OCTOBER 2025

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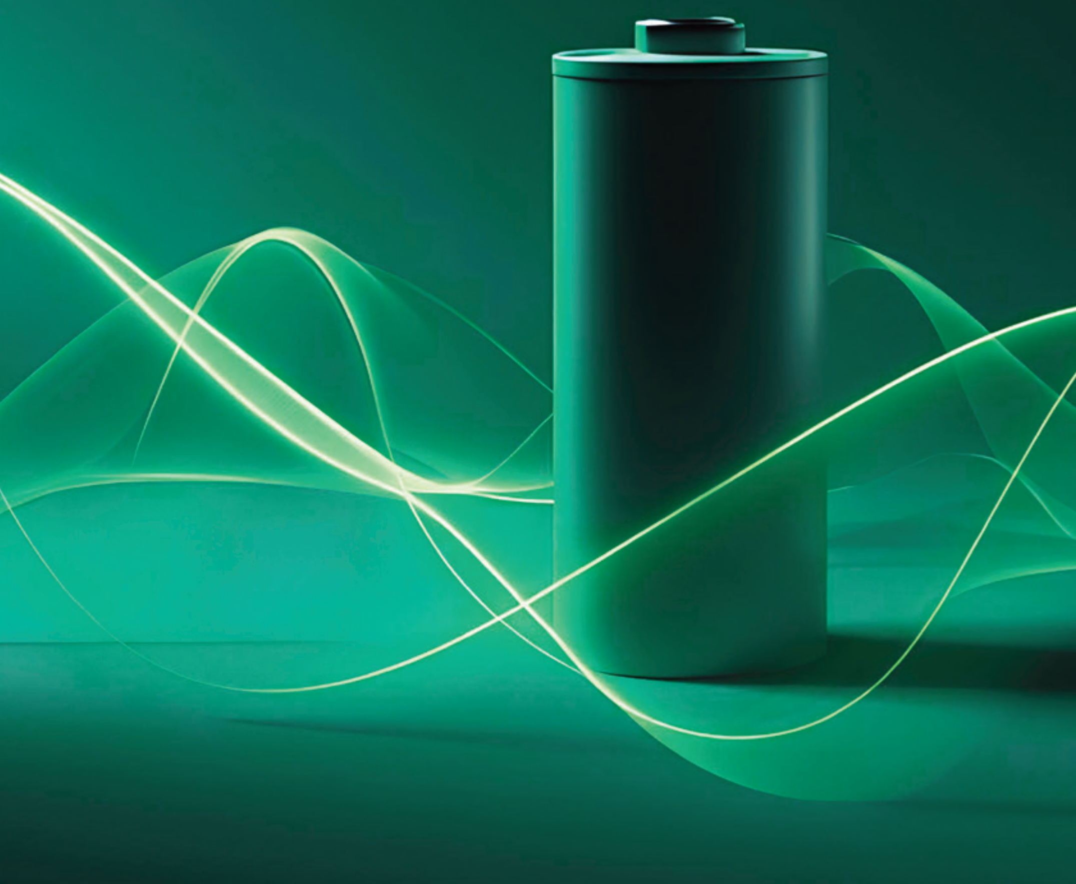
From Nyquist to Now

The Evolving Role of Electrochemical Impedance Spectroscopy



INCLUDING

Automotive EMC Testing Under Dynamic Driving Conditions

Build Your Own ESD Target

2026 PRODUCT RESOURCE GUIDE

OCTOBER 2025

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FEATURE ARTICLES

SPECIAL COVERAGE

COLUMNS

DEPARTMENTS

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AN EXPERT'S VIEW:
Element Materials Technology

Our featured expert this month takes readers behind the work—decoding complex regulations, uncovering performance insights, and helping shape safer, smarter technologies for what's next.

Navigate Battery Regulations with Confidence

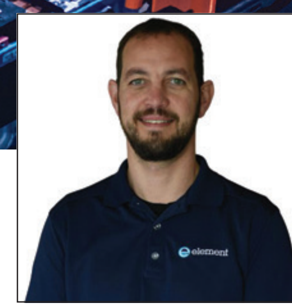
Element is leading the charge in battery testing, ensuring that the latest advancements meet stringent safety and performance standards. With the new Regulatory Battery Regulations always on the horizon, manufacturers face continued compliance challenges – from CE marking requirements, to NRTL, IEC and CB Scheme, to UN/DOT transportation mandates and enhanced safety testing.

Testing That Goes Beyond Standard Certification

At Element, we focus on a variety of stress testing, evaluating how batteries withstand all types of abuse, from extreme environmental conditions, electrical abuse, and mechanical/physical forces encountered in actual use. Complimenting those, our thermal runaway testing helps our clients understand the worst-case scenario and prepare for it. This meticulous approach uncovers discrepancies and provides critical real-world performance insights not found on specification sheets.

Regulatory Expertise, And Then Some

But the thorough battery manufacturer will not stop with just regulatory testing. To go above and beyond to place the best product on the market, or to integrate the best battery into your product, Performance testing to simulate life, charge cycles and overall quality of the battery is an equally important



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https://www.element.com/connected-technologies/battery-testing-services

pillar of our battery testing services. Quality reviews include benchmarking cell vendor products by way of conducting charge/discharge cycling, calendar life and aging and are a highly demanded area of our expertise.

And What Can We Learn from the Failures?

Whether it's a failing result of one of our tests in the lab or a product failure in the field, our Failure Analysis experts have the experience and know-how to determine what happened and why. Using state-of-the-art resources from CT Scans, Microscopy and SEM imaging as well our hands-on methods of cell, module and pack teardowns our teams take a multi-pronged approach to cause analysis and deliver to the client the intelligence and evidence to make the best decisions.

Excellence in Every Test

Our commitment to quality and safety drives us to continually evolve our methods, staying ahead of industry trends. As one of our technical experts emphasizes, "Battery testing is not just about meeting standards; it's about exceeding them to deliver products that perform reliably, safely, and efficiently in every situation."

Element remains a forward-thinking leader, pushing the boundaries of battery testing to support the future of technology. Ready to ensure your batteries meet tomorrow's standards? Reach out today.

Element – Your Partner in Battery Testing Excellence

Making tomorrow safer than today

FCC Removes Non-Compliant Carriers from Robocall Database

The U.S. Federal Communications Commission (FCC) is taking steps to reduce the impact of robocalls by delisting operators who have failed to meet the Commission's certification requirements.

Under an Order issued by the FCC, non-compliant voice service providers (185!) have been removed from the Commission's Robocall Mitigation Database (RMD) by the FCC's Enforcement Bureau. The RMD was established by the FCC in 2020 to help promote transparency regarding the compliance of voice service providers with Commission rules intended to reduce illegal robocalls made to consumers.

To remain listed on the FCC's RMD, current and new service providers were required to submit to the Commission by February 2024 their robocall mitigation plans and to update any previously submitted plans to include their commitment to respond within 24 hours to any traceback request given to them.

The service providers who have been delisted from the RMD reportedly failed to provide the required information, even after the Commission extended the deadline to December 31, 2024.

Three MedTech Companies Get FDA Warning Letters

The U.S. Food and Drug Administration (FDA) has reportedly sent warning letters to several medical device manufacturers for violations of its device marketing and good manufacturing practices requirements.

According to a news item posted to the website of the Regulatory Affairs Professional Society (RAPS), the FDA recently sent warning letters to three different medical device companies. In at least one case, a company was cited for promoting the use of its devices to treat medical issues that are outside the scope of the device's authorization.

In other cases, the companies were cited for their failure to implement current good manufacturing practices (CGMP) in connection with some of their products.

The companies reportedly cited by the FDA include Mectronic Medicale, a manufacturer of devices used to heat tissue to alleviate pain and muscle spasms, Visgeneer, which develops blood glucose monitoring systems, and Oasis Medical, a California-based drug company.

FDA Affirms Safety of Certain PFAS in Some Medical Devices

The U.S. Food and Drug Administration (FDA) has released data that it says affirms the safety of certain per- and polyfluoroalkyl substances (PFAS) used in medical devices.

In a recent update to its webpage "PFAS in Medical Devices," the FDA reports the findings of a 2021 review of the safety of fluoropolymers used in medical devices, conducted in partnership with ECRI, a Department of Health and Human Services-designated Patient Safety Organization. The joint study reportedly collected data from over 1800 health care provider organizations around the country and also reviewed over 1750 published and peer-reviewed scientific articles.

According to the FDA, the review found "no conclusive evidence of patient health issues" in connection with the use of the PFAS polytetrafluoroethylene (PFTE) as a material.

In further support of its findings, the FDA notes that many fluoropolymers are comprised of molecules that are too large to cross through cell membranes and…"are very unlikely to cause toxicity to patients." Further, the agency says fluoropolymers have "unique properties" that are essential to device functionality, and that "no other materials (currently) exist that can perform the critical roles of fluoropolymers in these devices."

Amateur Radio Operators Prepared for Hurricane Season

With the Atlantic hurricane season under way, all of us are reminded of the dangers of hurricanes and the need to prepare for the worst proactively.

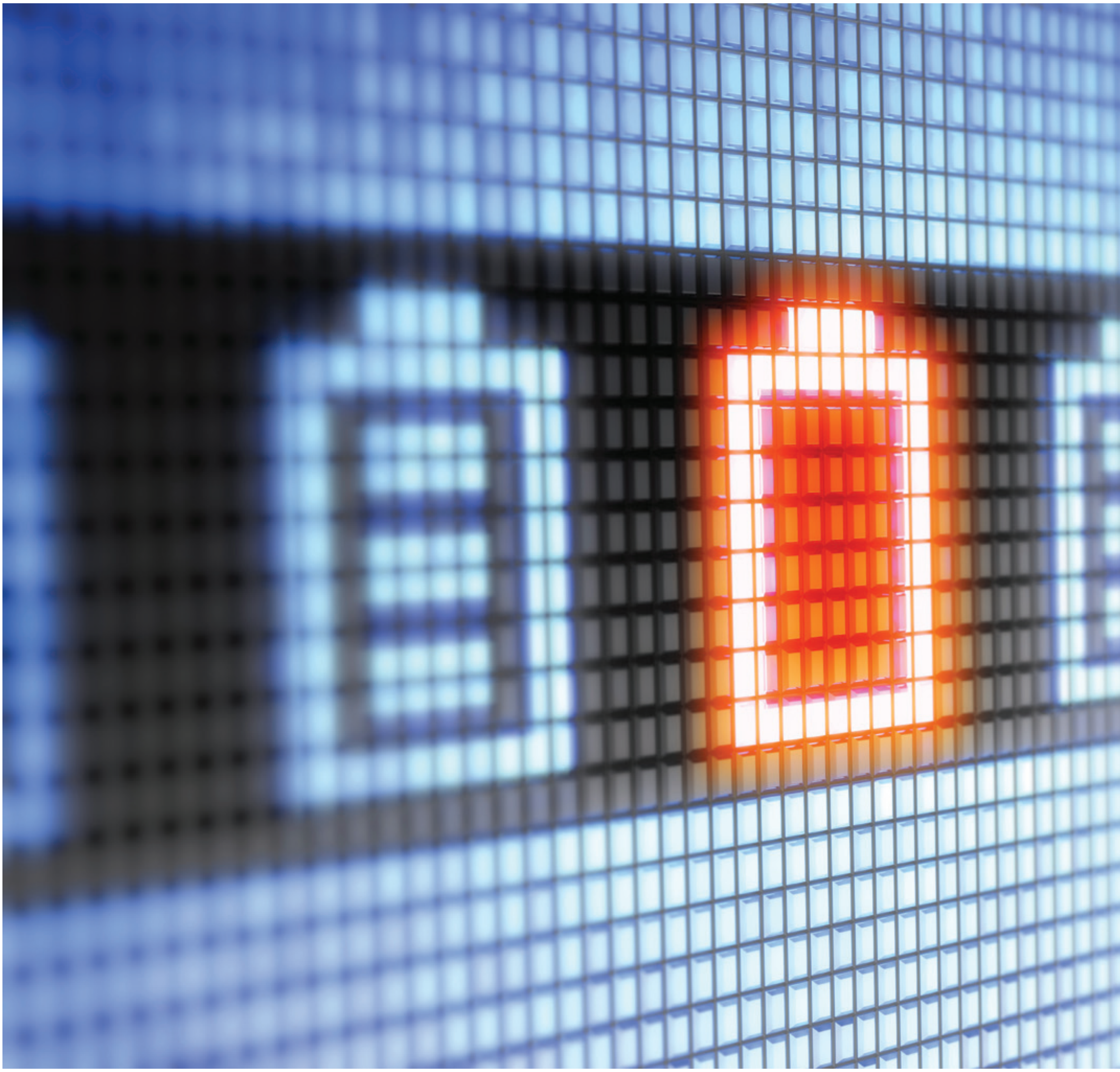
Of course, amateur radio operators have always been at the forefront of efforts to help maintain essential communications during hurricanes and other natural disasters. And after Hurricane Erin, Josh Johnson, the ARRL's Director of Emergency Management, reminded amateur radio operators to evaluate their options and make plans for how they can best support ongoing communications during hurricanes to come.

"These early storms remind us that now is the right time for amateur radio operators to begin thinking about how they can help, if and when these storms begin to ramp up and cause damage," says Johnston in an article posted to the ARRL website. "We know that conventional communications can fail, and amateur radio will be there to fill the gap."

Johnston's advice to amateur radio operators is to check their equipment now, including radios, antennas, and power supplies, and also to confirm the local emergency frequencies to be used during communications outages. In addition, the ARRL posts weekly updates on the National Hurricane Center's VoIP Hurricane Prep Net to provide operators with situational updates.

FROM NYQUIST TO NOW:
THE EVOLVING ROLE OF ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS)

Enhanced Battery Test Insights with Electrochemical Impedance Spectroscopy



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By Christian Loew and Bob Zollo

Battery cells constantly change in form factor, capacity, chemistry, and application. And new types enter the market daily. However, all this traction is not changing one thing: the need for battery cells to be tested to ensure safety, performance, quality, and reliability.

Once a battery has passed its early development stages with an open structure, it becomes a closed one, limiting the possibilities of examining the different layers and components in a non-disruptive way. This makes it harder to gain insight into the battery. But different tests can help to get a deeper understanding of the battery's structure and behavior without destroying it.

In this overview, we will cover one powerful method, electrochemical impedance spectroscopy (EIS).

THE THEORY BEHIND EIS AND HOW THE DATA CAN BE UTILIZED

An EIS instrument works by applying a sinusoidal AC current to the cell and then measuring the AC voltage response of the cell. The ratio of voltage to current is resistance R, if measured at DC. However, when an AC current is applied, this measurement is impedance Z, consisting of the real part R and an imaginary part X. The AC current is swept (often over a wide range of frequencies, such as 0.1 Hz to 10 kHz), and the voltage response is measured at each frequency in the sweep.

Sometimes, a more efficient method is employed that just checks voltage at a few specific frequencies, which simplifies the EIS instrument, lowering its cost and speeding up the time it takes to perform the EIS measurement sweep. Another variation on EIS is to apply a current pulse and use mathematics, such as a fast Fourier transform (FFT), to extract the frequency content of the response of the cell.

However, regardless of which EIS stimulus scheme is used, the fundamental concept is the same: apply a range of frequencies of current to the cell and measure its voltage response at each frequency.

Once the stimulus is applied and the response captured, a chart known as a Nyquist plot is generated by plotting the real impedance on the horizontal axis and the inverse of the imaginary impedance on the vertical axis (see the upper portion of Figure 1 on page 10). The software that controls the EIS will generate the Nyquist plot from the raw sweep data. The Nyquist plot is a common way to represent the electrochemical impedance.

The physical processes are distributed at different frequencies:

- Inductance of wires and cell structure (at high frequencies);
- Double-layer charging at mid frequencies (100 Hz) is followed by the resistive charge-transfer process at lower frequencies (1-100 Hz); and
- At low frequencies (<1 Hz), the materials diffusion processes at the electrode are observed.

The EIS data and the Nyquist plot can be further manipulated using equivalent circuit modeling to extract an electrical equivalent circuit model (ECM) of the cell (see the lower portion of Figure 1. This ECM will show specific features in the cell, such as the cell's internal resistance.

NYQUIST VS. BODE PLOT

Spectra, in general, can be plotted in different ways. The most common one is the Bode plot for frequency response analysis, such as the attenuation or gain.

A Bode plot is normally not only one plot but two separate plots, a magnitude plot and a phase plot. The magnitude plot uses a logarithmic scale on the x-axis for the frequency, and the y-axis contains the magnitude or attenuation. The phase plot uses a logarithmic scale as well for the frequency, but plots the phase over it.

Bode plots are very powerful for systems with filter characteristics. The way the plot is generated, changing behavior at frequencies can be detected and verified easily. This is why Bode plots are the most common for identifying the bandwidth of an amplifier or the cut-off frequency of a filter.

A Nyquist plot is generated differently, as there is no direct labeling or frequency scale in the plot. There is only one plot where the x-axis refers to the real part and the y-axis to the inverted imaginary part. Each point in the plot is one frequency, and, in regular cases, lower frequencies appear on the right side while higher frequencies appear on the left side.

