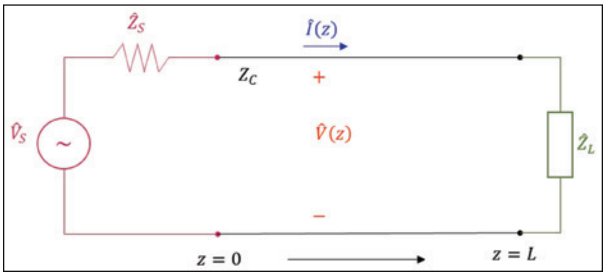

Figure 1: Circuit Model 1: the source located at $z = 0$ and the load at $z = L$

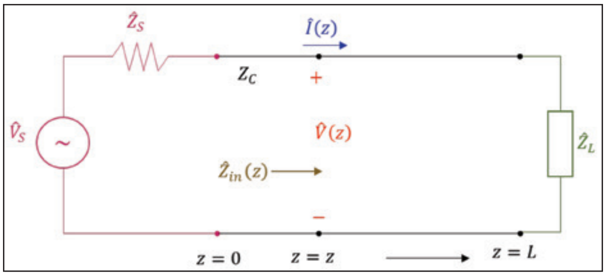

Figure 2: Circuit Model 2: the load located at $d = 0$ and the source at $d = L$

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In either model, the input impedance to the line at any location is always calculated looking toward the load. Recall from [3]: The input impedance to the line at any location d away from the load can be obtained from

$$\hat{Z}_{in}(d) = Z_C \frac{1+\hat{\Gamma}(d)}{1-\hat{\Gamma}(d)} \tag{1}$$

where $\hat{\Gamma}(d)$ is the voltage reflection coefficient at any location d, away from the load, and can be expressed in terms of the load reflection coefficient as

$$\hat{\Gamma}(d) = \hat{\Gamma}_L e^{-j2\beta d} \tag{2}$$

The load reflection coefficient can be expressed in terms of its magnitude and angle as

$$\hat{\Gamma}_L = \Gamma_L e^{j\theta} \tag{3}$$

Utilizing Eq. (3) in Eq. (2), we obtain

$$\hat{\Gamma}(d) = \Gamma_L e^{j\theta} e^{-j2\beta d} = \Gamma_L e^{j(\theta - 2\beta d)} \tag{4}$$

We refer to $\hat{\Gamma}(d)$ as the *phase-shifted* load reflection coefficient. Note that the phase-shifted load reflection coefficient has the same magnitude as the load reflection coefficient, but the phase of $\hat{\Gamma}(d)$ is shifted by relative to the phase of $\hat{\Gamma}_L$.

On the Smith Chart, obtaining $\hat{\Gamma}(d)$ from $\hat{\Gamma}_L$ means keeping the magnitude, Γ_L, constant and decreasing the phase by $2\beta d$. Phase decrease corresponds to the clockwise rotation on the Smith Chart. This is shown in Figure 3.

Let's return to Eq. (1). Dividing both sides by the characteristic impedance of the line, Z_C , we obtain the *normalized* input impedance to the line at any location d away from the load,

$$\hat{z}_{in}(d) = \hat{Z}_{in}(d) / Z_C \quad (5)$$

or

$$\hat{z}_{in}(d) = \frac{1+\hat{\Gamma}(d)}{1-\hat{\Gamma}(d)} \quad (6)$$

Let's compare this expression with the one for normalized load impedance [2],

$$\hat{z}_L = \frac{1+\hat{\Gamma}_L}{1-\hat{\Gamma}_L} \quad (7)$$

The mathematical form of these two equations is the same! If $\hat{\Gamma}_L$ is replaced by $\hat{\Gamma}(d)$ then $\hat{z}_L$ gets replaced by $\hat{z}_{in}(d)$.

On the Smith Chart obtaining $\hat{z}_{in}(d)$ from $\hat{z}_L$ means keeping the magnitude of $\hat{z}_L$ constant and decreasing the phase by $2\beta d$. This is shown in Figure 4.

