APRIL 2025

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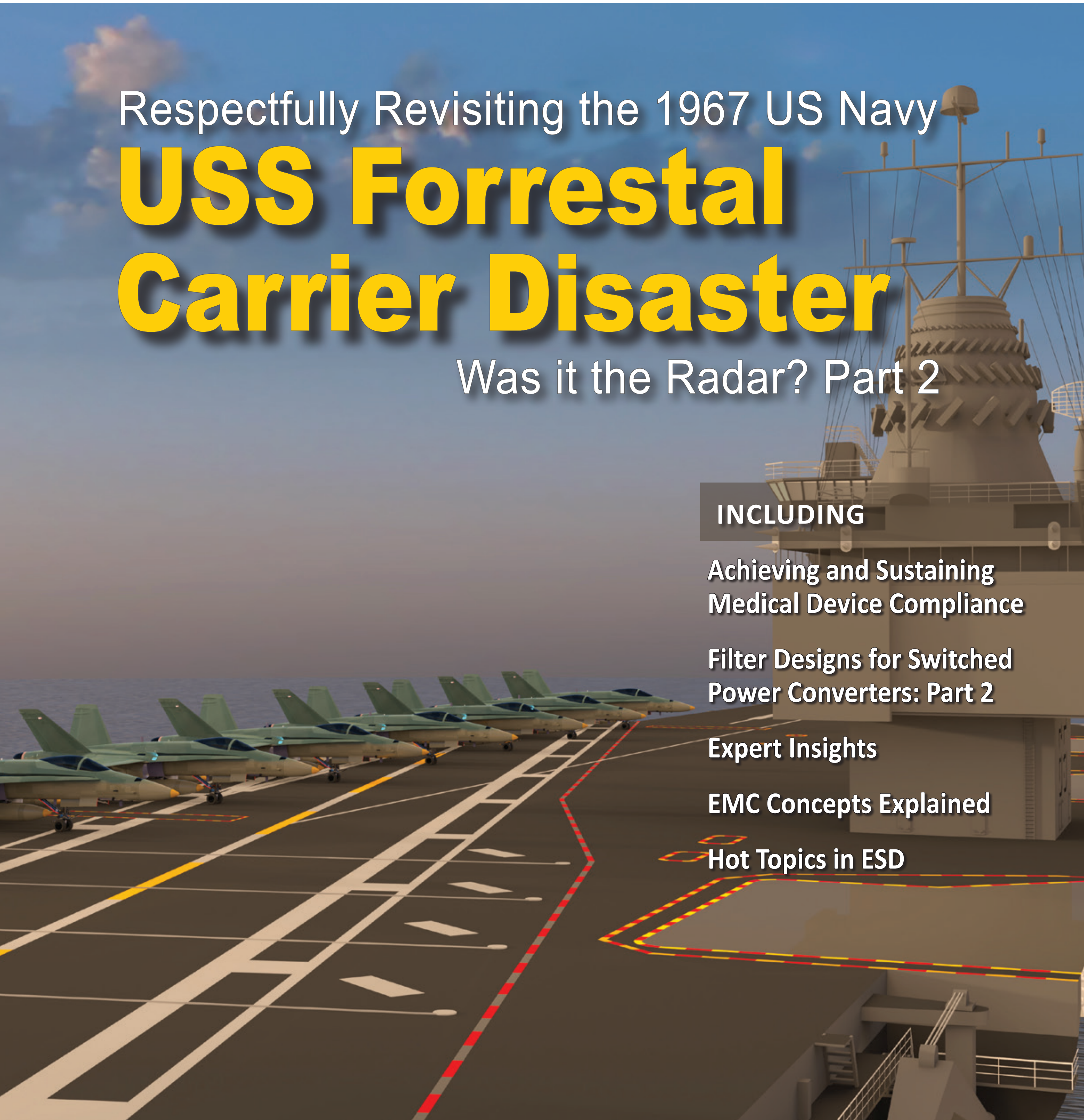

Respectfully Revisiting the 1967 US Navy

USS Forrestal Carrier Disaster

Was it the Radar? Part 2

INCLUDING

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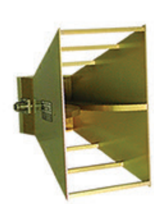

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FEATURE ARTICLES

COLUMNS

DEPARTMENTS

Companies Seek Waiver of Rules for UWB Systems

Tesla and two additional technology companies are seeking waivers of current U.S. Federal Communications Commission (FCC) regulations to obtain equipment authorization to use advanced ultra-wideband (UWB) technologies in their respective products.