Plotting the impedance measurements generated during an EIS measurement in a Nyquist plot provides several benefits: Visual detection of processes, easy model fitting, noise tolerance, and simplicity. The Nyquist plot also makes it easier to detect chemical processes in the battery. For example, a charge transfer is indicated by a semicircle, and a 45° line represents diffusion (both can be seen in Figure 1).

As these processes can be easily separated visually in the plot, they could also be used to fit equivalent components to it as part of an ECM. For example, the logarithmic scale of a Bode plot could amplify

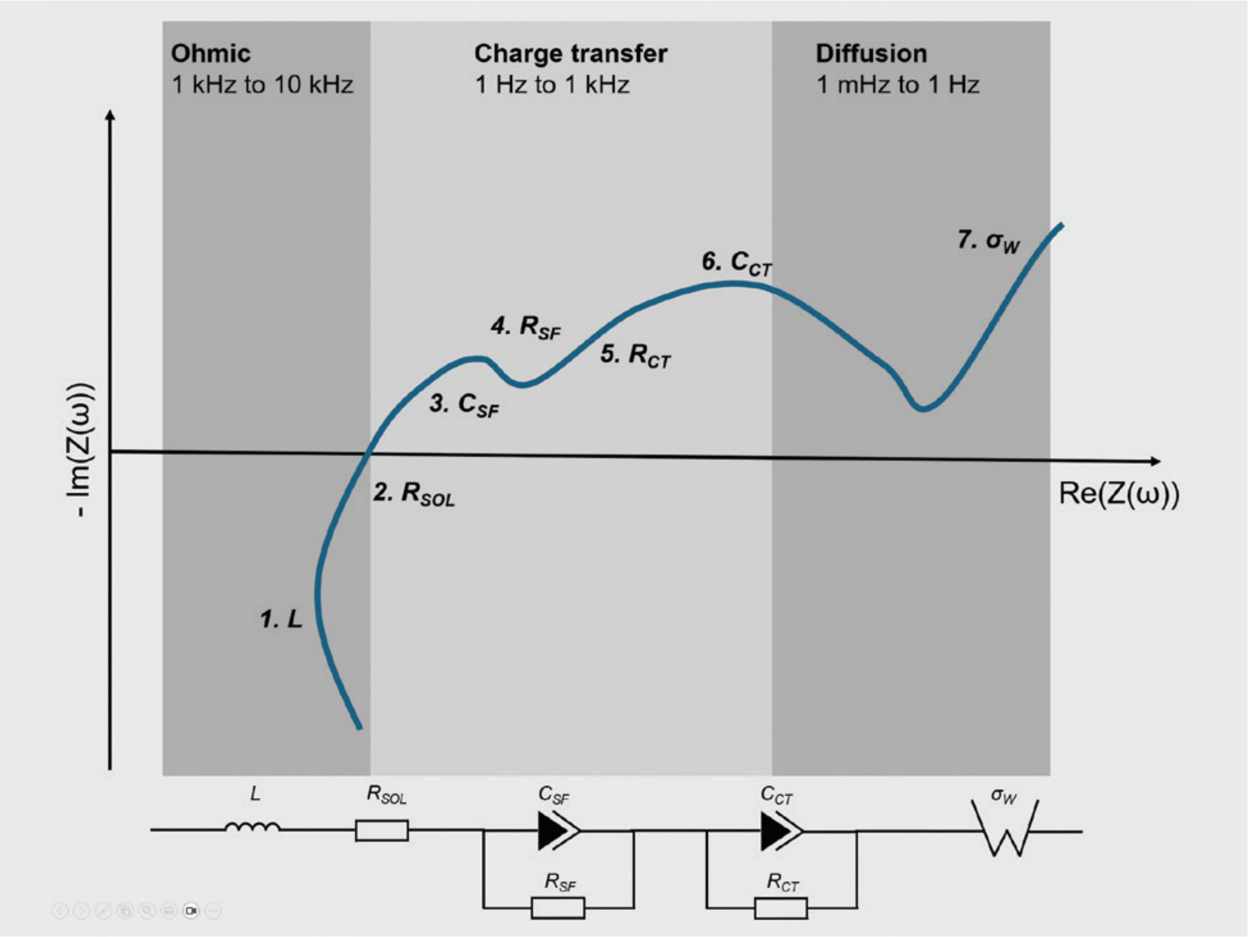


Figure 1: Shown is a Nyquist plot for a cell (top) and equivalent circuit model generated from that Nyquist plot (bottom)

noise, especially in lower frequencies. This does not happen with a Nyquist plot, where the frequency is not labeled and only one plot is needed to present the measured value.

IMPEDANCE VS. RESISTANCE

Resistance and impedance are related and depend on each other, but are not interchangeable. Resistance is the fundamental characteristic, identifying how much a material opposes the current flow at a voltage/potential. Ohm's Law is the representation of this:

$$R = \frac{V}{I}$$

Resistance is a scalar quantity and measured in ohms (Ω). The limitations of the resistance are in its static nature. A battery is a complex, dynamic system with different dependencies.

The impedance Z could be seen as the extension of the resistance. It contains a resistive part R and, in addition, either a capacitive or inductive part X. As it is an advanced construct, a scalar representation is not possible. Mathematically, a vector or complex number is used. The resistive part is represented by the real portion, and the imaginary part represents the capacitive or inductive portion. The imaginary part contains a frequency dependence.

$$X_C = -\frac{j}{\omega C}$$

$$X_L = j\omega L$$

$$Z = R + X$$

As described earlier in this article, electrochemical impedance spectroscopy measures at various frequencies in a sweep. The test performed with a sinusoidal stimulus provides back an impedance with

EIS is a classic test performed in a laboratory, but there are differences in the way the test can be performed and what equipment is used. One way is to use a dedicated EIS instrument in a dedicated environment. Another option is to use a battery test system with high dynamics.

real and imaginary parts at the given frequency. Resistance measurements are normally performed with a constant current stimulus or, for batteries, mainly as pulses. The voltage response is measured, and based on the known stimulus and the measurement, the resistance can be evaluated via Ohm's law.

Resistance and impedance have their use case for battery characterization and to rate the performance, quality, and health, but serve different purposes. Resistance refers mainly to the internal resistance of a battery. This could be used as an indicator of health and age within a known battery family: same chemistry, capacity, type. But the resistance is not selective. It is one value for the given state of charge (SoC) and includes all subparts in the battery.

As described earlier, the impedance is more selective. Depending on the frequency and shape of the responses in the Nyquist plot, it could be used to identify which part of the battery is behaving in which way.

EIS IN THE TEST LAB AND BEYOND

EIS is a classic test performed in a laboratory, but there are differences in the way the test can be performed and what equipment is used.

One way is to use a dedicated EIS instrument in a dedicated environment. This allows the most in-depth test and analysis, but it is usually limited to a single channel. As it is a direct connection between the test instrument and the device under test, the whole signal chain can be optimized to allow the test to operate at higher frequencies.

In this aspect lies the greatest challenge and source of noise for EIS. The higher the stimulus frequency goes, the greater are the influences of the signal chain, consisting of cables, contactors, and fixtures. The test procedure is reaching into areas where RF effects become more relevant. With a single channel and direct connection, cable shielding, stiffness, connector optimization, and selection can be considered and adjusted to the bandwidth that should be achieved. This allows a high upper frequency limit but limits flexibility.

Another option is to use a battery test system with high dynamics. This allows performing EIS measurements during an extended test, including an aging test, a capacity test, or a performance test. While the bandwidth could not compete with a standalone system, its benefits are in the usability. No rewiring is needed, all available channels can be used, and the data is available in the same environment as the rest of the battery test results.

This is possible in cases where the battery test system is able to generate sinusoidal signals and can read back the responses accurately. Limitations here are primarily caused by the bandwidth limits of the power electronics in the battery test systems, which are not optimized for signal generation, and the cable, or, more precisely, the signal chain. A frequency up to 10 kHz can be achieved. This already provides deeper insight into the battery's performance, which can be achieved without rewiring and external equipment. This is boosting efficiency in a high-scale lab with higher numbers of test channels and DUTs tested in parallel.

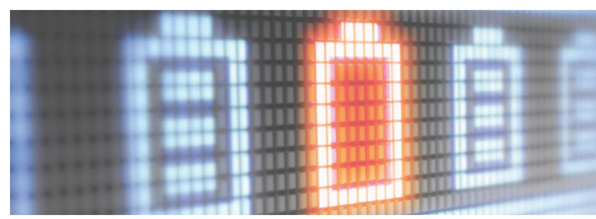
Despite the usefulness of EIS in test laboratories, battery management systems (BMS) are more recently being developed that utilize the measurement type. The idea is to use EIS to better determine the state of health (SoH) of individual cells in a battery pack or to detect defects and issues faster and with higher precision. This is a new approach that could help in the future, not only to determine the health and status of a battery during its regular operation, but also for second-life applications. With direct EIS measurement

EIS can be used to learn a great deal about the processes inside the cell (like charge transfer and double-layer charging). It can be manipulated via ECM software to create an equivalent circuit that describes specific elements inside the cell.

capability, age and remaining longevity can be determined more easily. This could help to achieve a grading faster and more precisely, rating the batteries for further use with higher reliability and precision.

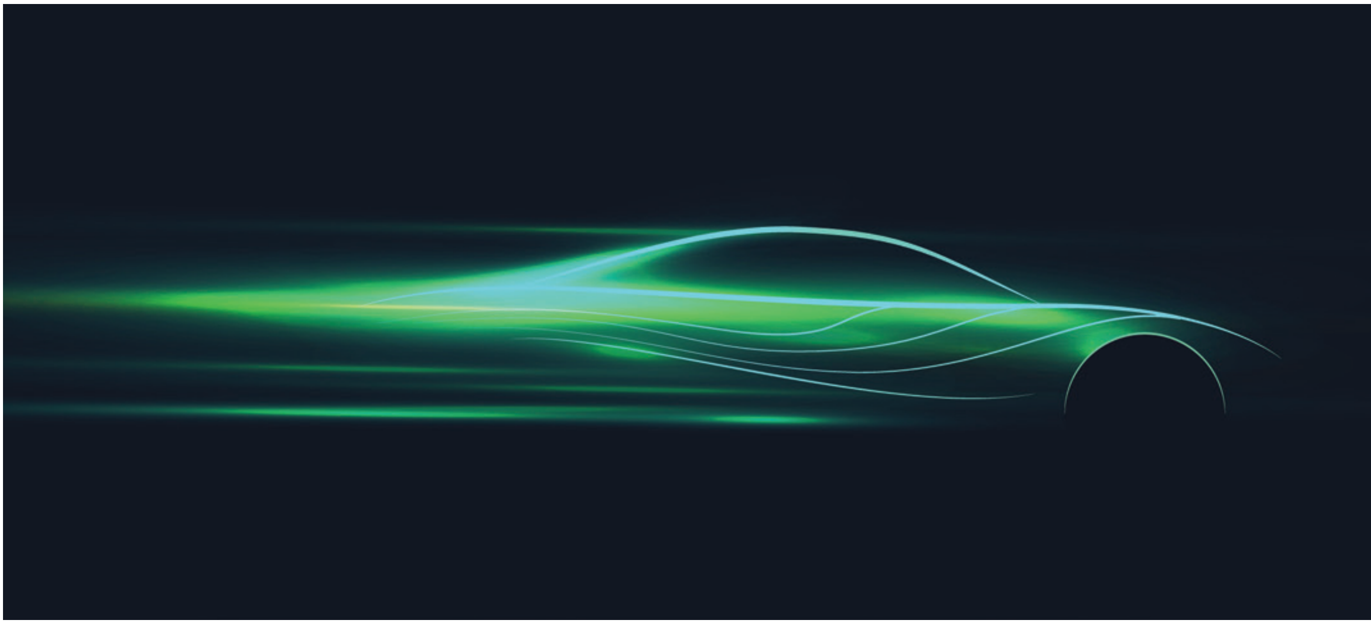
WHAT TO REMEMBER

EIS can be used to learn a great deal about the processes inside the cell (like charge transfer and double-layer charging). It can be manipulated via ECM software to create an equivalent circuit that describes specific elements inside the cell. Using EIS can also help us understand the aging process more efficiently and more holistically. It allows detecting aging influences early on and provides a better prediction of the battery's final performance.



AUTOMOTIVE EMC TESTING UNDER DYNAMIC DRIVING CONDITIONS

Beyond Static Testing: Integrated Approaches for EV EMC Validation



The shift from internal combustion engine (ICE) automobiles to electric vehicles (EVs) has come with an array of new subsystems and components that introduce new EMC considerations. The level of complexity involved in automotive electromagnetic compatibility (EMC) testing increases with dynamic driving conditions, where manufacturers not only have to refer to the framework standards offered but must also improvise and establish new internal standards to ensure the vehicle and its internal components all function properly under all driving conditions. A number of challenges may arise when building a suitable test bench that thoroughly tests EVs and electrical components.

This article discusses the importance of EMC testing in the automotive industry, as well as dynamic EMC test systems and their inherent challenges. It also describes the development of a unified EMC test platform for dynamic driving conditions.

THE EMI INFLUENCE OF THE E-DRIVE

As electromobility rapidly evolves, a growing number of OEMs are adding battery EVs (BEVs) with an electrified powertrain to their product offerings. The electric powertrain consists of two main components:

- High-voltage battery system
- E-drive (inverter + electric motor)

Both systems directly contribute to electromagnetic interference (EMI). E-drives are generally composed of one to two electric motors and a high switching frequency inverter to control the electric motors (see Figure 1). They are often permanent magnet machines (PMM), where high-performance PMMs offer up to 500 Nm of torque and 35,000 rpm. Such performance is challenging to test on test benches limited to an enclosed space.

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By Reiner Goetz

The most critical component in terms of EMC is the inverter. These operate on high battery voltages and use rapid switching frequencies to enhance controls, power output, and efficiency. The fast switching of high currents from a few kHz to well above 10 kHz and the fast switching of high voltages with steep gradients causes unwanted EMI. This problem will worsen as more and more GaN inverters are introduced, as their RF output is anticipated to reach up to ten times the value of traditional Insulated-Gate Bipolar Transistors (IGBTs).

The EMI problem worsens with the integration of more sensors and communications technology (e.g.,Bluetooth®, Wi-Fi, LTE) that may be easily disturbed by the EMI from the E-drive. Sensitive radar, LiDAR sensors, and cameras that are integrated into Advanced Driver-Assistance System (ADAS) systems will be affected by excessive EMI. This is an unacceptable risk in safety-critical systems such as brake assistance and cruise control, making EMC testing a top priority for OEMs.

A LOOK AT AUTOMOTIVE EMC TESTING

EMC Testing: Overview

As shown in Figure 2, EMC testing can be broken down into EMI and electromagnetic susceptibility (EMS). EMI can be defined as the unintentional emissions from the equipment under test (EUT), while EMS measures how much disturbance is possible before the EUT stops working.

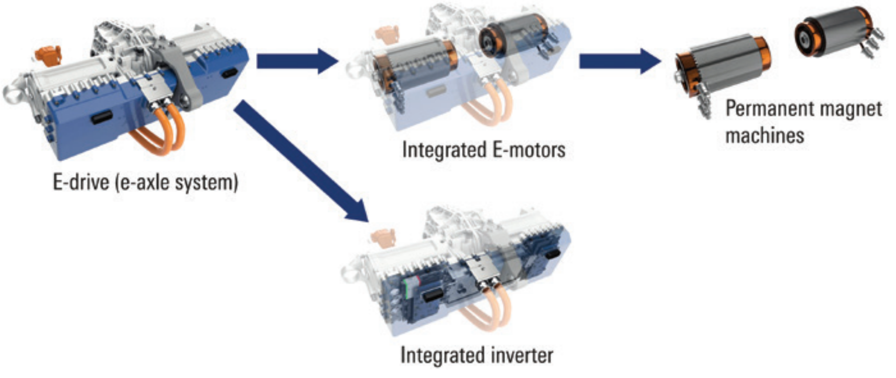


Figure 1: Subsystems within an electrified propulsion system © 2023 AVL List

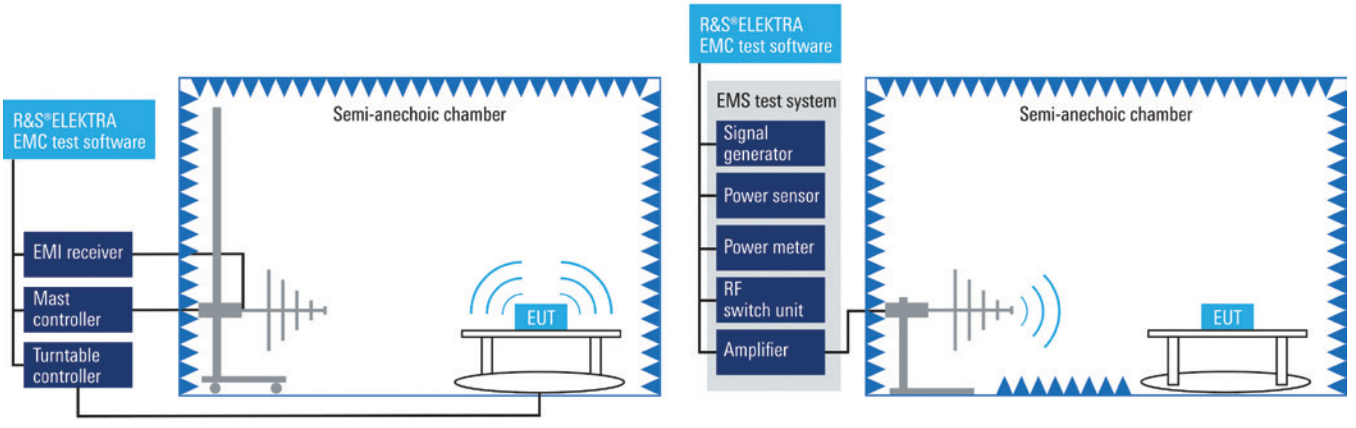


Figure 2: Radiation emissions test setup (top) and radiated susceptibility test setup (bottom)

Figure 3: Full compliance test systems for powertrain components from hybrid vehicles and EV (left) and a full compliance test system for ICE vehicles, hybrids, BEVs and FCEV

It is vital to begin EMC testing at an early stage of development, as modifying components in an already developed vehicle will be costly and time-consuming. Figure 3 shows EMC test benches for component testing and vehicle testing. Test benches have grown in complexity. For example, e-axle tests might involve an environmental chamber or a thermal condition system to simulate environmental conditions, as well as two oppositely mounted load machines (motors) that connect to the output shafts of the e-axle. This simulates the vehicle at various speeds and road gradients in different driving conditions.