When using Smith Chart, the distance d is expressed in terms of wavelengths. A complete rotation around the Smith Chart corresponds to a phase change of 360° or 2π radians.

$$2\beta d = 2\pi \quad (8)$$

The phase constant β is related to the wavelength λ by

$$\beta = \frac{2\pi}{\lambda} \quad (9)$$

Thus

$$\frac{2\pi}{\lambda} d = \pi \quad (10)$$

from which

$$d = \frac{\lambda}{2} \quad (11)$$

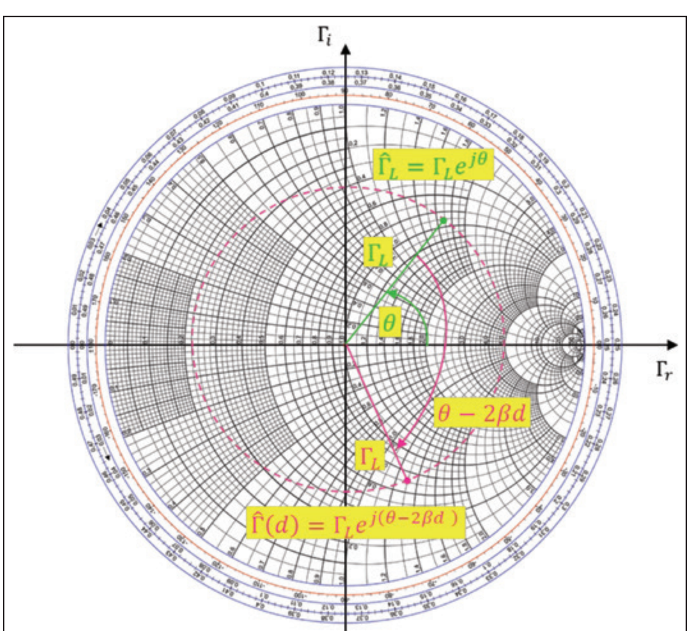

Figure 3: Transformation of $\hat{\Gamma}_L$ into $\hat{\Gamma}(d)$

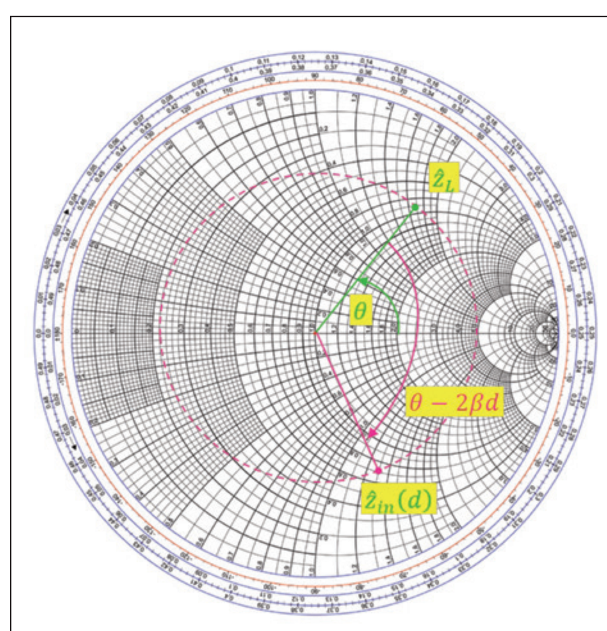

Figure 4: Transformation of $\hat{z}_L$ into $\hat{z}_{in}(d)$

This means that one complete rotation around the Smith Chart corresponds to the distance change of λ/2. The rotation around the Smith Chart, either in degrees or wavelengths, is denoted on the outer three scales around its perimeter, as shown in Figure 5.

We have shown how to obtain $\hat{z}_{in}(d)$, the normalized input impedance to the line at a distance d away from the load. What about $\hat{z}_{in}(z)$, the normalized input impedance to the line at a distance z away from the source?

$\hat{z}_{in}(z)$ can be easily obtained from $\hat{z}_{in}(d)$ since the two distance variables are related by [3,4],