According to a Public Notice issued by the Commission, Tesla is seeking a waiver of current UWB restrictions to implement a UWB optimal positioning system that would operate in the 7.5-8.5 GHz frequency range to facilitate the wireless charging of its electric vehicles.

Concurrently, U-tec Group is seeking a waiver so that the company can secure an equipment authorization for a UWB door lock system called ULTRALOQ that would operate in the 6-10 GHz frequency range. And Lumi United Technology is seeking a waiver for its own UWB door lock system that would also operate in the 6-10 GHz range.

EU Commission Issues Infringement Decision on Failure to Transpose EU RoHS

The Commission of the European Union (EU) has stepped up its efforts to ensure that Member States implement the provisions of the EU Directive on hazardous substances in electrical and electronic equipment.

According to a press release, the Commission has issued infringement decisions to 27 individual Member States for failure to notify the Commission of their transposition efforts related to 11 different EU directives. The notices cover directives addressing the reporting of air pollutant emission projections, the exchange of information between law enforcement authorities in Member States, ferry safety, and others.

Of greatest significance to our readers is the Commission's infringement notice issued to Cyprus for its failure to communicate its actions to date to implement the provisions of the EU's Directive on the restriction of hazardous substances in electrical and electronic equipment (EU 22014/1416, more widely known as the RoHS Directive). Cypress has two months from the date of the Commission's infringement notice to provide the Commission with an update on their efforts and to complete the transposition of the RoHS provision into national law.

U.S. Senate Moves AM Radio for Every Vehicle Act Out of Committee

Bi-partisan legislation that would mandate access to AM radio technologies in all new vehicles sold in the U.S. has passed another milestone.

The U.S. Senate Committee on Commerce, Science, and Transportation voted to approve S.315, otherwise known as the AM Radio for Every Vehicle Act. The legislation mandates that U.S. consumers continue to have access to AM radio technology in new vehicles sold in the country.

In recent years, there has been much discussion about whether AM legacy technology should continue to be installed in new vehicles. However, broadcasts on the AM band can provide a critical communications lifeline in natural disasters when other radio technologies go offline.

A companion bill to S.315, H.R. 979, was introduced in the U.S. House of Representatives shortly after the Senate Committee's action. The companion legislation, H.R. 979, will now be forwarded to the House Commerce Committee for review and discussion.

FCC Blocks Equipment Sales After False Authorization Claims

The U.S. Federal Communications Commission (FCC) is proceeding with efforts to block the sale of previously authorized communications equipment from a China-based company.

According to an Order to Show Cause issued by the Commission, Luminys Systems Corporation submitted false statements and other information in connection with the company's applications for two separate FCC equipment authorizations.

Specifically, the company stated in its applications that the equipment was not produced by an entity under the Commission's "Covered List" of producers whose communications products are ineligible for equipment authorization. However, Luminys reportedly obtained authorization for two separate devices, both designed for use in a mobile solar trailer, which were produced by Luminys entity Dahua, an entity that is listed on the FCC's Covered List.

The Commission implemented regulations in 2024 that prohibit entities on its "Covered List" from participating in the FCC's equipment authorization program. Entities on the Covered List are those that, in the Commission's view, "pose an unacceptable risk to the national security of the United States or the security and safety of United States persons." The Covered List includes major global wireless manufacturers, including Huawei and ZTE, which reportedly have ties to the government of the People's Republic of China and Chinese state-owned enterprises.