The Challenge of Testing at Typical Operating Conditions

The critical challenge for EMC measurements lies in the car mimicking real driving conditions as closely as possible. It is not enough to have a vehicle idling or completely motionless, as it would be difficult to characterize the system's electromagnetic noise

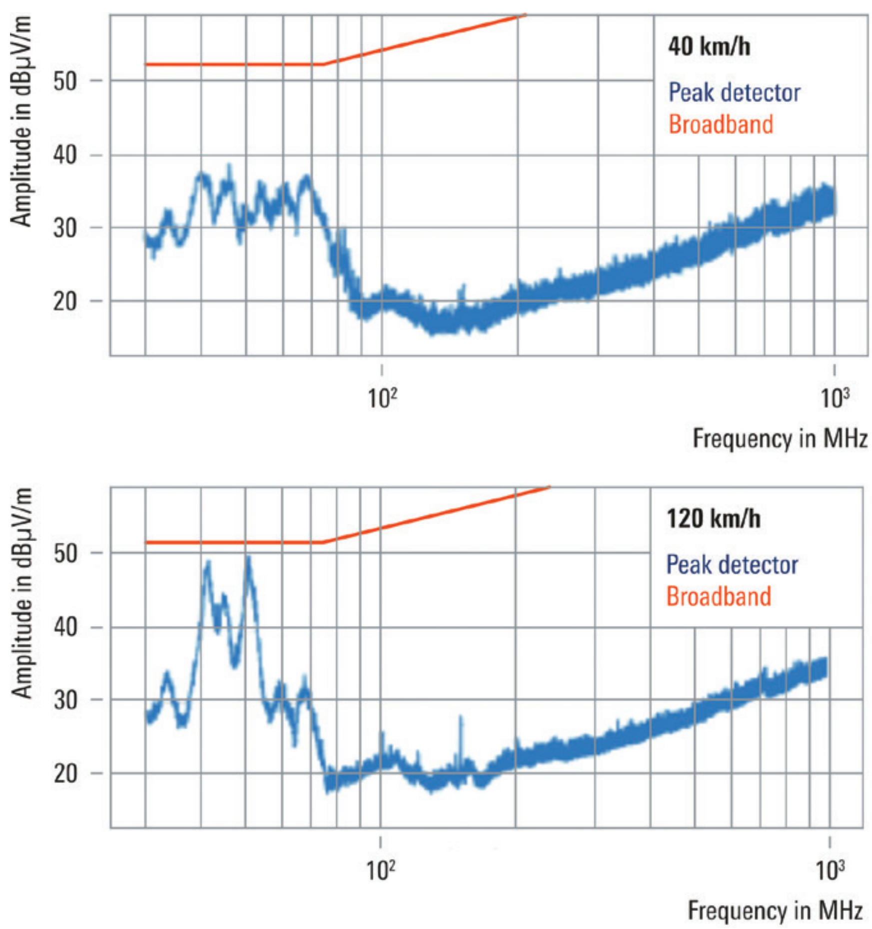


Figure 4: Emissions tests for the same vehicle running at 40 km/h (top) and 120 km/h (bottom), showing very different results

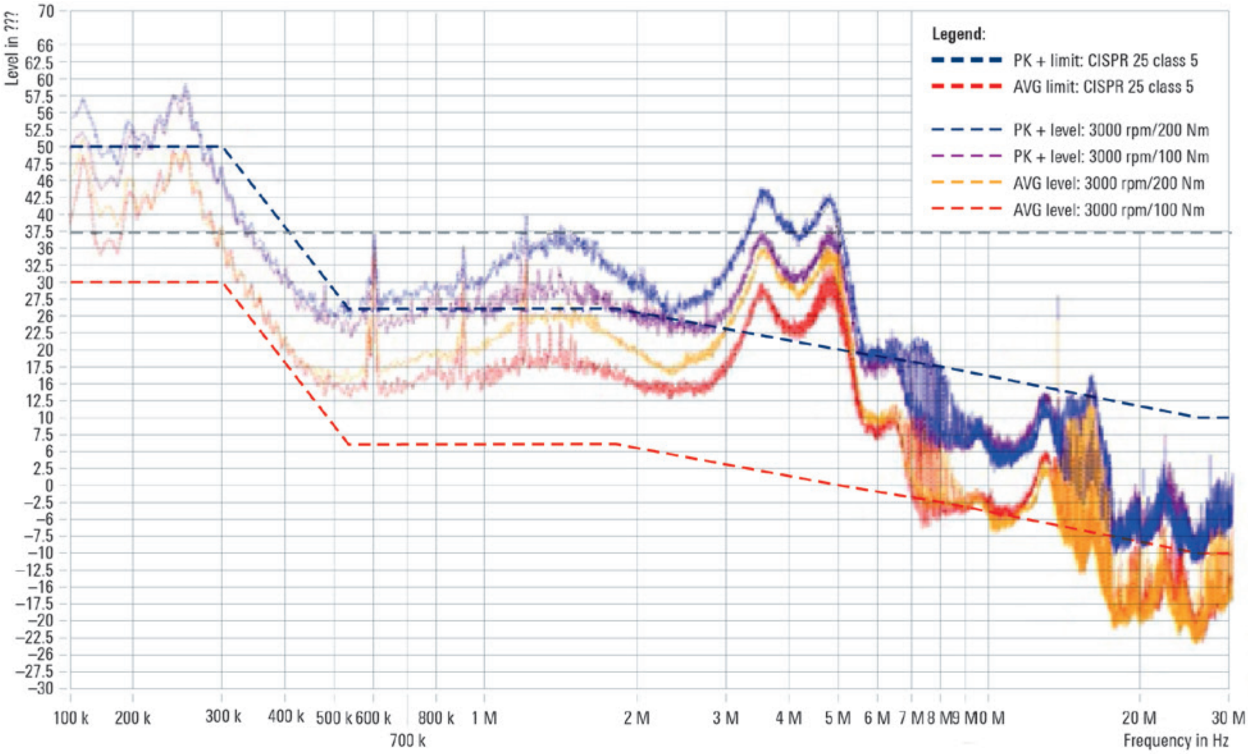


Figure 5: EMC measurements on HV line with current probe at 100 Nm and 200 Nm torque levels with CISPR peak (Pk+) and CISPR average (AVG) detectors

properly. Standards create rough guidelines for testing EVs, so even when adhering to these requirements, the product still may not perform as anticipated.

As an example, the CISPR12 standard requires EVs to be tested while at a constant speed of 40 km/h. However, emissions are quite different at varying speeds (Figure 4). When the vehicle runs at a speed of 120 km/h, emissions nearly reach the CISPR12 standard limits. This problem becomes even more pronounced under dynamic vehicle conditions such as vehicle acceleration or speed reduction and battery charging (recuperation).

The Challenge of Testing Under Dynamic Speed and Recuperation

Figure 5 shows the load change effect on the high voltage (HV) line. There are higher broadband interference emissions when the car is accelerated or decelerated that go well above the limit of the CISPR25 Class 5 standard.

(Note: The measurements were performed in a precompliance environment. The background level interference emissions are higher than demanded by the standards.)

Setting these dynamic speed (rpm) and torque (Nm) conditions on an EUT has grown in complexity. In the past, it was possible to run EMC test software on a vehicle that was simply running at a constant speed. However, this is not sufficient for accurately characterizing a vehicle's emissions. Now, more complex speed profiles or driving cycles (DC) are used for vehicle energy simulation and evaluation with standard profiles such as the worldwide harmonized light vehicle test cycle (WLTC) and new European driving cycle (NEDC) for Europe and 10 mode (J10) for Japan (Figure 6).

However, there are still more operating conditions that must be tested in a specific sequence, including:

- Constant speed
- High speed
- Low speed
- Acceleration
- Deceleration
- High torque
- Low torque

In other words, several parameters (e.g., speed, torque, current, voltage) will change at different times to more effectively simulate real driving conditions in various environments (e.g., rural, city, highway, mountain, cold, hot). The main test challenge lies in synchronizing the measurement flow (all the parameter values) between the EMC measurement

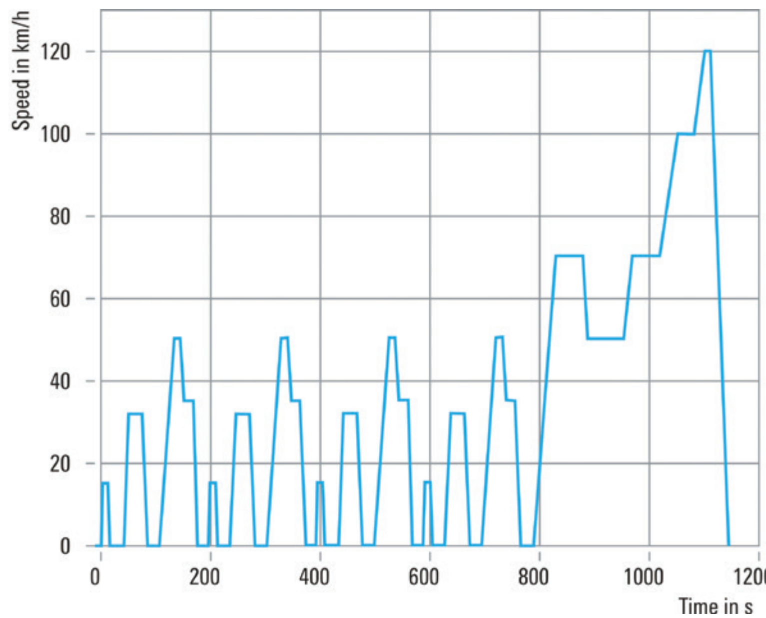


Figure 6: The urban driving cycle speed profile under the NEDC

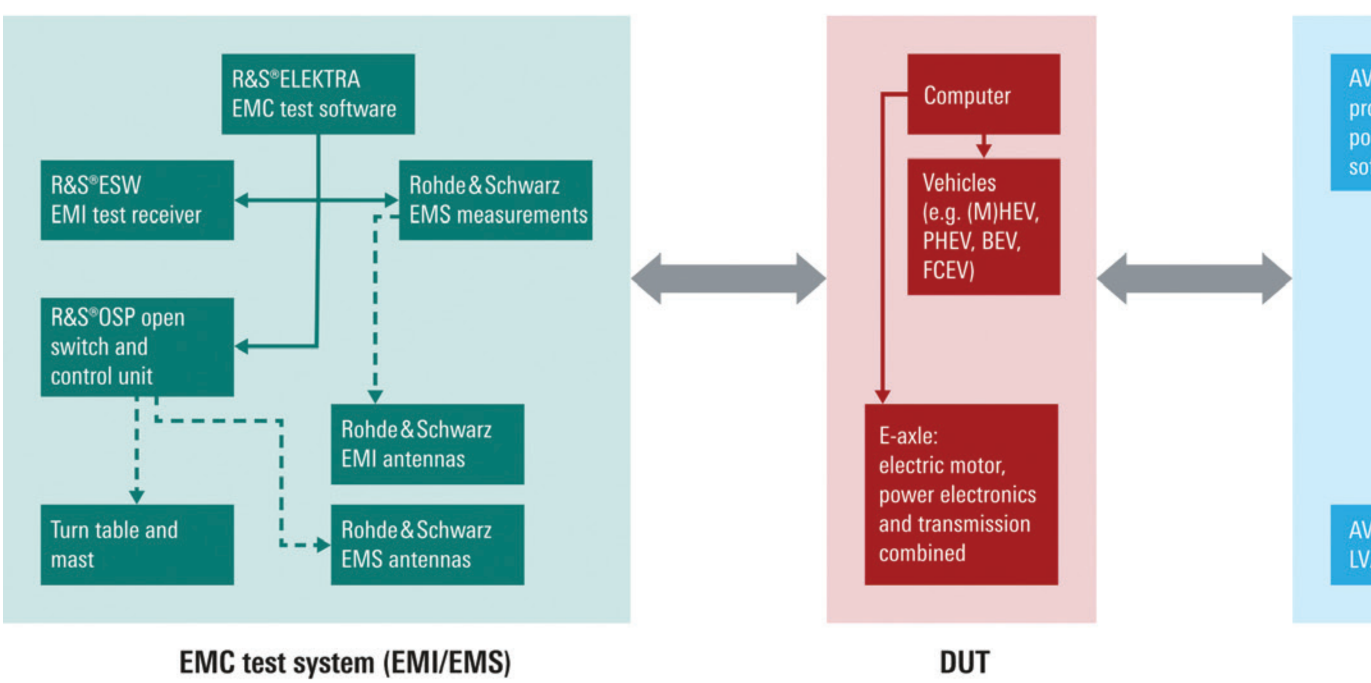


Figure 7: An overview of the complete test solution for EMC testing under dynamic driving conditions

software and the test bench. Since there is now more functionality integrated into the test bench itself, the synchronization becomes more difficult.

Finding worst-case issues with the EUT by varying parameters such as torque and speed, for example, requires more advanced communications between the EMC automation software and the test bench that simulates the road and driving conditions.

THE LANDSCAPE OF EMC STANDARDS

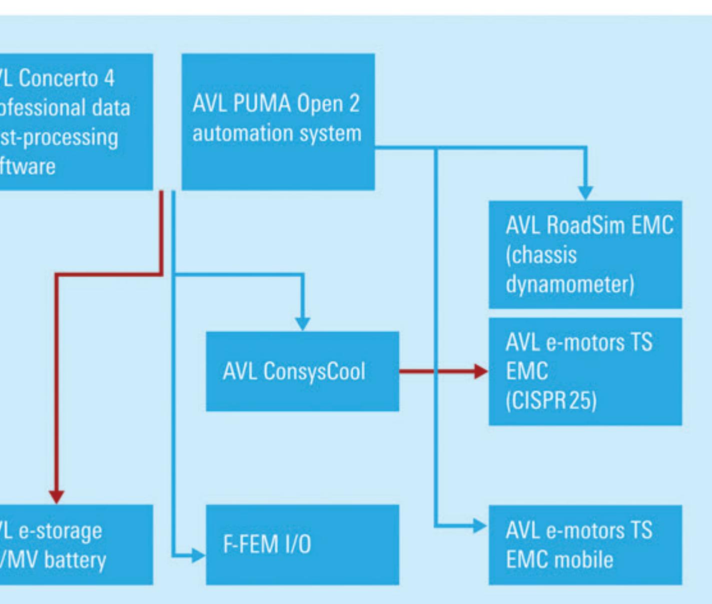
There are many EMC standards available for vehicle testing, including ISO 11451 series for full vehicle EMS and ISO 11452 series for subassembly EMS testing. The CISPR series is often referred to for emissions with off/onboard receivers and wireless power transfers. Additionally, there are regional standards such as the GB, Chinese standards. Certain EMC standards reference all of the more general standards but add details or apply modifications. The UN ECE R10 standard for EMC homologation/approval of vehicles, for example, is more or less globally applicable and a minimum OEM requirement.

On top of this, OEMs add their own EMC testing standards and requirements. While some may change a few parameters to modify the testing to their own specific needs, most will raise the bar of the general standards even higher. Existing EMC standards may not be sufficient to ensure their products work properly. Establishing international standards is often a long, drawn-out process that involves studies, multiple proposals, and alignment between different parties.

A NEW APPROACH TO DYNAMIC AUTOMOTIVE TESTING

A Look at an Automotive Test Solution

Figure 7 shows the automotive test solution for EMC testing under dynamic conditions that our technical experts have developed in partnership with AVL, a mobility technology company. At the center of this approach is the device under test (DUT) or EUT that can be an e-axle, an electric motor, or even an entire vehicle. On the left is the complete EMC test system



Test bench or chassis dynamometer

Practical implementation of synchronized dynamic EMC testing involves several key capabilities. The system must be able to automatically cycle through various operating conditions (speed, torque, load) while continuously monitoring EMC parameters across the frequency spectrum.

that includes automation software, an EMI receiver, a generator, an amplifier, antennas, and a turntable. On the right is the complete test bench that will vary depending on the EUT. It includes test bench control software, a battery simulator, a chassis dynamometer, motor control, an environmental chamber, etc.