$$d = L - z \quad \Leftrightarrow \quad z = L - d \tag{12}$$

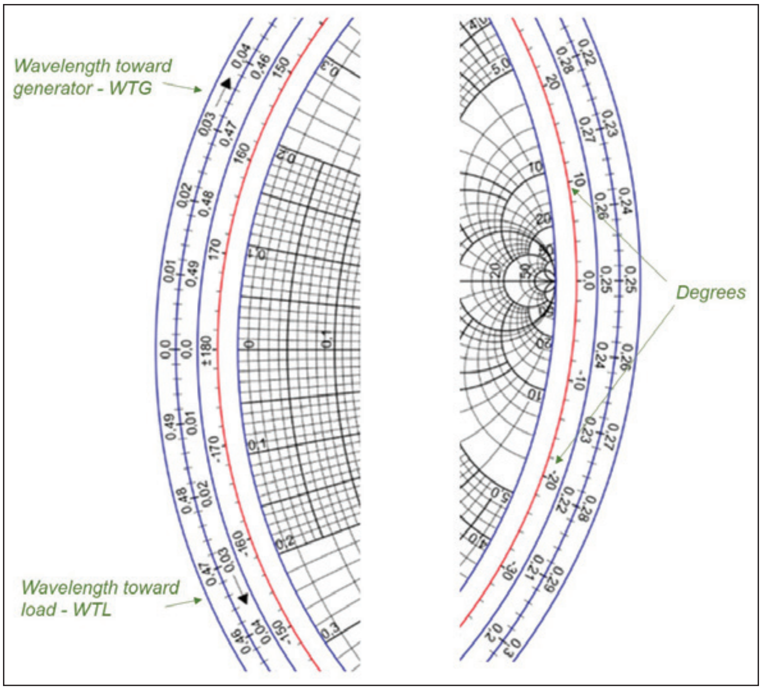

Figure 5: Outer scales of the Smith Chart

Thus, if we are given z, the distance from the source, we can calculate d, the corresponding distance from the load, and use the procedure just described to obtain the input impedance to the line at that location.

In summary, to determine the input impedance to the line at any distance from the load or the source, using Smith Chart, the following steps need to be taken:

1. Calculate the load reflection coefficient

$$\hat{\Gamma}_L = \frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C} \tag{13}$$

2. Obtain the normalized load impedance

$$\hat{z}_L = \frac{1+\hat{\Gamma}_L}{1-\hat{\Gamma}_L} = r_L + jx_L \tag{14}$$

3. Locate this impedance on the Smith Chart at the intersection of the resistance and reactance circles.
4. Calculate the distance from the load, d, or the source, z, in terms of wavelengths.
5. To obtain the normalized input impedance to the line at a distance d from the load, move clockwise on the constant radius circle from $\hat{z}_L$.
6. Multiply the normalized input impedance by the characteristic impedance of the line, Z_C, to obtain the actual input impedance.

$$\hat{Z}_{in}(d) = Z_C \hat{z}_{in}(d) \tag{15}$$

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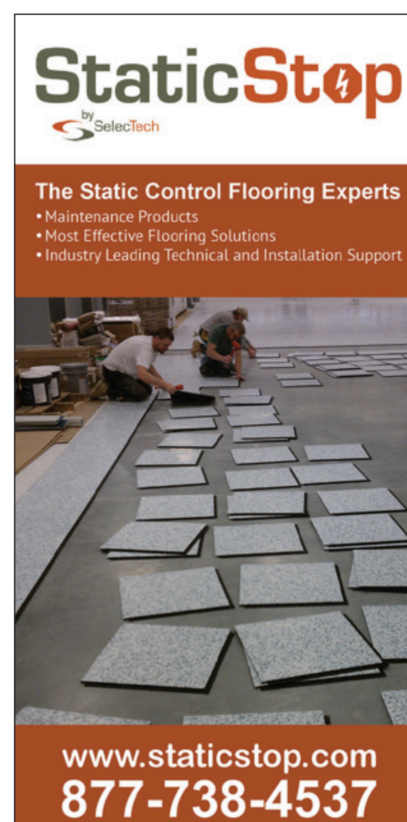
PRODUCT Showcase



THE TRANSISTOR: AN INDISPENSABLE ESD PROTECTION DEVICE - PART 2

By Lorenzo Cerati, Dolphin Abessolo-Bidzo, Mirko Scholz, and Marko Simicic for EOS/ESD Association, Inc.

The invention of the bipolar transistor and later the MOS transistor evolution into wide applications for ESD protection in the semiconductor technologies was previously published in the January 2023 issue of this magazine. In this second and final part of the article, we discuss the MOS transistor in the role of ESD protection for high-voltage applications and take a look into a possible future of ESD protection devices for high-performance computing applications.

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USING MOS TRANSISTORS AS ESD PROTECTION CLAMPS IN HIGH VOLTAGETECHNOLOGIES

Typically, when we speak about high voltage technologies, we refer to integrated circuits having pins with voltage rating higher than 10V. These technologies combine different elements: digital and analog signals processing are managed together with Power transistors. In this way, it is possible to provide high voltage and high current to the loads. Some typical examples of possible applications are power control and conversion circuits, power drivers, automotive applications, and sensors or actuators driving circuits. Anyway, the list may be easily extended to many more cases.