Immediately following the issuance of the Commission's Order to Show Cause, Luminys filed for an extension of time to respond to the Order. However, the extension request was promptly denied by the Commission due to "an unacceptable risk to national security."

EMC BENCH NOTES

Troubleshooting with a Nearby Antenna

By Kenneth Wyatt

Over the last several months, we showed how to use near-field probes to characterize and interpret dominant harmonic energy sources on PC boards and how to use RF current probes to characterize the coupling of these energy sources to power and I/O cables. This time, we'll discuss how to use a nearby antenna to monitor actual emissions from a product or system.

While many designers attempt to perform radiated emissions troubleshooting at an outdoor site or in a semi-anechoic chamber using a third-party test lab facility, I've found a much more efficient method is to perform this using a nearby antenna right on your own work bench (Figure 1). Performing this testing in-house also allows additional tools and resources to be close at hand.

Best of all, a calibrated EMI antenna is not really required, as all we care about are relative changes! In one case, I was testing an industrial printer and connected a 1m-long piece of wire to the spectrum analyzer and stretched it out nearby. I've even had clients use a nearby Wi-Fi antenna for troubleshooting. So long as you can see the harmonic emissions, you can try various mitigations and observe the results in real time!

Some may question the use of an antenna so close to the product under test, as this is within the near field at the lower frequencies. While near field measurements can't be directly compared to far field measurements, for troubleshooting purposes we're just looking for relative changes, not absolute. For example, if we know we're failing at 230 MHz by 5 dB, then we'll strive to lower that on the work bench by 10 dB or more, just to be safe.

If you wish to compare with actual compliance test lab data, you'll need to space a calibrated antenna at 3m or 10m and account for all the measurement system losses and gains. We'll describe how to do that next time.

Currently, the antenna I prefer is a log periodic design built from PC board material. These are available at low cost from Kent Electronics, and the larger 400 to 1000 MHz model I prefer costs just $53 (with attached SMA connector) as of this writing. While not resonant in the range 30 to 400 MHz where most of the larger harmonic emissions reside, I've found that positioning the antenna about 1m from the EUT allows me to see the emissions well enough to troubleshoot.

I published an article a few years ago that describes how to make the PVC fittings to hold the antenna and fasten it to a simple table-top camera tripod (Reference 1).

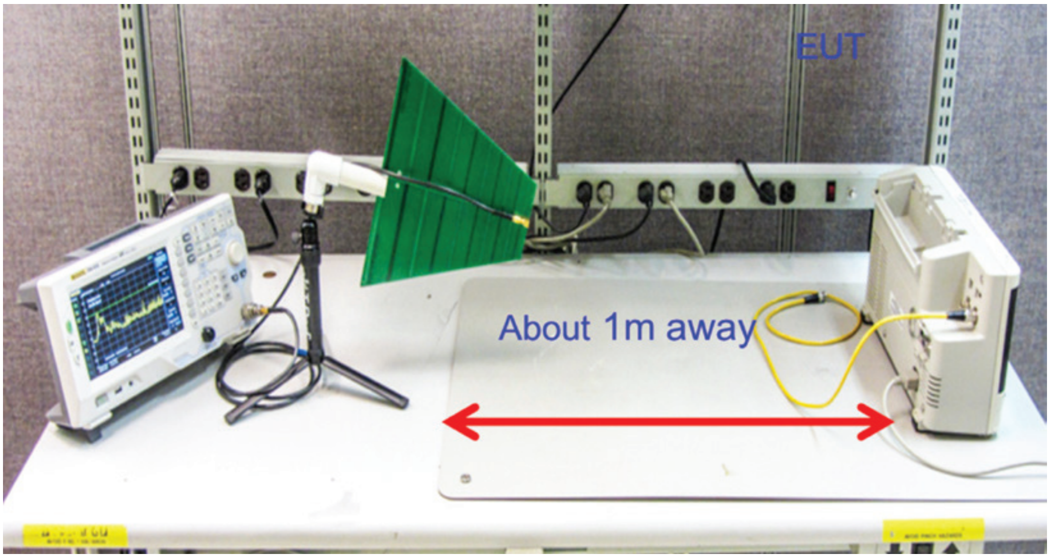

Figure 1: Troubleshooting test setup using a small antenna near the EUT.