TEST SYSTEM SYNCHRONIZATION

In the past, users would need to use the software for the EMC test system and test bench separately, but in parallel, to perform any testing. This task becomes much more complicated under dynamic conditions with varying sequences of torque, speed, etc. The integrated approach ensures that users operate only one software package while the other is automatically remote-controlled. Figure 8 shows a block diagram with some of the test synchronization.

For measurement synchronization between the EMC measurement test flow and the test bench/DUT control, the test bench state, DUT state, DUT properties, EMC test parameters and EMC test system state are communicated constantly and analyzed for progress in real time. For example, EMC test parameters such as the test level, modulation, and critical frequencies represent necessary information to transmit to the test bench software. Measurement results, graphics, tables, and reports can also be transferred from one software package to the other. But, for this to happen, many interfaces are necessary, as well as a database in both software packages.

IMPLEMENTING DYNAMIC EMC TESTING

Practical implementation of synchronized dynamic EMC testing involves several key capabilities. The system must be able to automatically cycle through various operating conditions (speed, torque, load) while continuously monitoring EMC parameters across the frequency spectrum. During testing, the system identifies critical frequencies where

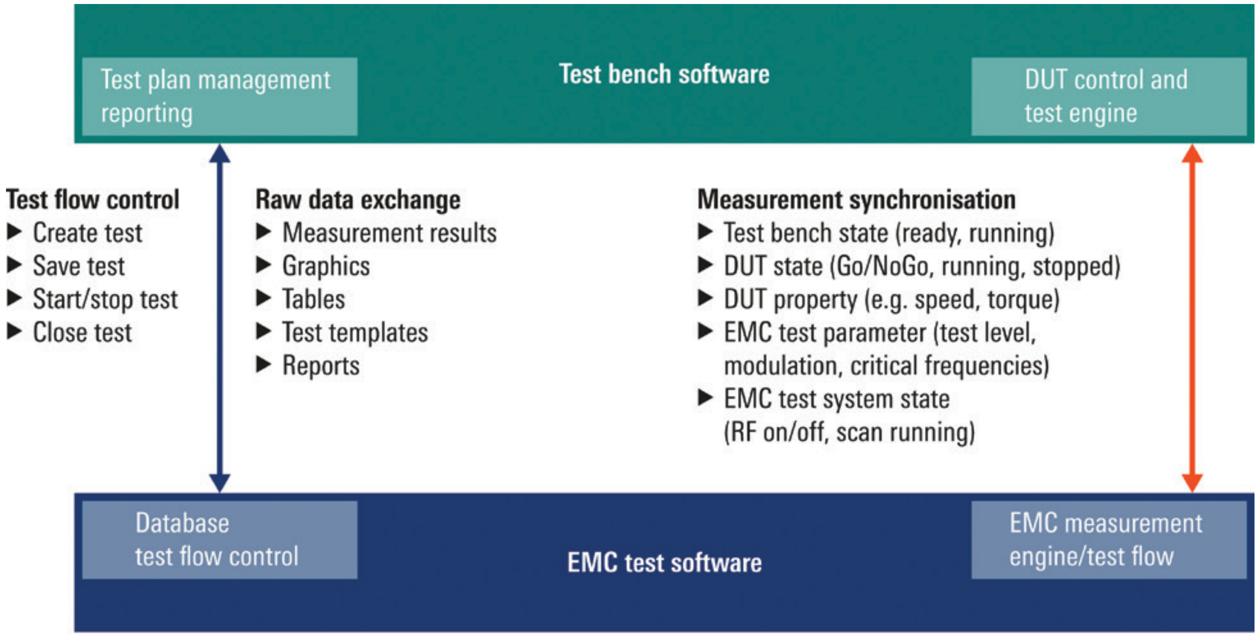


Figure 8: Test synchronization between the test bench software and the EMC test software

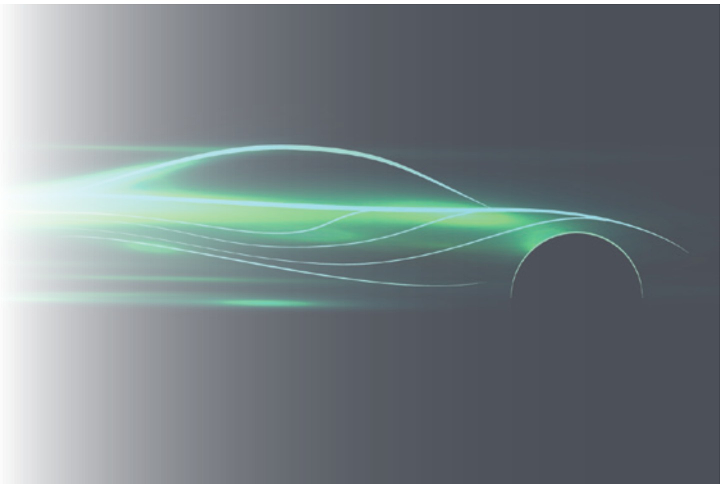
emissions peak under specific operating conditions, then automatically returns to those exact operating points for detailed analysis. This approach reveals problematic frequencies that might be missed in static testing and provides the precise operating conditions where compliance issues occur. For EMC testing, the system can evaluate device performance with and without applied loads at each test frequency, providing a complete picture of how dynamic conditions affect EMC performance.

SUMMARY

From high-voltage battery packs and high-performance E-drives to advanced in-vehicle functions and communications technologies, vehicles are growing in complexity. This added complexity is creating new EMC challenges where current EMC standards do not yet cover the issues affecting newer systems/vehicles, such as EVs and ADAS functions. EMC has the greater challenge of testing under dynamic, or more realistic, driving conditions to characterize an EUT's EMI and EMS accurately.

This is a challenge that often involves users manually controlling the test bench software and EMC measurement system, with little to no collaboration between the two systems. The combined approach presented in this article provides full testing coverage in one integrated system, where one software package can remotely and automatically control the other. This eases EMC testing – particularly dynamic automotive testing – where complex sequences can be easily run.

The combined solution also simplifies testing for OEMs with custom-tailored EMC testing and allows companies to be ahead of the market and easily prepare for new EMC compliance requirements with testing beyond current established standards.



BUILD YOUR OWN ESD TARGET

Building IEC 61000-4-2 Compliant Test Equipment on a Budget

Our internal EMC laboratory had decided to verify (not certify, as it's not an accredited lab) all the equipment we use for pre-compliance EMC tests. The goal was to find some defective equipment and to repair or replace it to avoid the possibility of generating inaccurate test results.

One of the trickiest pieces of equipment to verify was the ESD gun because specialized equipment is needed for the verification test. Off-the-shelf ESD targets are relatively expensive (>1500 USD), so we decided to build a do-it-yourself (DIY) version. (See our final design in Figure 1 and Figure 2.)

DIY ESD TARGET OVERVIEW AND DESIGN CHOICES

After reading through IEC 61000-4-2, Testing and measurement techniques – Electrostatic discharge immunity test, which specifies the type of ESD target to use and its calibration procedure, and reading some articles on the topic, we decided to make the circuit in two separate parts, including a voltage divider and an ESD target.

The requirement for the maximum tested ESD voltage was set at 15 kV. The voltage divider was made by simply placing 100 MΩ and 1 MΩ high voltage resistors in series (HVR3700001004FR500 and HVA12FA50M0). We used two 50 MΩ in series to increase the voltage rating of the resistors we used. A single 50 MΩ resistor withstands a maximum voltage of 8 kV. So, with two in series, our device could withstand a maximum voltage of 16 kV. Three test points were placed so that connections with the ESD gun and multimeter would be easier to make.

Matic Novak is a Senior EMC and Safety Test Engineer at Aviat Networks, based in Slovenia. His work focuses on ensuring that electronic devices operate safely and effectively in their intended environments. Novak can be reached at matic.novak@aviatnet.com.

By Matic Novak

We constructed our ESD target by finding a connector with enough distance between the center pin and the outer pins to fit eight 16.5 Ω 0805 SMD resistors connected in parallel (ERJ-P06F16R5), which defines the <2.1 Ω input impedance at DC, consistent with the IEC 61000-4-2 standard. 2.0625 Ω is the equivalent input impedance of the eight 16.5 Ω selected resistors placed in parallel, which satisfied the criteria in the standard of under 2.1 Ω.

Resistors were chosen as they have the maximum voltage of 400 V. Maximum voltage during the ESD event would be 15 kV (max voltage requirement)/(330 Ω (output impedance of the ESD gun)/2.1 Ω (impedance of the ESD target)) = 96 V. The maximum voltage can reach a slightly higher value (due to a parasitic capacitance in the ESD gun) that is in parallel to the 330 Ω resistor, which allows for higher current. The ESD target resistor's datasheet also specifies resistance to 3 kV ESD pulses.

Our chosen connector has an SMA connector and a distance of 7 mm between the center and outer pins. A similar part with an N-type connector can be chosen for a similar pin distance. Some copper was exposed with plating to more easily connect the grounding clip of the ESD gun.

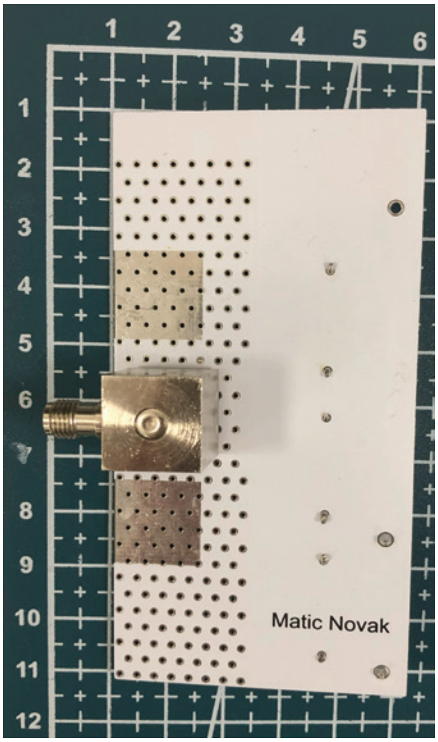


Figure 1: Top side of the DIY ESD target

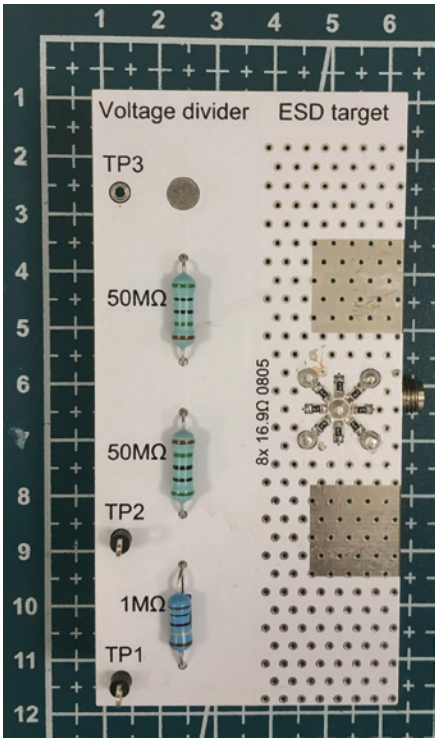


Figure 2: Bottom side of the DIY ESD target

COMPARING DIY ESD TARGET TO THE IEC 61000-4-2 STANDARD (INPUT IMPEDANCE, INSERTION LOSS)

We measured the input impedance using a 1 A current source and a multimeter, resulting in a value of 2.08 Ω. The circuit diagram for this measurement is shown in Figure 3, but this measurement was done only with the target in the measurement chain. Insertion loss is defined in IEC 61000-4-2 as ±0.5 dB up to 1 GHz, and ±1.2 dB from 1 to 4 GHz, with respect to the nominal value S_{21} of the insertion loss, as described in Equation 1.

$$S_{21} = 20log\frac{2Z_{sys}}{(R_{in} + 50\Omega)}dB \qquad \text{Eq 1}$$

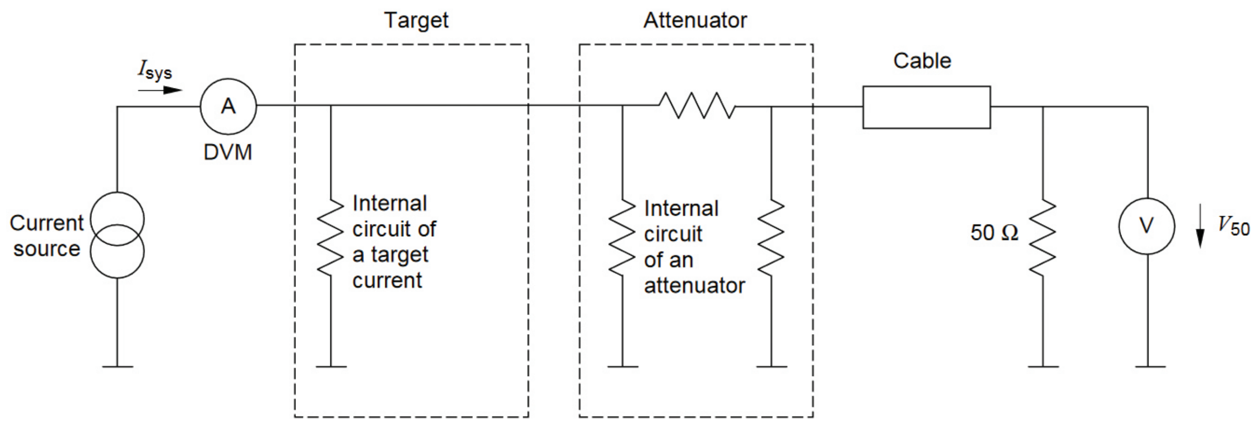


Figure 3: Circuit diagram to determine the low-frequency system transfer impedance (from IEC 61000-4-2)

R_{in} is the DC input impedance of the target-attenuator-cable chain, when loaded with 50 Ω, which was measured as 2.03 Ω. A circuit diagram of the measurement is shown in Figure 3, where the input voltage was divided by $I_{sys,}$ resulting in 2.03 Ω.

Meanwhile, the low-frequency transfer impedance of the same chain, labelled Z_{sys}, was measured at 0.197 Ω. This is also shown in Figure 3, where V_{50} is divided by I_{sys} to obtain this value. S_{21} was then calculated as -42.4 dB with Equation 1.

Insertion loss measurement was performed using a Keysight P5007A VNA. The EUT was the ESD target with a soldered connector, resulting in a back-to-back test sample. RF cable and 20 dB attenuator were in the test chain. (See Figure 4 for the measurement diagram and Figure 5 for test setup photo.) The measurement shown in Figure 6 was just within the 0.5 dB requirement up to 1 GHz.

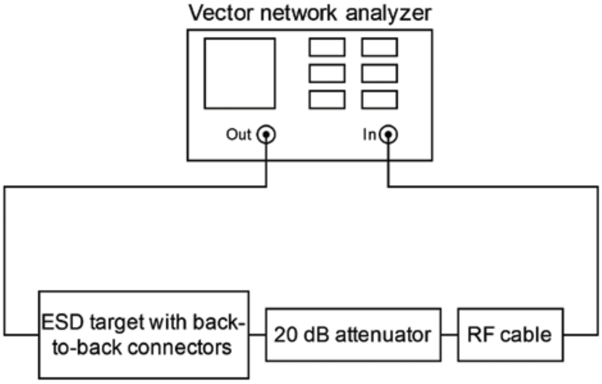


Figure 4: Diagram of the insertion loss measurement

IEC 61000-4-2 also references a vertical calibration plane with the ESD target mounted in the center. This is to prevent radiated pulses from interfering with the oscilloscope, together with a Faraday cage. This was necessary in the past when the analog oscilloscopes were not significantly shielded. But today's digital oscilloscopes should be less sensitive to the radiated pulses of an ESD gun. Our test did not use the vertical calibration plane, but it can be seen as a potential upgrade.

Figure 5: Test setup of the insertion loss measurements

When we tried testing 15 kV contact discharges, the oscilloscope had an error, which was resolved with a reset.

Hence, when using high-voltage discharges and tips with a short rise time, a vertical calibration plane would be beneficial.

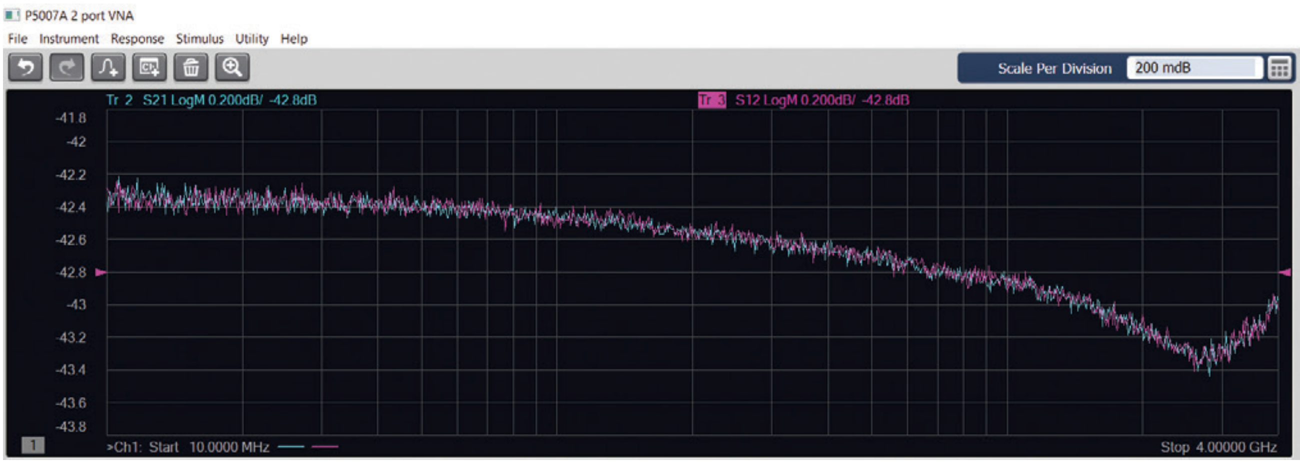


Figure 6: Insertion loss measurement of the ESD target

VERIFYING THE ESD GUN'S VOLTAGE

The ESD gun was grounded at test point 1 and the discharge tip was placed at test point 3. (See Figure 7 for the test setup diagram and Figure 8 for the test setup photo.) The voltage of the ESD gun in this example was set to 1000 V. ESD discharge did not occur, as the resistance was too high to discharge the internal capacitor. A multimeter was set to DC voltage and placed on test point 1 and test point 2 to measure voltage on the 1 MΩ resistor.