High voltage technologies show some specific characteristics which make them unique. First of all, the ESD design window is narrower and narrower. Especially for high voltage components, such as devices rated above 40V, the ESD window actually tends to vanish completely. So, it is challenging to have the right space to allow snapback-based ESD protections. Moreover, the high clamping voltage requires a normally large device with a remarkable area occupation. Then, we need to consider that typical high voltage components are potentially weak and ballasting is not so effective as for CMOS technologies. Finally, these technologies are showing several implants with a large number of parasitic transistors, both NPN and PNP. So, Latch-up risk is a serious threat.

Bipolar-based ESD solutions are widely used in HV Technologies, but several approaches can be adopted, taking into account the specific needs of the applications to be addressed and the device portfolio available in the different technologies. One relatively simple approach implies the usage of several Low Voltage ESD protections (such as, for example, series of grounded gate NMOS or GGNMOS devices). As reported in Figure 1, stacking a suitable number of elementary components, higher trigger and holding voltage levels can be reached. The exact number of the protections can be defined based on the application voltage requirements. The main drawback of this solution is that triggering and holding voltages cannot be independently modulated, but they will be a multiple of the initial value. Precise tuning of these values in case of narrow ESD windows can be, therefore, a very challenging task.

Alternatively, the parasitic NPN embedded in HV-NMOS devices (Drain/Body/Source) can be also adopted as ESD protection. In this case, the voltage capability is guaranteed by the original MOS device, which is designed to sustain high voltage in off-state. The main issue related to this type of component is that they are quite fragile in snapback-mode due to a large instability of the triggering mechanism inducing a premature filamentation and eventually permanent damage at relatively low current levels. Several techniques were reported in the past to improve the overall robustness of HV-NPN ESD protections, such as the usage of dedicated deep implants [8], a dedicated layout implementation to modulated the body resistance [9], and also the addition of dedicated triggering circuits, directly embedded into HV transistor to turn on the bipolar action in a controlled way [10].

Finally, bipolar protections in HV technologies may also be implemented using PNP devices. This is a rather common approach, especially for safety-critical applications where no snapback-based protections are allowed due to their Latch-up sensitivity. The main advantages of PNP protections are the almost complete absence of snapback effects (see Figure 2), the fact that these do not require any ballasting to get a uniform current flow, and their layout-friendliness as matrix-based layouts are easily implementable.

ESD PROTECTION IN FINFET TECHNOLOGIES AND BEYOND

We observe two main scaling trends driving CMOS technology advancement today. The first trend is about continuing Moore's Law of shrinking the transistor and increasing its performance – part of the ***design-technology co-optimization methodology*** or DTCO for short. The second trend is about packaging chips and chiplets together into a single system – part of the more recent ***system-technology-co-optimization methodology*** or STCO for short.

To increase performance, the DTCO trend is pushing the transistor evolution towards the gate-all-around type of architecture, like the nanosheet transistor. This enables stronger channel control and, therefore, better performance in terms of a digital circuit design – lower power consumption and faster response. With this evolution, most, if not all, of the transistor current will flow through a channel surrounded by the gate. The substrate silicon is not truly needed for the digital circuit, so it becomes a parasitic channel. With this, the parasitic bipolar transistor that is very useful in