TROUBLESHOOTING PROCESS

By now, you should have characterized the emissions profile of the dominant harmonic energy sources within your product using near field probes, as well as characterized the couplings to interior and exterior cables using an RF current probe.

With this data in mind, it should be easier to identify the specific sources and couplings that result in radiated emissions. The usual "radiating structures" will include I/O and power cables and seams and apertures in shielded products. For the majority of unshielded products, it will be cable or PC board radiation (or both).

Most narrowband emissions will tend to be grouped around 50 to 300 MHz and are largely due to radiating structures that start to approach 1/4 to 1/2 wavelength. For example, a 1m long cable (typical USB) will resonate at 45 to 100 MHz, depending on whether the shield connects to PC board or line-powered product with a shielded chassis. Refer to my article on cable resonance in Reference 2.

AMBIENT TRANSMISSIONS

One problem you'll run into immediately when testing radiated emissions outside a shielded room is the number of ambient signals from sources like FM and TV broadcast transmitters, cellular telephone, and two-way radio. This is especially an issue when using external antennas.

I'll usually run a baseline plot on the analyzer using "Max Hold" mode for a couple of minutes to build up a composite ambient plot. Then, I'll activate additional traces for the actual measurements. For example, I often have at least two plots or traces on the screen: the ambient baseline and the actual measurement. It greatly helps to become familiar with your area's RF spectrum usage.

Fortunately, there are three ways around this:

1. In most cases, you'll observe a range of product emissions in a harmonic relationship. Very often, these harmonics are created from the same source, and if one or more are masked by ambient signals, then working on the others that are more visible will generally bring the whole batch down, as well.
2. In some cases, there will be a critical harmonic masked by an ambient transmitter. A common example is a 100 MHz harmonic hidden underneath a strong FM broadcast station at the 99.9 MHz channel. In this case, I'll try reducing the resolution bandwidth from 100 or 120 kHz down to as little as 1 kHz or less. This often "filters out" the modulation from the FM station, allowing you to observe the hidden harmonic. This also presumes the harmonic is an unmodulated continuous wave (CW) signal. Just be sure reducing the RBW doesn't also reduce the harmonic amplitude. If your harmonic is modulated, this may not work, so you could try selecting a higher related harmonic, as in (1).
3. Move your testing well away from urban transmitters (easier said than done these days) or test in the early morning hours.

Remember that strong nearby transmitters can affect the amplitude accuracy of the measured signals as well as create mixing products that appear to be harmonics, but are really combinations of the transmitter frequency and mixer circuit in the analyzer. You may need to use an external bandpass filter at the desired harmonic frequency to reduce the effect of the external transmitter. An example would be an FM broadcast band "stop band" filter.

MITIGATING COUPLINGS PATHS

Now that we can observe the actual emissions from the EUT, we need to turn our attention to the coupling paths that connect the internal energy sources to radiating structures. In the near field environment of a typical table top product, we'll most likely be dealing with capacitive and inductive coupling.

Capacitive coupling is mainly due to large changing voltages with time (high dV/dt) and can be modeled as two plates near each other. A good example is the fast-changing switching voltage of a typical DC-DC converter. The coupling could be occurring between the switch device's heat sink and a nearby ribbon or flex cable.

Inductive coupling is mainly due to large changing currents with time (high di/dt) and can be modeled as two loops near each other. Cable-to-cable coupling is a good example. Another example would be cable-to-transformer coupling.

If clock harmonics are being coupled to cables and radiating, then you'll need to look at your PC board layout and stack-up. Are clock traces running too close to I/O traces? Is the clock oscillator or resonator located too close to an I/O connector?