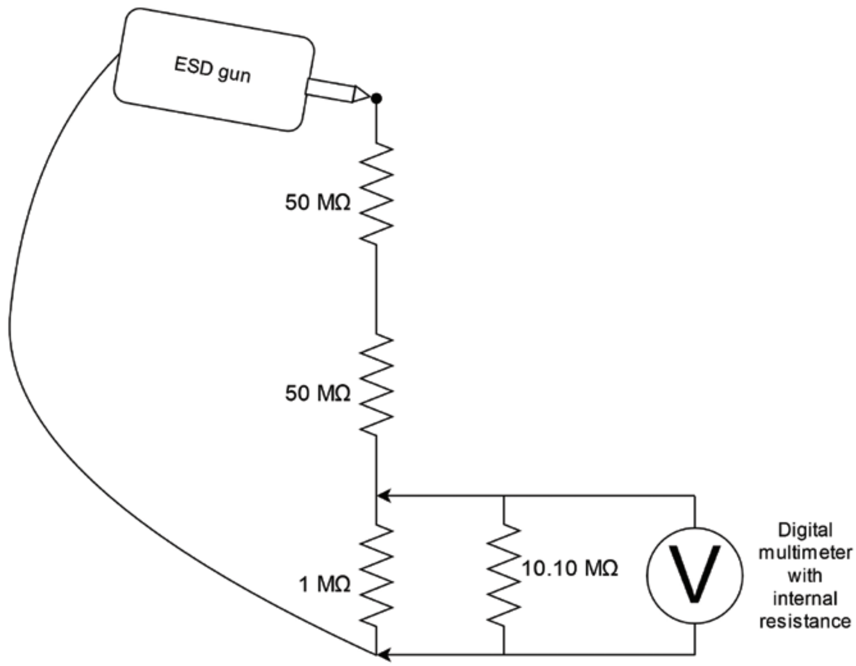


Figure 7: Diagram of the ESD gun's voltage verification

It was important to take into account the internal resistance of the multimeter on the specific voltage range we were measuring. This should be measured with a second multimeter set to resistance mode and the first multimeter should be manually set to the voltage range that will be used during voltage measurement.

The measurement showed an internal resistance of 10.10 MΩ on the 60 V range. We added 9.8% to the 9.07 V measurement to correct for the multimeter's internal resistance and then multiplied the result by 101 to get the ESD gun voltage from the resistor divider. And we got the final measurement of 1005.8 V, which was within the 5% of output voltage tolerance, as described in IEC 61000-4-2.

Figure 8: Verifying the ESD gun's voltage

VERIFYING ESD GUN'S PULSE SHAPE

We used a DSO9404A oscilloscope from Agilent with a BW of 4 GHz and 20 GSa/s. The used channel was in the 50 Ω mode (we were careful not to overload the input!). The ESD target was connected to a 20 dB attenuator with a frequency range of DC-18 GHz. We checked the attenuator datasheet to ensure it could withstand the ESD pulse. (Note that it sees only the voltage on the 2.1 Ω impedance (~116 V at 15 kV pulse)). The RF cable had low attenuation at 4 GHz, passing the ±1.2 dB requirement in IEC 61000-4-2.

We connected the ground clip of the ESD gun to the exposed GND pad on the ESD target and placed the contact discharge tip to the center pin of the ESD target. The oscilloscope was set to a single trigger. (See Figure 9 for the test setup and Figure 10 on page 29 for the resulting waveform.) Tektronix application notes mention that ripples in the captured waveform are due to a small calibration plane, which we didn't verify.

Peak voltage was measured at 590 mV, which should be divided by the Zsys - 0.197 V/A, to get 3 A of measured current. The voltage at 30 ns was 390 mV (1.97 A); at 60 ns, it was 175 mV (0.89 A).

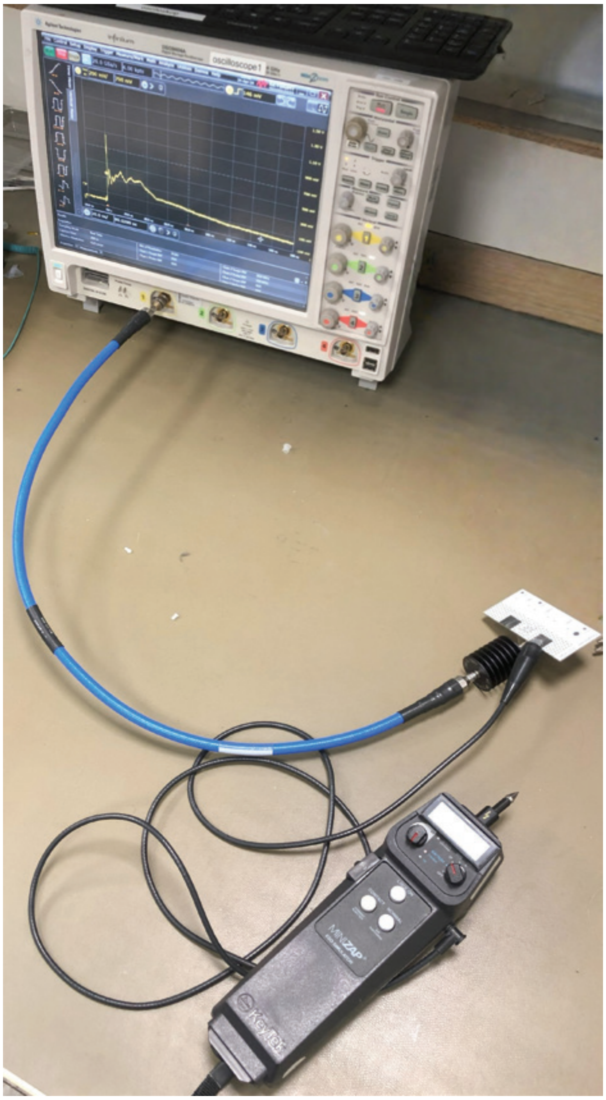


Figure 9: Test setup for verifying the ESD gun's pulse shape

Rise time was measured at 0.6 ns. We found that the rise time of some tips is much shorter than others. It can be as low as 100 ps, which makes the ESD test harder to pass because the pulse then contains higher signal frequencies that are harder to filter out. In the accredited labs, they should have a tip with a rise time of about 0.8 ns.

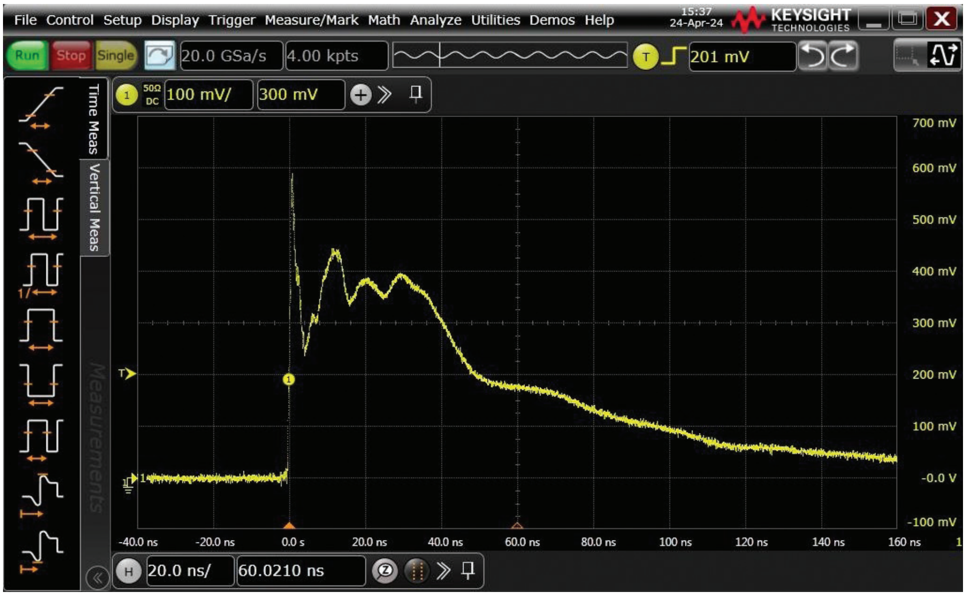


Figure 10: Waveform of the ESD pulse

Pulse shape for 1000 V ESD discharge is defined in IEC 61000-4-2 with these parameters:

- First peak current of discharge is 3.75 A ± 15%
- Rise time is 0.8 ns ± 25 %
- Current at 30 ns is 2 A ± 30 %
- Current at 60 ns is 1 A ± 30 %

All of our measurements passed the standard's requirements, except the first peak current of discharge, which was 3 A and should be a minimum of 3.19 A. This is most likely due to the specific tip that was used for this test (Keytek model MZ TPC-2A). Other tested tips had a much higher first peak current and faster rise time. We also tried to test air discharge by placing Kapton tape around the discharge pin on the ESD target to cover the GND pins. Kapton tape has a 4 kV voltage resistance, so a few layers are enough to withstand the 15 kV pulse.

We should note that the pulse shape tests are not completely reproducible, because small differences in the positioning of the ESD gun and ESD target can change the results slightly. When testing air discharge, the approach speed will change the measured pulse. We also tested 15 kV contact discharges with an additional 20 dB attenuator to limit the voltage to the oscilloscope channel under 5 V. The ESD target worked as expected but, with the high rise time ESD gun tip, the oscilloscope had an error, which was resolved with a reset.

CONCLUSION

The DIY ESD target is useful for pre-compliance laboratories that do not require accredited equipment for their measurements but that verify testing equipment every year to make sure it still works as expected. Compared to an off-the-shelf ESD target, the DIY version is much less expensive but it still provides good measurement accuracy based on the IEC 61000-4-2 standard. A potential improvement would be to make the ESD target mountable in a vertical calibration plane, which would improve the oscilloscope's immunity to radiated ESD pulses.

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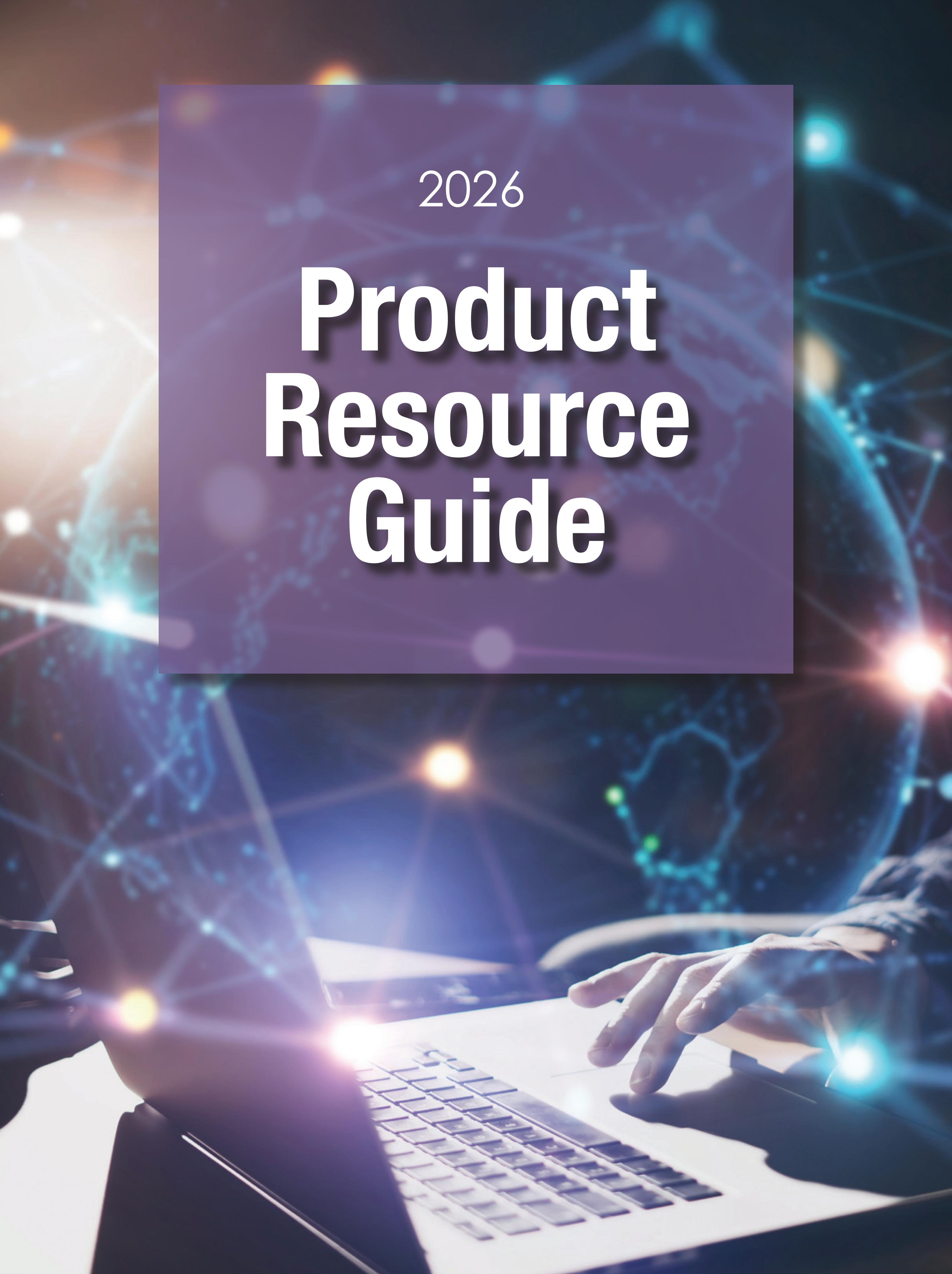
Product Resource Guide



2026 Product Resource Guide

Finding the right products to meet your unique compliance requirements can be challenging. Multiple considerations play into your decision-making process.

In this special issue, we highlight seven product categories—and offer guidance on choosing and using the right products and services for your applications.

Contributing Author
Don MacArthur
"The Practical Engineer"

Future Trends and Innovations in RF Absorbing Materials

By Don MacArthur

Radio Frequency (RF) absorbing materials play a crucial role in mitigating interference and enhancing the performance of electronic devices. As technology advances, the demand for more efficient and sustainable RF absorbing materials continues to grow. This article explores the latest trends and innovations in RF absorbing materials, focusing on advancements in material science, sustainability, and their impact on Electromagnetic Compatibility (EMC) and compliance engineering.

ADVANCEMENTS IN MATERIAL SCIENCE

New Developments in RF Absorbing Materials and Their Potential Impact on EMC and Compliance Engineering

Recent advancements in material science have led to the development of new RF absorbing materials with enhanced properties. These materials are designed to effectively control and mitigate interference, ensuring cleaner signal paths and improved device performance. Some notable developments include:

- **Ferrite Compounds:** These materials are commonly used in consumer electronics to absorb high-frequency RF signals effectively. They offer excellent performance and are widely used in various applications.
- **Magnetic Silicones:** Ideal for environments requiring both thermal and RF management, these materials provide a dual function, making them highly versatile.
- **Carbon-loaded Foam:** This lightweight material is prevalent in military and aerospace applications, offering a broad range of frequency absorption.
- **MXenes:** These two-dimensional (2D) transition metal carbide/nitride materials demonstrate superior properties, such as tunable electrical conductivity and unique layer structures. They are promising candidates for high-efficiency RF absorption.
- **Acoustic Metamaterials:** These materials utilize intelligent design strategies to achieve subwavelength-scale structures, providing new possibilities for energy dissipation mechanisms.

These advancements are expected to have a significant impact on EMC and compliance engineering by improving the performance and reliability of electronic devices across various industries.

SUSTAINABILITY

The Push Towards Environmentally Friendly RF Absorbing Materials and Their Benefits

The push towards sustainability in RF absorbing materials is driven by the need to reduce environmental impact and promote eco-friendly practices. Some key developments in this area include:

- **Bio-based Materials:** Researchers are exploring the use of biodegradable materials derived from biomass, such as kapok fiber-derived carbon microtubes. These materials offer excellent microwave-absorbing performance while being environmentally friendly.
- **Recyclable Materials:** Non-toxic, recyclable materials are gaining popularity due to their reduced environmental footprint. Evaluating the lifecycle and disposal methods of these materials contributes to a more sustainable approach.