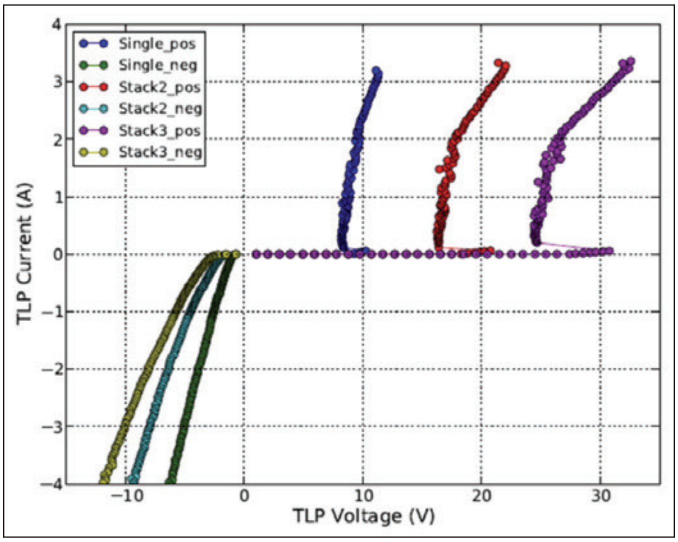

Figure 1: 100ns-TLP characterization of LV GGNMOS in series

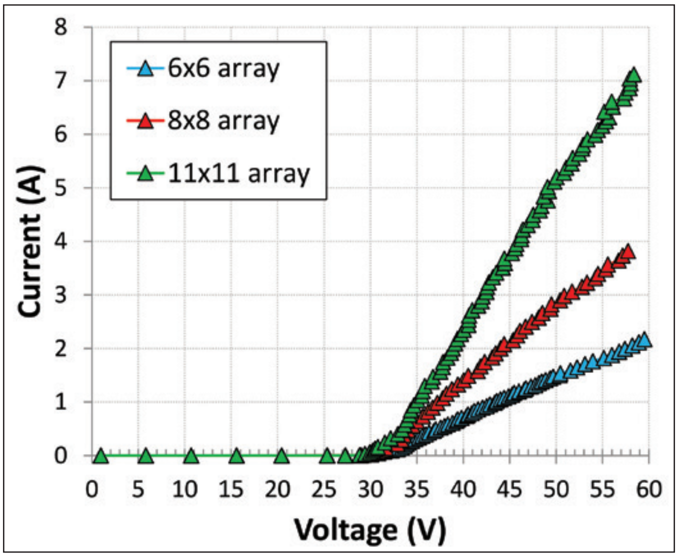

Figure 2: 100ns-TLP characterization of PNP-ESD arrays

ESD protection designs becomes a secondary effect – a parasitic effect of a parasitic channel.

The furthest concept on this roadmap is the CFET [1]. Here the n-FET is completely isolated from the substrate silicon. Only the p-FET remains in contact with the substrate. Therefore, it becomes impossible to form the parasitic bipolar transistor. This is indeed good news for the designers who worry about the unwanted latch-up effect. Unfortunately, the ESD protection designers might feel quite the opposite. The impact of technology scaling on the ESD protection designs has been described in a more detailed way in [2].

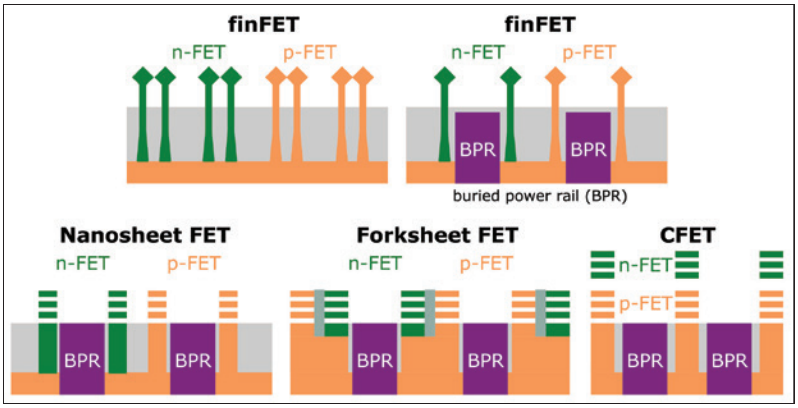

Figure 3: The imec tentative device scaling roadmap beyond the 5 nm node following the design-technology co-optimization (DTCO) trend – from FinFET to CFET. The buried power rail (BPR) is a performance booster enabling further scaling [3]. Note that from the nanosheet FET onwards, the main FET channel is physically separated from the silicon substrate.

However, the future is not so dark for the ESD protection designers. The roadmap in Figure 3 is for the core transistor, but we also have the thick-oxide input-output (I/O) transistor (not shown in the figure). Naturally, the IO devices also must follow the core transistor roadmap as they use the same fabrication process. However, they usually need a few different steps, for example, to form the thicker gate dielectric. For the nanosheet FET, this difference might be to skip the etch step that releases the nanosheets and use the superlattice finFET as the I/O device instead (described for a nanowire device in [4]). This enables better contact to the substrate silicon and therefore brings the parasitic bipolar effect back to the front seat.

STCO (system-technology-co-optimization), on the other hand, looks at integrated circuit technology more from a perspective of 2.5D and 3D chip integration. Compared to DTCO, where the device itself is scaled down, in STCO, the chip interconnect pads are scaled. That enables bonding of chips fabricated in different technologies into a single package or system. Basically, we are looking at a system of deconstructed chips (chiplets), each fabricated with a process optimized for their function, for example memory, logic, analog or even optical communication. No matter the option from the STCO roadmap, they have a common trend: substrate thinning, which can reach extreme dimensions down to 500 nm [5]. This thinning is the focus point for our story on the system-technology-co-optimization methodology (STCE) scaling trend and the bipolar transistor.