When it comes to internal PC board couplings I find it's often due to a poor choice in stack-up design. For best EMC performance, every signal layer should have an adjacent solid return plane. As well, every power plane or routed power layer should also have an adjacent solid return plane. For more information, refer to my series on low-EMI PC board design with part 1 starting in Reference 3.

System-level issues can also lead to radiated emissions. For example, how internal cables are routed can make a big difference. Is there an internal flex cable routed too close to one of your high-energy sources? Are motor drive cables routed in the same bundle as sensor or I/O cables? Known noisy cables should always be separated from quiet signal or I/O cables. A really good troubleshooting technique is to remove I/O cables one by one while monitoring with the antenna.

For shielded products, all sheet metal must be bonded together at frequent intervals. Long seams between enclosure pieces can act as radiating antennas if the length starts approaching 1/4 to 1/2 wavelength. Ott (Reference 4) has a chart of shielding effectiveness versus slot length versus frequency. For example, a slot length of 2 inches (5cm) has a shielding effectiveness of only 10 dB at 1000 MHz. A good design goal would be a shielding effectiveness of 20 dB, which would require seam lengths of just 1/2-inch (about 13mm) at 1000 MHz. Keep this in mind for ventilation patterns.

Adhesive copper tape is a good troubleshooting tool when applied over possible seams (Figure 2). A near field probe (either H- or E-field) can help identify longer seams. I typically use a marking pen to identify the beginning and end of a leaky seam. Then, I can measure the length and use that with the dominant frequency to assess whether the seam is approaching resonance.

For products with metal enclosures, apertures, like LCD displays, keyboards, and ventilation holes can also be sources of emissions. A common issue with LCD displays is the lack of bonding between the display housing and product enclosure. Using copper tape or EMI gasketing are good mitigating techniques. It's not unusual for me to cover an entire product with heavy-duty aluminum foil during troubleshooting while I carefully cut out around potential apertures one at a time in order to identify the dominant emission source (Figure 3).

SUMMARY

The last several installments of EMC Bench Notes have covered my basic approach to troubleshooting one of the most common EMC issues, that is, radiated emissions. My process of characterizing energy sources with near field probes and then measuring cable harmonic currents with a current probe and following up with a close-spaced antenna has proven to be a fast and efficient way to attack emissions over several decades. I'm sure it will help you as well.

Next month, we'll explore how to set up an in-house or temporary pre-compliance setup for measuring absolute levels of radiated emissions where you can compare to official test limits. While there are obvious issues when testing outside a shielded semi-anechoic chamber, this method will help confirm pass/fail well in advance of final compliance testing.

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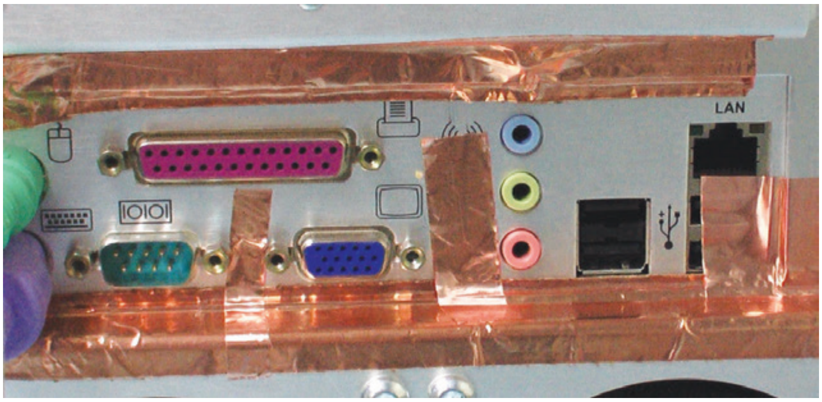

Figure 2: Sometimes, liberal use of copper tape is required over seams!