- **Lightweight and High Absorption Capacity:** Sustainable materials with high absorption capacity and broad effective absorption bandwidth are being developed to address electromagnetic pollution.

The benefits of using environmentally friendly RF absorbing materials include reduced electronic waste, lower energy consumption, and improved overall sustainability of electronic devices.

SUMMARY/CONCLUSION

The future of RF absorbing materials is promising, with continuous advancements in material science and a growing emphasis on sustainability. These developments are expected to enhance the performance and reliability of electronic devices while reducing their environmental impact. As the demand for more sophisticated electronic devices increases, the role of RF absorbing materials in EMC and compliance engineering will become even more critical. ◈

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Understanding RF Amplifiers

By Don MacArthur

In the realm of radio frequency (RF) electronics, amplifiers play a pivotal role in enhancing signal strength and maintaining the integrity of transmitted data. This article delves into four critical parameters—gain, noise figure, linearity, and efficiency—providing insights into their significance and how they shape RF amplifier performance.

GAIN: THE MEASURE OF AMPLIFICATION

Gain, a fundamental parameter, quantifies the amplification provided by an RF amplifier. It is expressed in decibels (dB) and represents the ratio of output power to input power. Higher gain implies a stronger output signal for a given input, which is crucial in applications where signal attenuation over long distances is a concern.

The impact of gain on amplifier performance is multifaceted. While high gain can enhance signal strength, it must be balanced with other parameters to avoid distortion and maintain signal quality. In practical terms, an amplifier with an optimal gain ensures that the transmitted signal is robust enough to reach its destination without being drowned by noise or interference.

NOISE FIGURE: GUARDING SIGNAL INTEGRITY

The noise figure of an RF amplifier is a measure of the degradation of the signal-to-noise ratio (SNR) as the signal passes through the amplifier. It is expressed in decibels and indicates how much noise the amplifier adds to the signal. A lower noise figure signifies better performance, as it means the amplifier introduces minimal additional noise.

In RF systems, maintaining a high SNR is paramount for ensuring clear and accurate signal transmission. An amplifier with a low noise figure is essential for applications such as satellite communications, radar, and sensitive receiver systems, where even small amounts of added noise can compromise system performance. Therefore, the noise figure is a critical specification that engineers must consider when designing RF amplifiers for high-fidelity applications.

LINEARITY: PRESERVING SIGNAL PURITY

Linearity in RF amplifiers refers to the ability of the amplifier to produce an output signal that is a linear representation of the input signal. This parameter is crucial for maintaining signal integrity, particularly in applications involving complex modulation schemes. Non-linearity in amplifiers can lead to distortion, intermodulation products, and spectral regrowth, all of which degrade signal quality.

A linear amplifier ensures that the amplified signal retains its original characteristics without introducing unwanted artifacts. This is especially important in communication systems where the purity of the signal is essential for accurate data transmission. In practice, ensuring linearity often involves careful design considerations and trade-offs with other parameters such as gain and efficiency.

EFFICIENCY: POWER MATTERS

Efficiency in RF amplifiers is defined as the ratio of RF output power to the total input power consumed by the amplifier. High efficiency is particularly critical in power amplifiers, where significant amounts of power are involved. Efficient amplifiers not only reduce energy consumption but also minimize heat generation, which can affect the reliability and longevity of the device.

In applications such as wireless communication infrastructure, satellite transmitters, and broadcast systems, the efficiency of power amplifiers directly impacts operational costs and thermal management. High-efficiency amplifiers help reduce electricity bills and cooling requirements, making them a preferred choice in commercial and industrial RF applications.

BALANCING ACT: THE INTERPLAY OF PARAMETERS

Designing an RF amplifier involves a delicate balance between these key parameters. High gain must be achieved without compromising noise figure or linearity. Similarly, enhancing efficiency should not lead to excessive non-linearity or increased noise. Engineers must consider the specific requirements of their application and carefully optimize each parameter to achieve the desired performance.

SUMMARY

In conclusion, understanding the intricacies of gain, noise figure, linearity, and efficiency is essential for designing high-performance RF amplifiers. By carefully balancing these parameters, engineers can develop amplifiers that deliver robust, clear, and efficient signal amplification, meeting the demands of modern RF communication systems. ◈

REFERENCES AND FURTHER READING

Here are some references that can help you dive deeper into the key parameters and specifications of RF amplifiers:

1. Fundamentals of RF Power Amplifiers: This document by NXP provides a comprehensive overview of RF power amplifier topologies, their applications, and important considerations for component selection.
2. Understanding RF Data Sheet Parameters: This application note by NXP Semiconductors reviews RF transistor and amplifier module parameters, including gain, noise figure, linearity, and efficiency.
3. Understanding Operational Amplifier Specifications: This application report by Texas Instruments covers the basics of amplifier specifications and how to select the right operational amplifier for specific applications.
4. A Guide for Choosing the Right RF Amplifier for Your Application: This article from Analog Devices discusses how to select the right RF amplifier based on features such as gain, noise, bandwidth, and efficiency.
5. Introduction to NMR/MRI Amplifiers: This guide by CPC Amps explains amplifier specifications in the context of NMR and MRI applications.

These resources will provide a solid foundation for understanding the key parameters and specifications of RF amplifiers.

Design and Operation of Antennas

By Don MacArthur

In the world of electromagnetic compatibility (EMC) compliance, ensuring that electronic devices meet regulatory standards is paramount. A key component in achieving this compliance is the use of antennas, which are essential for testing and measuring electromagnetic emissions and susceptibility. This article explores the role of antennas in compliance testing, focusing on their construction and materials, setup and calibration, and maintenance and care. By understanding these critical aspects, engineers and technicians can ensure accurate and reliable measurements, ultimately leading to devices that perform optimally and comply with stringent regulatory requirements.

CONSTRUCTION AND MATERIALS

Antennas are critical components in various communication systems, and their construction and materials play a significant role in their performance. The choice of materials and design considerations for compliance testing antennas, such as biconical antennas, is essential to ensure accurate and reliable measurements.

Biconical antennas, for instance, are commonly used in compliance testing due to their broadband capabilities. These antennas are typically made from high-conductivity materials like copper or aluminum to minimize signal loss and improve efficiency. The design of biconical antennas includes conical-shaped elements that provide a wide frequency range, typically from 20 MHz to several hundred MHz. Additionally, these antennas often feature an integrated balun (balanced to unbalanced) structure to match the impedance of the elements to the transmission line.

SETUP AND CALIBRATION

Setting up and calibrating compliance testing antennas is crucial to ensure accurate measurements. The setup process involves placing the antenna in the desired test environment, such as an open area test site (OATS) or a semi-anechoic chamber. The calibration process establishes the relationship between the values indicated by the measuring instrument and a reference standard.

For radiated emission measurements, the calibration must follow specific standards, such as ANSI C63.4-2014 or CISPR 16-1-4, which define the procedures for determining antenna factors (AF). Calibration measures field strength at specified distances using standard test procedures.

MAINTENANCE AND CARE

Proper maintenance and care of compliance testing antennas is essential to ensure their longevity and performance. Regular maintenance includes cleaning the antenna elements to remove any dust or debris that may affect the signal quality. It is also important to inspect the antenna for any signs of wear or damage and to replace any faulty components promptly.

CALIBRATION

In addition to regular maintenance, periodic calibration is necessary to maintain the accuracy of the antenna. Calibration intervals should be determined based on the manufacturer's recommendations and the frequency of use. Keeping a detailed record of calibration dates and results can help track the antenna's performance over time.

Pro Tip: When setting up compliance testing antennas, always ensure a clear line of sight between the antenna and the device under test

When setting up compliance testing antennas, always ensure a clear line of sight between the antenna and the device under test (DUT). Any obstructions or reflections can introduce inaccuracies in your measurements. Keep detailed logs of your calibration settings and environmental conditions during each test session. This helps maintain consistency across tests and makes troubleshooting any anomalies much easier. Keeping a clean testing environment and regularly inspecting your antenna for wear and tear can further enhance the reliability of your measurements.

SUMMARY

In compliance testing, antennas are crucial for measuring and ensuring electronic devices meet regulatory standards. The construction and materials of these antennas, typically using high-conductivity metals like copper or aluminum, ensure efficient performance. Proper setup and calibration, following standards such as ANSI C63.4-2014 or CISPR 16-1-4, are essential for accurate measurements. Maintenance practices, including regular cleaning, inspection, and periodic calibration, help sustain antenna performance and longevity. Understanding these aspects ensures reliable measurements and compliance, ultimately leading to optimal device performance. ◈

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Design Considerations for EMC Test Chambers

By Don MacArthur

Electromagnetic compatibility (EMC) test chambers are critical facilities where electronic devices are tested for their ability to function properly without emitting or being affected by electromagnetic interference (EMI). Designing an EMC test chamber requires careful consideration of several factors to ensure accurate and reliable testing. This article explores the key design considerations for EMC test chambers, focusing on material selection, chamber size, and configuration.

MATERIAL SELECTION

The materials used in the construction of EMC test chambers play a pivotal role in their performance. The primary materials to consider are RF absorbers and shielding materials.

RF Absorbers

- **Types of RF Absorbers:** There are various types of RF absorbers, including ferrite tiles, pyramidal foam absorbers, and hybrid absorbers. Each type has its unique properties and applications. Ferrite tiles are effective at lower frequencies, while pyramidal foam absorbers perform well at higher frequencies. Hybrid absorbers combine the benefits of both types.
- **Performance Characteristics:** The effectiveness of RF absorbers is measured by their reflection loss and absorption efficiency. High-quality absorbers should offer high reflection loss, ensuring minimal RF reflections within the chamber, and high absorption efficiency to reduce the incidence of standing waves and reflections.
- **Installation Considerations:** Proper installation of RF absorbers is crucial for their performance. Absorbers should be evenly distributed and securely attached to the chamber walls, ceiling, and floor to ensure consistent performance across the entire testing area.

Shielding Materials

- **Types of Shielding Materials:** Common shielding materials include galvanized steel, copper, and aluminum. These materials are chosen for their high conductivity and ability to attenuate electromagnetic fields.
- **Shielding Effectiveness:** The effectiveness of shielding materials is measured by their shielding effectiveness, which quantifies the material's ability to block or attenuate electromagnetic fields. High-quality shielding materials should provide effective attenuation across a wide frequency range.
- **Structural Considerations:** The structural integrity of the shielding materials is important to maintain a continuous and effective shield. Overlapping seams, conductive gaskets, and proper grounding are essential to prevent leakage and ensure a complete shield.

CHAMBER SIZE AND CONFIGURATION

The size and configuration of EMC test chambers are critical factors that influence their effectiveness and versatility.

Chamber Size

- **Determining Size Requirements:** The size of the chamber should be determined based on the type of equipment to be tested and the test procedures. Larger chambers are required for testing larger devices or systems, while smaller chambers are suitable for individual components or small devices.
- **Compliance with Standards:** The chamber size should comply with relevant standards and guidelines, such as CISPR 16-1-4 and ANSI C63.4, which specify the minimum dimensions and clearances for EMC testing.

- **Future-Proofing:** Consider future testing needs and potential growth when determining the chamber size. Designing a slightly larger chamber can accommodate future testing requirements and avoid the need for expensive modifications.

Configuration

- **Chamber Layout:** The layout of the chamber should facilitate easy access to the device under test (DUT) and testing equipment. Adequate space should be provided for test personnel to move around and set up equipment.
- **Antenna Positioning:** Proper positioning of antennas is crucial for accurate measurements. The chamber should allow for adjustable antenna mounts and clear line-of-sight paths between the antennas and the DUT.
- **Control Room:** A separate control room adjacent to the chamber allows for remote operation and monitoring of tests. This setup minimizes interference and ensures safety for test personnel.

SUMMARY/CONCLUSION

Designing an effective EMC test chamber requires careful consideration of material selection, chamber size, and configuration. RF absorbers and shielding materials play crucial roles in ensuring accurate and reliable testing by minimizing RF reflections and attenuating electromagnetic fields. Proper chamber size and configuration are essential for accommodating different types of equipment and testing requirements while complying with relevant standards. By considering these factors, engineers can design EMC test chambers that provide accurate, reliable, and efficient testing environments, ultimately ensuring the electromagnetic compatibility of electronic devices.

By adhering to these best practices, engineers can ensure that their EMC test chambers are equipped to handle the rigorous demands of compliance testing, providing a reliable environment for evaluating the electromagnetic performance of electronic devices. ◈

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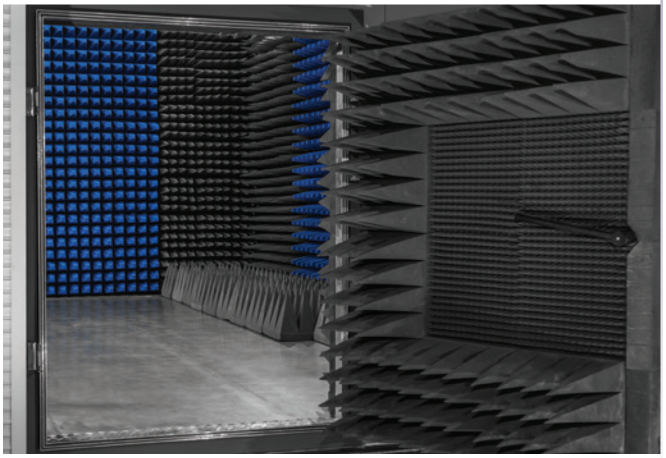
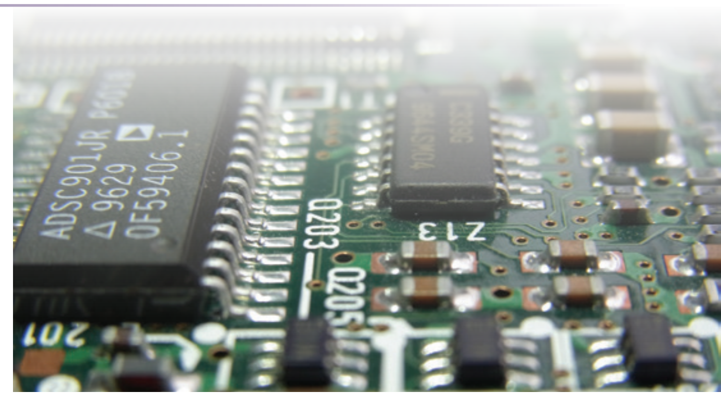


Building Compliant Electronics

By Don MacArthur



In the world of electronics, ensuring compliance with regulatory standards is paramount to the successful launch and operation of any device. Compliance covers a broad spectrum of requirements, including electromagnetic compatibility (EMC), safety, and environmental considerations. This article delves into the critical design considerations for selecting components, layout and placement on printed circuit boards (PCBs), and effective thermal management, all aimed at achieving compliance.

COMPONENT SELECTION

Selecting the right components is fundamental to meeting compliance requirements. Here are key criteria to consider:

- **Voltage Ratings:** Ensure that components can handle the maximum voltage expected in the application. Over-voltage can lead to breakdowns and compliance failures. Use components with voltage ratings that provide a safety margin above the maximum operational voltage.
- **Tolerance:** Components must operate reliably within their specified tolerance ranges. Choose components with tighter tolerances for critical functions to ensure consistent performance and compliance. For example, resistors and capacitors with low tolerance variations can help maintain signal integrity and reduce EMI.
- **Thermal Stability:** Components exposed to varying temperatures must maintain their performance characteristics. Select components with high thermal stability to avoid drift in values, which can affect circuit performance and compliance. Materials like ceramic or tantalum for capacitors and metal film for resistors are preferred for their thermal stability.
- **Certifications and Standards:** Use components that are certified to relevant standards such as UL, CE, or RoHS. These certifications indicate that the components meet specific safety, environmental, and performance criteria, aiding overall compliance.
- **Reliability and Lifetime:** Ensure the components are reliable and have a long operational lifetime. High-reliability components reduce the risk of failure, which is crucial for maintaining compliance over the product's lifespan.

LAYOUT AND PLACEMENT

Proper layout and placement of components on PCBs are crucial for minimizing electromagnetic interference (EMI) and ensuring compliance. Here are some best practices:

- **Minimize Loop Areas:** Reduce the area of current loops to minimize EMI. Keep signal traces and their return paths close to each other. Route the positive and negative traces together for differential signals to cancel out common-mode noise.
- **Segregate Analog and Digital Grounds:** To minimize noise coupling, separate the analog and digital grounds and connect them at a single point. This helps maintain signal integrity and reduce EMI.

- **Shielding and Ground Planes:** Use shielding and ground planes to isolate sensitive components and signals from noise sources. A solid ground plane reduces the impedance of return paths and provides a reference for signals, enhancing EMC performance.
- **Component Placement:** Place components to minimize the length of high-speed signal traces. Keep high-frequency components away from sensitive analog circuits. Place decoupling capacitors close to power pins of ICs to filter out high-frequency noise.
- **Layer Stacking:** In multilayer PCBs, use dedicated layers for power and ground planes. This reduces cross-talk and enhances signal integrity. Place signal layers adjacent to ground planes to contain EMI.