Thinning down the semiconductor substrate until it reaches the p-wells and n-wells will reduce the current gain of the bipolar transistor. The well depth depends on the used technology, of course. Still, the bottom of the implant well can be reached and the effects on the bipolar transistor can be measured [6] for wafer thicknesses of 500 nm and below. This is good news for avoiding the unwanted latch-up effect but perhaps not the best news for ESD protection circuits.

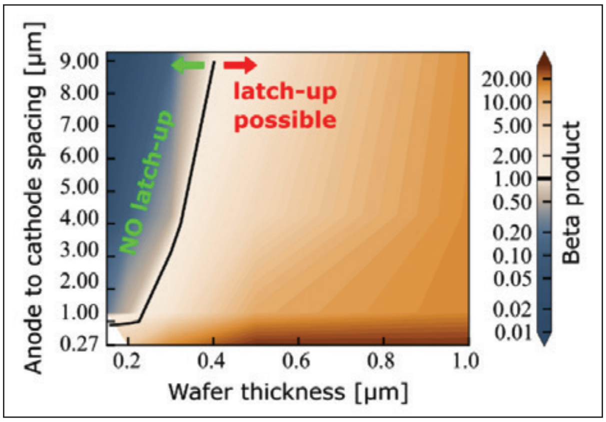

Figure 4: Product of the npn and pnp current gain values – thyristor (pnpn) beta product – as function of wafer thickness and spacing between the thyristor anode and cathode. When the beta product is below 1, latch-up becomes self-extinguishing.

Like for the device scaling trends, wafer thinning at first might seem like an issue for ESD protection designers. However, new technologies also bring new opportunities. One of these opportunities is presented by through-silicon-vias directly contacting the buried power rail and thus enabling the backside power delivery network. Thanks to this backside metallization, backside active contacts can be created at the cost of extra process steps. This enables us to form vertical junction devices [7].

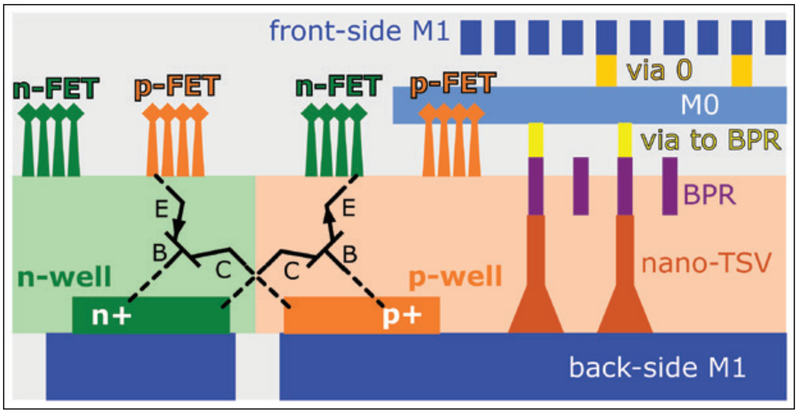

Figure 5: Sketch of a integrated circuit cross-section depicting a possible way to fabricate vertical diodes and bipolar transistors in advanced technologies. The core devices are finFETs. The buried power rail (BPR) connects to the back side metallization by nano-TSVs (through-silicon vias). Active backside contacts have been demonstrated in [7].

It should be highlighted, a vertical bipolar transistor can be made with one or two electrodes in the usual frontside together with the MOSFETs and the remaining electrodes on the backside of the wafer with the backside metal layers. Such a vertical bipolar transistor might indeed be an interesting opportunity for ESD protection designers.

SUMMARY

The bipolar transistor was invented 75 years ago and it is still widely used in many different applications and technology nodes. As shown in the two parts of this article, it is representing one of the most common elements to realize an effective and robust ESD protection network in advanced CMOS, in RF in high voltage and in finFET technologies, with a large variety of different flavors and implementations.

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Banana Skins

424 Modern spacecraft – Antique specifications

Spacecraft now and of the future are being controlled by EMC requirements of the past. Little has been done by the launch vehicle/spacecraft manufacturers to abandon MIL-STD-461C which was released in 1986 because most of the electronics equipment being used aboard current launch vehicles is approved by similarity and heritage to MIL-STD-461C and its predecessors. Twenty years later these electronic equipment items are still not tested to today's MIL-STD-461E requirements because there is a risk that the items will fail to meet the requirements and thus the cost will increase if it becomes necessary to redesign the equipment. That cost is insignificant compared with the cost of losing an entire mission!