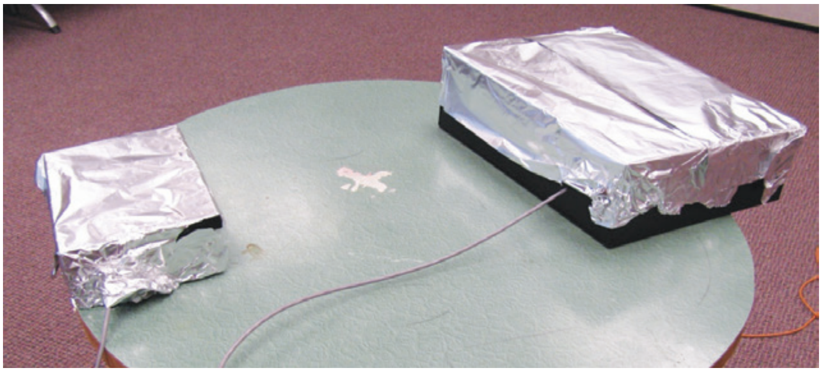

Figure 3: If it becomes too difficult to identify which seams or apertures are "leaky," covering the product completely with heavy-duty aluminum foil and cutting our small sections may help.

MILITARY AND EMC AEROSPACE

Grounds and Returns

By Patrick André

Looking back at the 2024 IEEE International Symposium on EMC, the one concept that is still ringing in my ears is what is often called "ground" but is actually a power or signal return or reference plane. The reason is that what is commonly called "ground" and what is a power or signal return, or that of a reference plane, is not the same. There were several talks on this concept given by many people who are much brighter than I am and have proven to me they know what they are talking about. And yet, I recently read an article whose author seemed confused about what a ground was.

The concept of electrical "ground" has its basis in the "earth-return telegraph" and the first telephone connections. Signal lines were routed between two points, but the return path used was the ground, literally the earth. The earth is also used for electrical safety return paths, neutral reference, and split phase power reference. In the United States, the electrical power panel in the home or commercial locations (when correctly installed) have the neutral lines and safety grounds tied to a common bus bar, which should be routed to a ground rod near the power panel.

When a signal line is routed in a wire with an adjacent return, or when a power or signal trace is routed over a return plane, the adjacent wire and return plane should not be considered "ground," and I recommend not addressing it as such. Far too often, I have worked with an engineer who will create a wonderful filter for the power line and have a number of capacitors from power to return without having any inductance or other filtering on that return line. This is typically because the designer has a concept that the return is "ground" and treats it as a hole to throw all types of electrical noise into. The results are usually not desirable as found when the EMC laboratory performs conducted emissions on the return lead.

Consider this: A system uses 28 VDC aircraft power. There will be 28 VDC on the pins of the input connector. What if the same system used +14 VDC on one pin and -14 VDC on the other pin? The voltage applied would still be 28 VDC between the power and return pins, but now, instead of considering the return a "ground," the designer must consider it a -14 VDC return power. How would the design change? When I asked designers this, they said the -14 VDC line would need the same type of filtering used on the +14 VDC line—correct answer.

But this is the same for the 28 VDC return line. It should not be considered as a ground but as a power line with a voltage that happens to be near a zero-volt reference. The return line is a current caring conductor, having inductance in the lead and traces, capacitance with other metal in the area (wires, traces, components, chassis, and so forth), and can allow radio frequency energy to flow in and out of the equipment on that line. Unimpeded, the return becomes a source of emissions and a path for susceptibility to enter the equipment.

But what of voltage? An aircraft may become charged during flight, and without earth nearby when flying at 33,000 feet, the voltage of the whole structure may shift up or down significantly. At the input connector of the system, the power line may be at 10,000 volts while the return is at 9,972 volts; a difference of 28 VDC appears across the power pins, and the system operating the same as it did when referenced to a 0-volt earth ground. Thus, voltages are relative between two points and may be significantly different than remote locations. However, this is not a concern for us.