THERMAL MANAGEMENT

Managing heat dissipation is critical for compliance-critical components, as excessive heat can affect performance and lead to failure. Here are some techniques for effective thermal management:

- **Heat Sinks:** Attach heat sinks to components that generate significant heat. Heat sinks increase the surface area for heat dissipation, keeping component temperatures within safe limits.
- **Thermal Vias and Planes:** Use thermal vias and planes to transfer heat away from hot components. Thermal vias connect the component pads to internal or external copper planes, spreading the heat and improving dissipation.
- **Active Cooling:** In high-power applications, active cooling methods like fans or liquid cooling systems may be necessary. Active cooling helps maintain safe operating temperatures for compliance-critical components.
- **Component Spacing:** Provide adequate spacing between components to allow for natural convection cooling. Crowded layouts can impede airflow and exacerbate thermal issues.
- **Thermal Interface Materials:** Use thermal interface materials (TIMs) to enhance heat transfer between components and heat sinks. TIMs fill air gaps and improve thermal conductivity.

SUMMARY/CONCLUSION

Achieving compliance in electronic designs requires careful consideration of component selection, layout and placement on PCBs, and thermal management. By selecting components with appropriate voltage ratings, tolerance, and thermal stability, ensuring proper layout and placement to minimize EMI, and implementing effective thermal management techniques, engineers can create designs that meet regulatory standards and perform reliably.

By adhering to these design considerations, engineers can ensure that their electronic products meet compliance requirements and deliver optimal performance and reliability. ◈

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Case Studies and Real-World Applications of EMI Filters

By Don MacArthur

Electromagnetic interference (EMI) can disrupt the performance and functionality of electronic devices, leading to potential safety hazards and reliability issues. EMI filters are essential components that help mitigate these interferences by blocking unwanted electromagnetic noise. This article delves into real-world applications of EMI filters in consumer electronics, automotive systems, and industrial equipment, highlighting their significance and effectiveness in ensuring smooth and reliable operation.

CONSUMER ELECTRONICS

In the realm of consumer electronics, EMI filters play a crucial role in maintaining the performance and safety of devices such as smartphones and laptops. These devices are often packed with high-density circuitry and operate at high frequencies, making them susceptible to electromagnetic interference from various sources.

Smartphones: Modern smartphones are equipped with numerous functions, including wireless communication, touchscreens, and high-resolution displays. EMI filters are used to protect these sensitive components from interference that can come from both internal and external sources. For instance, EMI filters help in reducing noise from power lines and radio frequency (RF) circuits, ensuring clear signal transmission for voice calls and data communication. In addition, these filters protect the touchscreen from noise generated by the display, enhancing the overall user experience.

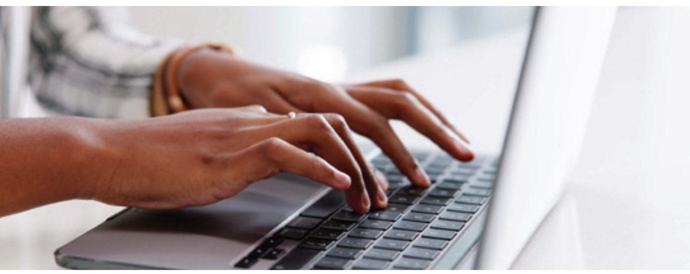
Laptops: Laptops integrate multiple subsystems such as processors, memory, storage, and communication modules. EMI filters are employed to prevent noise from power supplies and switching regulators from interfering with these subsystems. By incorporating EMI filters in the power lines and signal lines, laptops can achieve stable operation, reduced electromagnetic emissions, and compliance with regulatory standards like the Federal Communications Commission (FCC) Part 15 for electromagnetic emissions.

AUTOMOTIVE SYSTEMS

The automotive industry has witnessed a significant increase in the use of electronic systems, particularly in electric and hybrid vehicles. These vehicles rely on high-voltage and high-frequency electronic components that can generate substantial EMI, affecting the performance of critical systems.

Electric and Hybrid Vehicles: Electric vehicles (EVs) and hybrid electric vehicles (HEVs) use power electronics extensively for motor control, battery management, and energy conversion. EMI filters are crucial in these applications to manage the high-voltage and high-frequency noise generated by power inverters, DC-DC converters, and electric motors. By filtering out unwanted noise, EMI filters ensure the reliable operation of the vehicle's electronic systems, including the communication between the motor control unit and the vehicle control system. This not only improves the vehicle's performance but also enhances passenger safety by preventing potential malfunctions caused by EMI.

In-Car Entertainment and Communication Systems: Modern vehicles are equipped with advanced entertainment and communication systems that rely on wireless communication, touchscreen interfaces, and high-fidelity audio systems. EMI filters are used to protect these systems from interference generated by other electronic components within the vehicle. For example, filters are incorporated into audio



systems to eliminate noise from power lines and maintain clear sound quality. Similarly, communication systems are shielded from EMI to ensure uninterrupted connectivity for navigation and infotainment.

INDUSTRIAL EQUIPMENT

In industrial settings, the reliable operation of machinery and equipment is paramount. EMI can disrupt the functionality of industrial control systems, sensors, and communication networks, leading to potential downtime and safety hazards.

Machinery and Automation Systems: Industrial machinery often operates in harsh environments with high levels of electromagnetic noise. EMI filters are employed to protect sensitive control systems, sensors, and actuators from interference. For example, in automated manufacturing processes, EMI filters help ensure accurate and stable operation of programmable logic controllers (PLCs) and motor drives. By filtering out noise from power supplies and signal lines, these filters enhance the precision and reliability of industrial automation systems.

Industrial Communication Networks: The proliferation of Industrial Internet of Things (IIoT) and smart manufacturing has increased the reliance on robust communication networks. EMI filters play a critical role in maintaining the integrity of these networks by preventing electromagnetic interference from disrupting data transmission. Filters are used in Ethernet lines, wireless communication modules, and other networking components to ensure reliable data exchange and prevent signal degradation caused by EMI.

SUMMARY/CONCLUSION

EMI filters are indispensable in various applications, from consumer electronics to automotive systems and industrial equipment. By mitigating electromagnetic interference, these filters enhance the performance, reliability, and safety of electronic devices. In consumer electronics, EMI filters ensure clear signal transmission and user satisfaction. In automotive systems, they protect critical electronic components from high-voltage and high-frequency noise, ensuring reliable vehicle operation. In industrial settings, EMI filters safeguard control systems and communication networks, preventing downtime and enhancing safety. As technology continues to advance, the importance of EMI filters in ensuring compliance with regulatory standards and maintaining optimal performance will only grow. ◈

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Key Features and Capabilities of Compliance Testing Labs

By Don MacArthur

In the fast-paced world of technology and electronics, ensuring that products meet stringent regulatory standards is critical for market entry and consumer safety. Compliance testing labs play a vital role in this process by verifying that electronic devices adhere to electromagnetic compatibility (EMC), safety, and other regulatory requirements. This article explores the key features and capabilities of compliance testing labs, focusing on accreditation and certification, state-of-the-art equipment, and the expertise and experience of lab personnel.

ACCREDITATION AND CERTIFICATION

Accreditation and certification are fundamental to the credibility and reliability of compliance testing labs. Accreditation to standards such as ISO/IEC 17025 indicates that an independent body has evaluated a lab and meets the required standards for testing and calibration competencies. ISO/IEC 17025 is the international standard for testing and calibration laboratories, ensuring they operate competently and generate valid results.

Certification from recognized bodies, such as the Federal Communications Commission (FCC) or the International Electrotechnical Commission (IEC), further validates the lab's capabilities. These certifications confirm that the lab follows standardized testing procedures and employs proper methodologies to achieve accurate and reliable results. For manufacturers, working with accredited and certified labs provides assurance that their products will meet regulatory requirements and avoid costly delays or rejections in the market.

STATE-OF-THE-ART EQUIPMENT

The quality of testing in compliance labs is heavily dependent on the equipment used. State-of-the-art equipment ensures precision, accuracy, and repeatability in testing procedures. Key pieces of advanced equipment commonly found in compliance testing labs include:

1. **Anechoic Chambers:** These are specialized rooms designed to completely absorb reflections of electromagnetic waves, providing an ideal environment for measuring radiated emissions and immunity. The chambers are equipped with absorptive materials and are free from external electromagnetic interference, ensuring accurate measurements.

2. **Spectrum Analyzers:** These instruments measure the magnitude of an input signal versus frequency within a specified frequency range. They are essential for identifying and analyzing electromagnetic interference (EMI) and ensuring that emissions comply with regulatory limits.

3. **Network Analyzers:** These devices measure the network parameters of electrical networks, which are essential for assessing the performance of RF and microwave components. They help in evaluating the impedance, return loss, and insertion loss, which are critical for EMC compliance.

4. **EMI Receivers:** These receivers are designed to measure electromagnetic interference from electronic devices. They are used to detect and quantify emissions, ensuring that products meet the necessary standards.

5. **ESD Simulators:** Electrostatic discharge (ESD) simulators replicate the electrostatic discharges that electronic devices might encounter during their lifecycle. They help test the resilience of devices against ESD events, which is crucial for ensuring product reliability and safety.

EXPERTISE AND EXPERIENCE

The expertise and experience of the engineers and technicians conducting compliance tests are as important as the equipment they use. Skilled personnel are essential for interpreting test results, identifying potential issues, and recommending corrective actions. Their deep understanding of regulatory standards, testing procedures, and best practices ensures accurate and reliable testing.

Experienced engineers and technicians can troubleshoot and resolve complex issues that may arise during testing, ensuring that products meet the necessary standards without unnecessary delays. Their knowledge also helps in optimizing designs to achieve better EMC performance, enhancing the overall quality and reliability of the products.

SUMMARY/CONCLUSION

Compliance testing labs are integral to the process of ensuring that electronic devices meet regulatory standards for EMC, safety, and other requirements. The key features and capabilities of these labs, including accreditation and certification, state-of-the-art equipment, and skilled personnel, contribute to accurate and reliable testing results. By partnering with accredited and certified labs equipped with advanced testing tools and staffed with experienced professionals, manufacturers can ensure that their products comply with regulatory standards, enhancing their marketability and consumer trust. ◈

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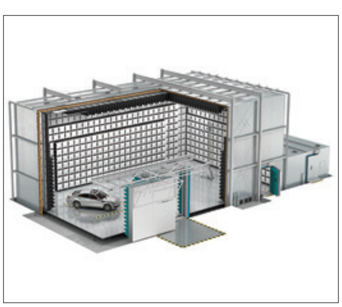

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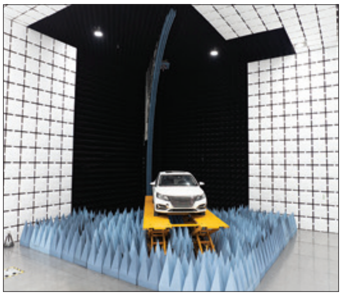
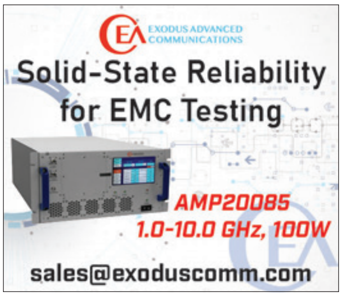


Fast Track to the Future of EMC Compliance

The future is now! As technology in our homes and industries becomes increasingly sophisticated, the potential for electromagnetic interference grows significantly. In the automotive world, where vehicles are essentially computers on wheels with varying levels of automation, ensuring the safety and reliability of these emerging technologies is more critical—and more challenging—than ever. With decades of expertise, ETS-Lindgren is Committed to a Smarter, More Connected Future.

PRODUCT MARKETPLACE



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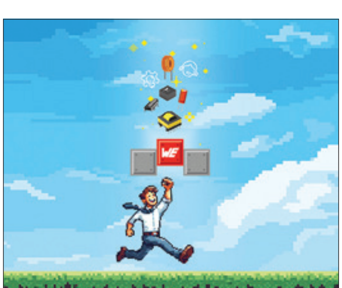

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SHIELDING TO PREVENT RADIATION

Part 4B: Far-Field Shielding Effectiveness of Solid Conducting Shield – Approximate Solutions – Version 2

By Bogdan Adamczyk

This is Part 4B of seven devoted to the topic of shielding to prevent electromagnetic wave radiation. The first article [1] discussed reflection and transmission of uniform plane waves at a normal boundary. The second article, [2], addressed the normal incidence of a uniform plane wave on a solid conducting shield with no apertures. The third article, [3], presented the exact solution for the shielding effectiveness of a solid conducting shield. In Part A of the fourth article [4], Version 1 of the approximate solution was derived. In this article, a more practical Version 2 of the approximate solution (obtained from Version 1) is presented.

Dr. Bogdan Adamczyk is professor and director of the EMC Center at Grand Valley State University (http://www.gvsu.edu/emccenter) where he performs EMC educational research and regularly teaches EM/EMC courses and EMC certificate courses for industry. He is an iNARTE-certified EMC Master Design Engineer. He is the author of two textbooks, "Foundations of Electromagnetic Compatibility with Practical Applications" (Wiley, 2017) and "Principles of Electromagnetic Compatibility: Laboratory Exercises and Lectures" (Wiley, 2024). He has been writing "EMC Concepts Explained" monthly since January 2017. He can be reached at adamczyb@gvsu.edu.

SHIELDING EFFECTIVENESS – APPROXIMATE SOLUTION – VERSION 2

An approximate solution for the reflection loss (Version 1) was derived in [4, Eq. (10)] as

$$R_{dB} = 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right| \tag{1}$$

Substituting h$_0$ = 120p and using Eq. (24) (from [4]) in Eq. (1), we get

$$R_{dB} = 20\,log_{10}\frac{30\pi}{\sqrt{\frac{8\pi^2 f\mu_r}{\sigma_r(5.8\times10^{14})}}} \tag{2}$$

resulting in

$$R_{dB} \cong 168.15 + 10\,log_{10}\left(\frac{\sigma_r}{f\mu_r}\right) \tag{3}$$

This is an alternative expression to Eq. (1) for the reflection loss for good and thick conductors in the far field. Note that the reflection loss is greatest for high conductivity-, low permeability- materials, and at low frequencies.

Now, let's derive an alternative expression for the absorption loss. The exact formula was given by Eq. (11) in [4] as

$$\begin{aligned} A_{dB} &= 20\log_{10} e^{\frac{t}{\delta}} = 20\left(\frac{t}{\delta}\right)\log_{10} e \\ &= (20)(\log_{10} 2.71828)\left(\frac{t}{\delta}\right) \end{aligned} \tag{4}$$

or

$$A_{dB} = 8.68588\left(\frac{t}{\delta}\right) \tag{5}$$

Skin depth in good conductors is given by [4]

$$\delta = \frac{1}{\sqrt{\pi f\mu\sigma}} \tag{6}$$

Using Equations (22) and (23) (from [4]), in Eq.(6), we get

$$\delta = \frac{1}{\sqrt{\pi f\mu_r\times4\pi\times10^{-7}\sigma_r\times5.8\times10^{7}}} = \frac{1}{15.132\sqrt{f\mu_r\sigma_r}} \tag{7}$$

Substituting this result into Eq. (5), we get an alternative formula for the absorption loss of good conductors in the far field as (with the conductor thickness *t* in meters)

$$A_{dB} = 131.434 \times t\sqrt{f\mu_r\sigma_r} \tag{8}$$

When the conductor thickness is expressed in inches, this formula becomes

$$A_{dB} = 3.338 \times t\sqrt{f\mu_r\sigma_r} \tag{9}$$

This is the alternative expression to Eq.(11) in [4] for the absorption loss for good and thick conductors in the far field. Note that the absorption loss is greatest for high conductivity-, high permeability- materials, and at high frequencies.

The total shielding effectiveness is

$$S_{dB} = R_{dB} + A_{dB} \tag{10a}$$

or, utilizing Equations (3) and (9)

$$S_{dB} \cong 168.15 + 10\,log_{10}\left(\frac{\sigma_r}{f\mu_r}\right) + 3.338 \times t\sqrt{f\mu_r\sigma_r} \tag{10b}$$

Material	σ_r	μ_r
Copper	1	1
Steel (SAE 1045)	0.1	1000

Table 1: Relative conductivity and permeability of copper and steel

FAR-FIELD SHIELDING EFFECTIVENESS – COPPER VS. STEEL - SIMULATIONS

In this section, we compare far-field shielding effectiveness of copper and steel (SAE1045).
Table 1 shows the relative conductivity and relative permeability of these two shield materials.

Let's begin with the reflection loss, computed from

$$R_{dB} \cong 168.15 + 10\,log_{10}\left(\frac{\sigma_r}{f\mu_r}\right) \tag{11}$$

Figure 1 shows the reflection loss in the frequency range 100 Hz – 1 GHz. Note that the reflection loss of copper is higher over the entire frequency range.