In the 20 years that have elapsed since MIL-STD-461C was released, the EMC environment has undergone major changes. High speed digital devices have been created that have fundamental clock and bus frequencies that span the entire LV/SC frequency range from the UHF Band Flight Termination Systems through S-Band telemetry and C-Band tracking transponders. Personnel involved in ground operations can carry and use hand held transceivers and cellular telephones close by sensitive electronics equipment. There are now many more orbiting receivers and emitters, plus range assets have increased dramatically since 2001. It's way past time to bring requirements up-to-date!

It is important to note that daily KSC (Kennedy Space Center) monitoring has detected levels from off site emitters that are theoretically beyond the horizon and at times detected levels higher than the theoretical free space maximum. This is possibly due to multipath and atmospheric ducting effects.

The vehicle may fly closer to an emitter during launch and thus be exposed to higher field levels than it is exposed to on the launch pad. There are also downrange emitters that can cause strong fields at the vehicle. In this case the trajectory of the vehicle must be considered. Data bases that are developed by the Joint Spectrum Center are used to determine these levels. The Launch Services Program has recently funded Aerospace to predict ascent field levels for each mission based on the flight trajectory.

In addition, once the spacecraft separates from the vehicle the on-orbit fields must be considered if it will be in a near earth orbit. It is common for tracking radars to use spacecraft as targets of opportunity and field levels from both US and other emitters can be as high as 100's of volts/meter. Additionally there are other extremely high level emitters (over the horizon back scatter RADAR, etc.) that produce levels in the 1000's of V/m that SC trajectories may inadvertently cross. Table 3 shows the worst case ascent and on-orbit field levels being specified in the proposed MIL-STD-1541B. Some of the emitters reflected in this table such as Cband tracking radars are mitigated, however some can not be, especially foreign emitters.

(Extracts from: "Modern Spacecraft – Antique Specifications," Ron Brewer, Launch Service Program, Analex Corporation, IEEE International Symposium on EMC, Portland, OR, USA, August 14-18 2006, ISBN: 1-4244-0294-8/06.)

425 Equipotential design of systems

Using the original concept, the system failed for EFT testing at 1kV in a capacitive coupling clamp. The reason was that the distributed control units and the central screen were connected using screened cables, but the screen was terminated at both ends by a pigtail connection. By changing the screen termination into a low impedance connection, mounted directly at the chassis entrance of the modules, the EFT test passed up to 5kV.

The failure of temperature sensors has been found many times in practice, always with similar reasons of failing: no good equipotential reference over the complete system. Typical for a set of sensors and transducers is the fact that they are very distributed

TABLE 3. SUGGESTED RF SUSCEPTIBILITY LEVELS

AEROSPACE RPT TOR-2005(8583)-1 Table 6.16c1-1. RFI Susceptibility

Verification Levels (V/m) for worst case (Polar) Orbit, Any Launch Area

Frequency Hz	Factory/Transport Launch Proc/Pad	Ascent	On-Orbit 100 nmi	On-orbit 500 km	On-Orbit 1000 nmi
10k – 1.99M	**25**[1*], 20[2,3]	**20**[2,3]	**20**[2,3]	**20**[2,3]	**20**[2,3]
2 – 99M	**50**[1], 20[2,3]	**20**[2,3]	**20**[2,3]	**20**[2,3]	**20**[2,3]
100 – 999M	**100**[2], 1500[1]	**100**[2], 1500[1]	**50**[4], 40[5], 100[2]	**20**[3,4], 100[2]	**20**[3,4], 100[2]
1 – 3.99G	**250**[6], 200[2], 2500[1]	**200**[2], 2500[1]	**190**[4], 100[5], 200[2]	**70**[4], 40[5], 200[2]	**20**[3,4], 200[2]
4 – 10.99G	**1000**[7], 2500[1], 44000[8]	**1000**[7], 2500[1]	**500**[4], 120[5], 200[2]	**200**[4], 50[5], 200[2]	**50**[4], 20[3,5], 200[2]
11 – 40G	**50**[9], 1500[1]	**20**[2,3], 1500[1]	**70**[4]	**30**[4]	**20**[2,3]

*Superscripts 1 – 9 refer to notes in AEROSPACE RPT TOR-2005(8583)-1

BOLD EF levels are the recommended design and verification levels for LV/SC over larger systems. Because in some cases the termination at both ends of a screened cable causes problems, the screen is not terminated at all, or only at one side. Which does not really offer a good protection at common mode level of interference, and certainly no more at higher frequencies of the ambient noise.