A difficulty can arise when a system power or signal return is referenced to the structure of the vehicle. Power and signal return may be the aircraft frame, tank, or vehicle chassis, but this is avoided in Naval ship power to avoid both corrosion and magnetization of ferrous materials in the hull. When a power or signal is routed in a wire to some remote connection location, and the return path is the vehicle structure, a large loop area is created between the current flowing in the two paths. This large loop can create radiated emissions problems with less than 10 µA of radio frequency current. Similarly, currents induced into those wires or into the structure from external sources can induce susceptibility in the system. These signals are considered common mode signals since they flow in or out of one or more wires from the equipment but return by a path that is not adjacent to these wires.

In my next article, I will discuss the concepts of common and differential modes in more detail, loop areas, why they are a concern, and other aspects of current flow.

WAS IT THE RADAR?

Respectfully Revisiting the 1967 US Navy USS Forrestal Carrier Disaster Part 2

Re-examining the Historical Records to Reaffirm the Disaster's Root Causes

DEDICATION

This article is humbly dedicated to the families, relatives, and friends of the 134 Sailors killed and 167 severely wounded on July 29, 1967 aboard the USS Forrestal. We honor the hundreds of additional survivors who suffered from a lifetime of PTSD and "survivor's guilt." The bravery and heroics of the Sailors who saved the USS Forrestal and its 5,400 lives by quenching the fire and preventing the carrier from capsizing cannot possibly be overstated.

Dr. Brian Kent is an engineering consultant and adjunct professor at Michigan State University. His 37-year USAF career included roles as the Chief Technology Officer (AFRL), Chief Scientist (AFRL Sensors Directorate) and Senior Scientist for Low Observable Technology. He supported NASA's Columbia investigation and Shuttle missions, holds multiple IEEE fellowships, and received a Presidential Rank Award. He's passionate about naval aviation history. Kent can be reached at brian.kent.phd@gmail.com.

By Brian M. Kent, Ph.D.

In 1967, while on patrol in the Gulf of Tonkin, the United States Navy Carrier USS Forrestal was executing wartime missions over North Vietnam. At 10:45 am local time, the ship was preparing to launch more than 27 A-4 Skyhawk and F-4B Phantom Fighter jets, all fully fueled and armed with a mixture of iron bombs, precision missiles, and Zuni rocket launchers. At 10:51 am, an F-4B experienced an un-commanded Zuni missile launch on the flight deck, striking a neighboring A-4 and starting a fire, causing a series of devastating secondary explosions. Quenching the fire nearly capsizes the ship, which is ultimately saved through the heroics of the sailors who served aboard the Forrestal.

Although the US Navy conducted an extremely thorough accident investigation, many subsequent technical articles in the aerospace and NASA literature, including current EMI design books, blame the initiation event on EMI from the onboard AN/SPS-43 VHF search radar. This article is aimed at reinforcing the official USN record regarding the accident's true root cause. The Forrestal's many "lessons learned" led in part to the creation of an entirely new discipline called "insensitive munitions" within the Electromagnetic Compatibility community and is therefore a critical event to understand.

In the February 2025 issue of *In Compliance* Magazine, Part 1 of this article laid the critical groundwork to describe how the US Navy conducted peacetime and wartime carrier operations in 1967 during the Vietnam War. Combat carriers were stationed 60 miles off the coast of North Vietnam in the Bay of Tonkin at a location named "Yankee Station." The supercarrier USS Forrestal (CVA-59) had transited from Norfolk, Virginia to Yankee Station, arriving on July 25, 1967. In Part 1, we presented the fateful events preceding the launch of the planned 1100-hour-long strike mission on July 29, 1967. We described how air operations were conducted, what equipment was used, what the deck personnel were doing, and some fateful decisions made in the days and moments leading up to the event.

We now pick up our story at 10:40 am local time on the flight deck of the USS Forrestal on July 29, 1967. Pilot Jim Bangert was in his F4-B cockpit preparing for the 1100 strike launch. His Brown Jersey plane captain had signaled the deck crews to bring over and attached the F-4B ground start cart necessary for Jim to start the two engines of his F-4B. His aircraft was equipped that day with two LAL-10 launchers, each with three 5" Zuni rocket launchers with a total of 24 rockets.