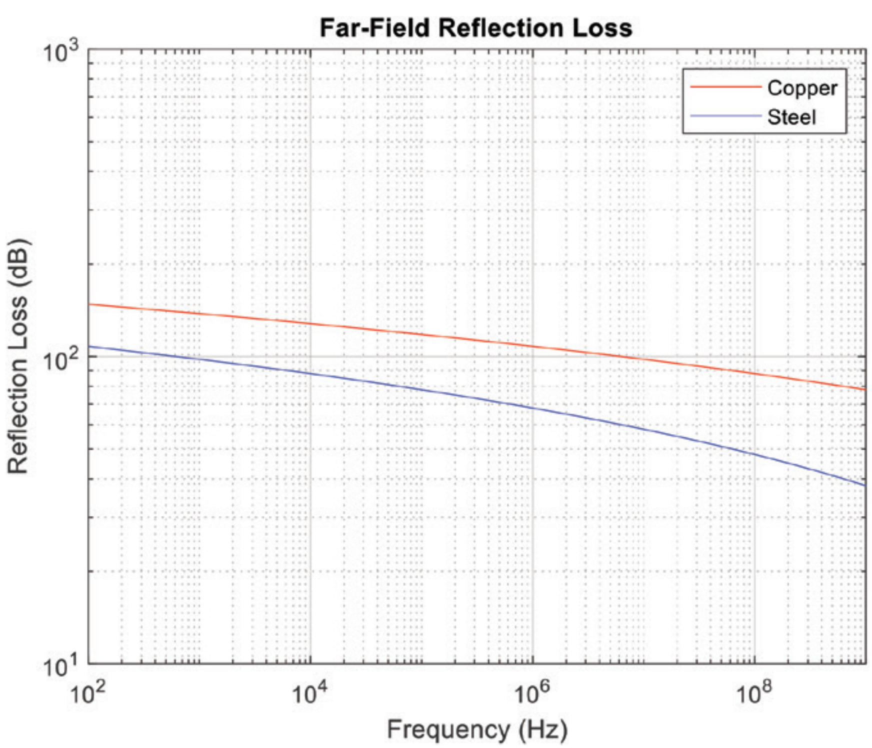

Figure 1: Reflection loss – copper vs. steel

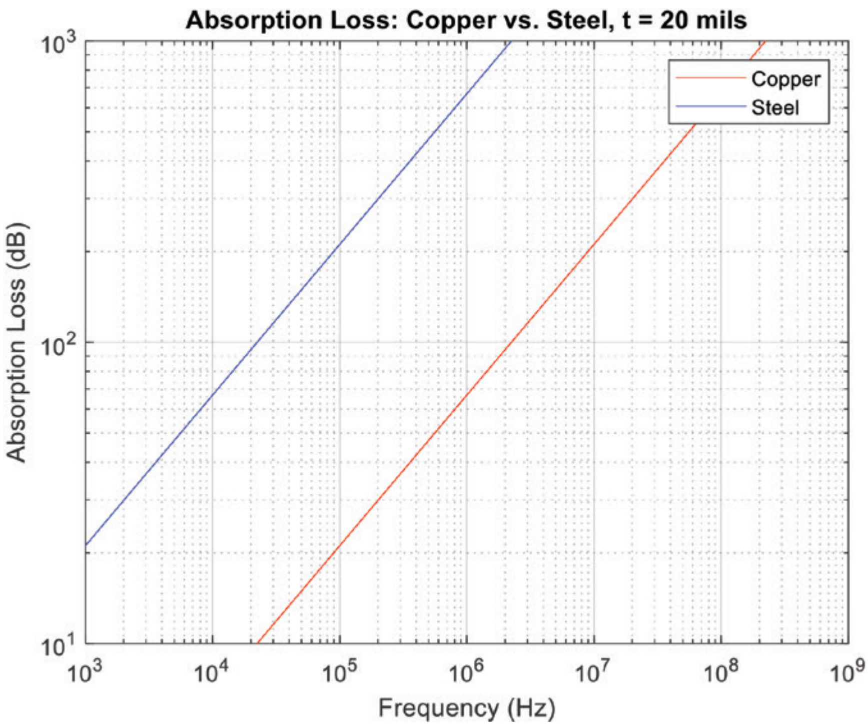

Figure 2: Absorption loss – copper vs. steel

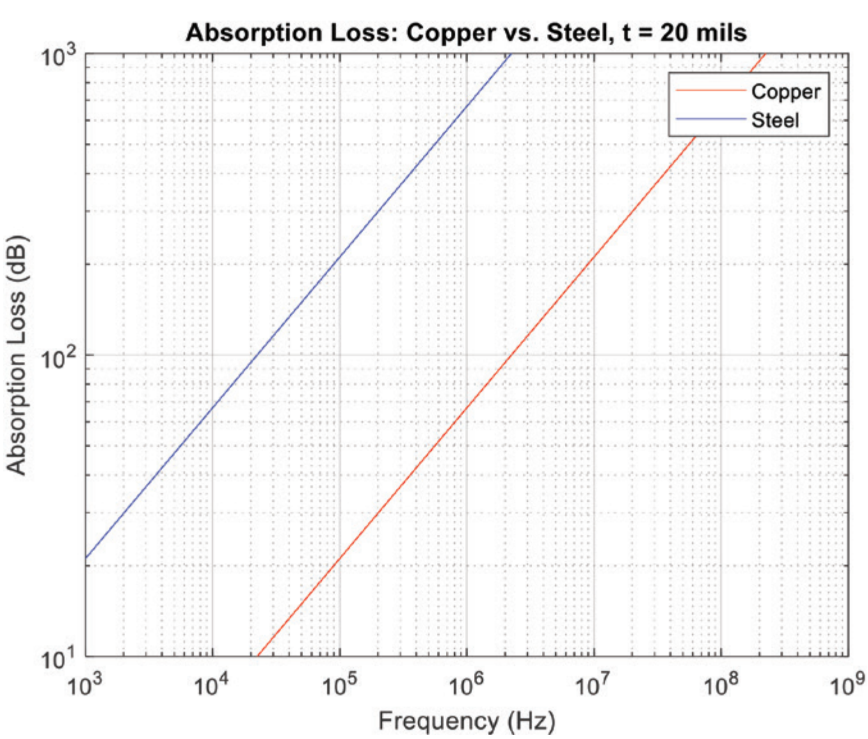

Figure 3: Total shielding effectiveness – copper vs. steel

The absorption loss, for 20-mil thick shields, is calculated from

$$A_{dB} = 3.338 \times t\sqrt{f \mu_r \sigma_r} \tag{12}$$

It is shown in Figure 2. Note that the absorption loss of steel is higher over the entire frequency range.

The total shielding effectiveness is calculated from Eq. (10b) and is shown in Figure 3.

Note that up to the frequency of about 4200 Hz, the shielding effectiveness of copper is higher than that of steel. Beyond that frequency, the opposite is true.

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IN-SITU ESD CURRENT SENSING IN A PICK-AND-PLACE MACHINE

By Ellen Merkel and Heinrich Wolf on behalf of EOS/ESD Association, Inc.

In the rapidly evolving semiconductor industry, the shift towards Multi-Chip Modules (MCM) and Systems in a Package (SiP) is notable. These advanced assemblies comprise multiple chiplets, sensors, and optoelectronic components, which are vulnerable to Electrostatic Discharge (ESD). The complex internal architecture of MCMs and SiPs—with their internal pins and through-silicon vias—poses challenges for ESD protection in assembly processes.

During the assembly of these systems, components may be exposed to ESD stress. Established methods for assessing the Charged Device Model (CDM) [1] robustness of individual devices exist, including advanced methods such as Capacitively-Coupled Transmission Line Pulsing (CC-TLP) [2]-[7] or low-impedance contact CDM (LICCDM) [8] [9]. While CC-TLP yields reproducible results even for bare dies or wafers, it uses current to determine the robustness level. Insufficient data currently exists regarding the correlation between charging voltages in production machines and discharge currents during the assembly process. This study proposes a method to measure discharge currents during the pick and place process, aiming to link this current to a pre-charge voltage and enhance the evaluation of ESD protection requirements for internal pins.

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Dr. Heinrich Wolf holds degrees from TUM and TU Berlin. He specializes in ESD protection for semiconductor technologies at Fraunhofer EMFT, with over 50 publications on ESD simulation and test methods. He also works in RF characterization up to 110 GHz and co-chairs international ESD standards committees.

THE DISCHARGE CURRENT SENSOR

By employing a dedicated Discharge Current Sensor (DCS), it is possible to gather real-time data on discharge currents, providing insights into the maximum currents that need consideration during the design phase of ESD protection schemes.

The DCS (Figure 1) developed for this study is a compact setup designed for integration within assembly machines. It utilizes a 50 Ω microstrip line (2) terminated by a miniature pogo-pin (3). Using up to 10 thin-film resistors between the pogo-pin and ground plane, it allows to accurately measure the discharge current. The sensor's design allows for minimal mismatch and high-frequency bandwidth.

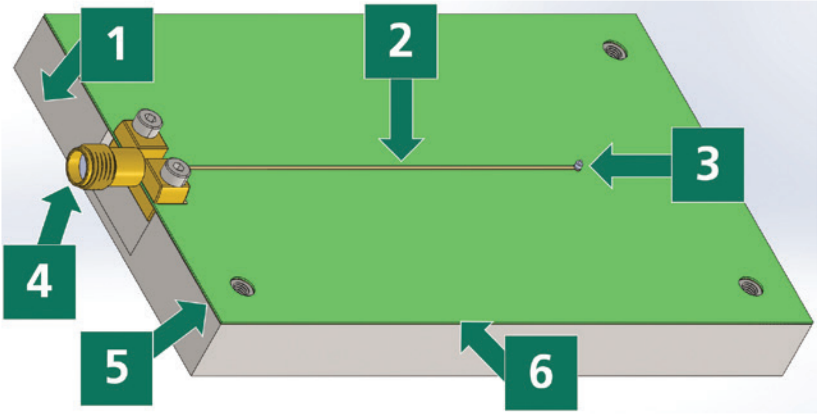

Figure 1: Discharge current sensor

INSIGHTS FROM LABORATORY MEASUREMENTS

Initial laboratory measurements using the DCS focused on three different die sizes and various pre-charge voltage levels. The DCS was placed below the pick-and-place head with the miniature pogo-pin facing the DUT (Figure 2). The DUT was charged with the charging probe and finally discharged via the pogo-pin into a microstrip line connected to a high bandwidth oscilloscope.

The laboratory experiments showed some first statistical data on discharge currents for voltage levels ranging between 4 V and 100 V (Figure 3) highlights the measured peak currents for pre-charge voltages < 30 V). Interestingly, the tests revealed that discharge currents were lower than anticipated compared to interpolated CDM values. Furthermore, the measured discharge currents displayed faster rise times (< 50 ps) and shorter pulse widths (< 100 ps). These findings emphasize the importance of real-world measurements in understanding ESD risks during assembly processes, suggesting that the current protection schemes may need re-evaluation to better align with actual industrial conditions.

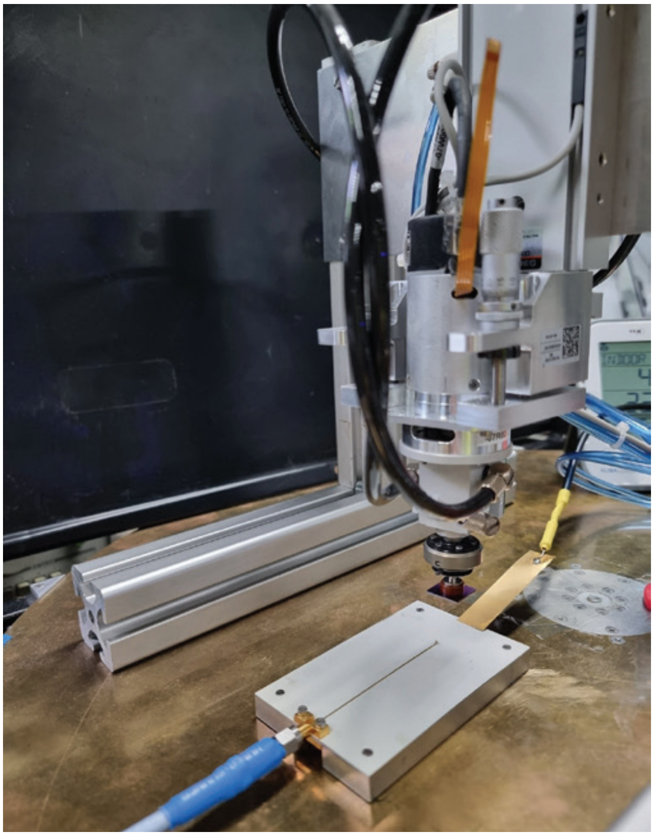

Figure 2: Measurement setup in laboratory

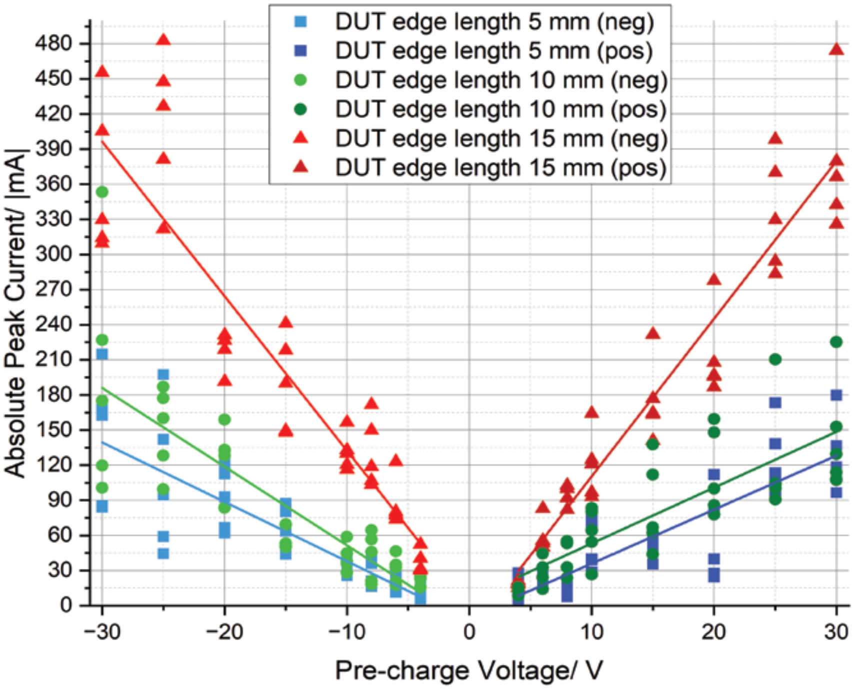

Figure 3: Measured peak currents for pre-charge voltages <30 V

Looking ahead, further statistical data collection is essential, necessitating the development of an automated measurement setup. Efforts are already underway to create a redesigned discharge current sensor that will allow high-volume measurements.

REAL-WORLD APPLICATION: IN-SITU MEASUREMENTS

The research progressed to in-situ measurements within a state-of-the-art pick-and-place machine. An isolated picking tool and fully metallized dies were employed to emulate the worst-case scenario. The tests consisted of picking a die (edge length 10 mm) from a blue tape carrier and placing it on the pogo-pin of the DCS. These tests illustrated that factors such as tool speed and the time between picking and placing of components significantly affect the discharge currents.

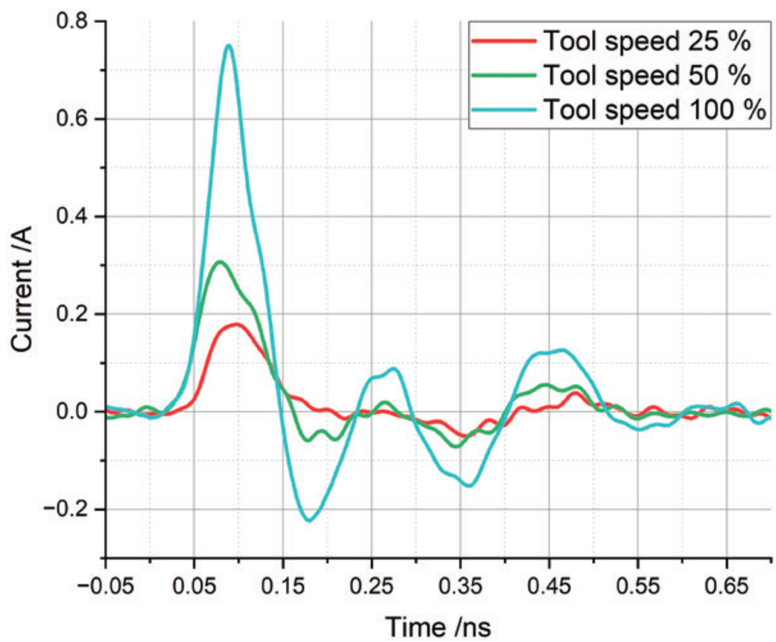

Figure 4: Dependency of the measured current on the tool speed

For instance, as tool speed increased, so did the discharge current, highlighting the need for careful control of assembly parameters to mitigate ESD risks (Figure 4). Additionally, the path taken by the picking tool—whether directly to the sensor or via an alignment camera—also significantly influenced the peak discharge current.

CONCLUSION AND FUTURE DIRECTIONS

This research introduced a DCS designed for in-situ ESD measurements in assembly machines. Laboratory experiments established a link between voltage levels and measured discharge currents, providing initial statistical data across three different device sizes. Notably, the discharge curves observed do not align with extrapolated data of the JS-002 standard, exhibiting lower peak currents, faster rise times, and shorter pulse widths. Additionally, tests in a pick-and-place machine reveal higher ESD risks associated with increased tool speeds and reduced intervals between charging and discharging the die. The sensor serves as a valuable tool for verifying and enhancing production machines, offering insights into assembly process risks that can help MCM and SiP designers in optimizing ESD protection tailored to specific needs.

Looking ahead, further statistical data collection is essential, necessitating the development of an automated measurement setup. Efforts are already underway to create a redesigned DCS that will allow high-volume measurements.

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