Most of the problems are occurring because subparts of a larger system are not well interconnected. In this case, the problem can be solved by 'insulating' the sensor itself (ex. by using optocoupled systems, or differential mode signal transmission), and by connecting the screen of the cable in a good way to the chassis as the incoming point of the central control unit. For safety reasons, special care must be taken for PE requirements, ending sometimes in an extra (parallel to the cable screen) PE wire connection.

(Extracts from: "Equipotential Design of Systems: Examples from Practicing," J Catrysse, W Debaets, N Dediene, EMC Europe 2000, 4th European Symposium on EMC, Technologisch Instituut vzw, Brugge, 11-15 Sept 2000, ISBN: 90-76019-14-2.)

426 Failures at electricity distribution substation

This study into disconnector-related EMI was initiated following series of failures experienced at Brenner substation – an Eskom 275/88kV open-air substation situated in Gauteng, South Africa. In particular it was noticed that Bandwidth Management Equipment (BME) installed in a cabinet inside the substation's telecommunications room would fail for a period of approximately 10 seconds each time disconnectors were operated in an adjacent high voltage yard [2].

The BME is a crucial part of the microwave communications link between the site and the National Control master station, and it takes 20 – 30 seconds to re-establish this link if the BME fails. Another cause for concern was that the BME occasionally failed during line faults [2].

(Extracted from: "Testing Hypotheses Concerning the Flow of Common Mode Current in a Substation," CD Walliser, JM Van Coller, PH Pretorius and AC Britten, EMC Europe 2000, 4th European Symposium on EMC, Technologisch Instituut vzw, Brugge, 11-15 Sept 2000, ISBN: 90-76019-14-2.)

427 Patriot missile system interference

The Wall Street Journal reports that military investigators are exploring the possibility the electromagnetic interference may have been the cause of two friendly fire incidents during the Iraq war involving Patriot missiles that resulted in downing of two allied fighters and the deaths of three airmen.

According to the Journal report, investigators have ruled out either manual error by the operators of the Patriot missile batteries, or mistakes by the missiles themselves, and are now focusing on whether the extremely close positioning of multiple missile batteries on the ground resulted in elevated levels of EMI that interfered with the systems' high-powered radars. Military officials admit that the Patriot missile batteries were moved around the battlefield during the war to protect U.S. and British ground troops, and at times were clustered in close proximity to one another. And, although all military systems are tested for EMI, the Journal quotes one source who said: "If you look at the intensity of the radiation in that battlefield area, I don't believe anyone would say that particular environment had been duplicated before. It was very, very intense."

(Extracts from "Patriot Missile Systems may be EMI Susceptible," NewsBreaks, Conformity, *September 2003, page 48. Also see Banana Skin No. 299.)*

428 Pilots pick up baby monitor transmissions

CNN reports that pilots approaching Luton airport in Great Britain recently picked up more than the monotone of the air traffic controller over their radios. Authorities reportedly worked 12 hours to track down the sound of a squealing infant that was picked up on the normal communications frequencies. They ultimately traced the noise to a baby monitor in a home located near the airport. Broadcasting babies aren't new. As we've previously reported (See *Conformity*, October 1997), or own Federal Aviation Administration receives numerous reports of similar incidents here in the United States as wireless communications devices proliferate.

(Extracts from: "Pilots pick up Baby Monitor Transmissions," NewsBreaks, Conformity, *August 2003, page 88. Also see Banana Skins No. 225 and 299.)*

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

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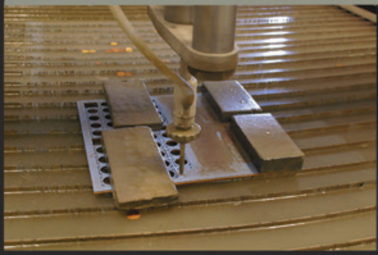

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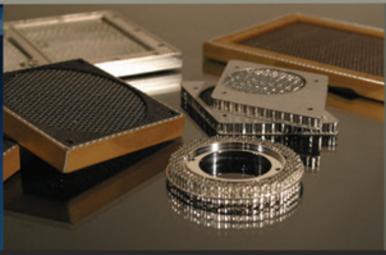

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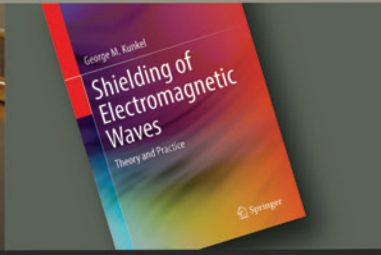

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