JULY 29, 1967 – YANKEE STATION AT 10:40 AM – THE ACCIDENT INITIATION

On the morning of July 29th, the USS Forrestal had plans to launch three separate strikes, one at 0700, one at 1100, and one at 1500. The strikes each consisted of a mix of aircraft, but we'll focus here on the air-to-ground missions of the A-4s and F-4Bs. Knowing full well the danger of holding the 26-year-old AN-M65A1 1000 lb. bombs on the carrier's "bomb dump" behind the main deck island, Captain Belling directed that all 26 weapons be expended on July 29th. Ten of these bombs were loaded on 5 A-4s and safely departed the ship on the 0700 strike launch without incident. Ten more AN-M65A1s were scheduled to go out on the 1100 strike, and the remaining six on the 1500 strike. At 10:40 in the morning, the last six AN-M65A1s did not yet have their "tail fin kits" installed when they arrived from the ammunition ship Diamond Head, so these six were sent midmorning down to the hanger deck to have the fins fitted for the 1500 strike mission.

At 10:40 am, all of the planned 27 combat aircraft for the 1100 launch were in various states of preparation and readiness. Aircraft were prepositioned and spread among the two front catapults (Catapult #1 and Catapult #2) and the two waste catapults on the angled deck (Catapult #3 and Catapult #4). Usually, the first aircraft to be launched were the S-3 tankers, A-3 reconnaissance aircraft, the E-2 Hawkeye radar surveillance, and the vanguard helicopter that takes station astern of the carrier during launches in case a pilot ditches their plane. These aircraft were being jockeyed in forward Catapults 1 and 2. The main body of strike aircraft composed of A-4s and F-4Bs were spread across the aft of the Forrestal and were to be launched on the waste Catapults 3 and 4. Already fueled, the ground carts began to circulate amongst these strike aircraft to start their engines.

Jim Bangert was an F-4B pilot assigned to aircraft #110, his aircraft currently occupying the furthest aft and starboard (right) side of the flight deck. As parked, he was angled slightly to the left. Bangert's F-4B would be using the new Zuni 5 rocket weapon system, and he had found out only moments earlier at his preflight briefing that his aircraft would be using the Zuni rocket system. Bangert was exceptionally safety conscious, and he served as his squadron's armament safety officer. Bangert was uncomfortable with the deck Red Shirt arming crews plugging in the LAL-10 launcher power "pigtails" before the catapult. His crew assured him that this new procedure was "approved." He knew the LAL-10 TER safety pin was his ultimate safety backup when he climbed into the cockpit, which gave him some comfort of safety.

Meanwhile, across the deck, A4 pilots Fred White, John McCain, and Dave Dollarhide were prepping their respective A-4 Skyhawk. A total of 5 A-4s on the left aft deck were equipped with two each of the AN-M65A1 1000 lb. bombs along with a 400-gallon JP-5 centerline fuel tank. Because these bombs were not the usual MK82/83/84 class weapon, they were attached to the A-4 using an older canvas strapping system instead of the typical MK80 series hard mount. After visually inspecting their payloads, all the A-4 pilots climbed into their cockpits using an 11 ft. detachable cockpit ladder. Once settled into their cockpits, the Brown Jersey plane captains armed their ejection seats and then removed the 11-foot cockpit ladders. Soon, the ground start cart will arrive, and they'll all be on their way.

At 10:45 am, Weapon Loader Petty Officer 2nd Class James Wilson of VF-11 connects the LAL-10 launcher friction fit power pigtail and removes the TER safety pin on Jim Bangert's F-4 prior to engine start. Bangert is already in the cockpit and knows nothing about the safety pin being removed. His F-4B, with 24 Zuni Rockets, is connected to one of Forrestal's ground start carts. He starts his right and left engines per protocol and lets the engines spool for a few minutes before switching his aircraft to its two internal 400 Hz generators. It is now 10:51 am. The configuration of the Forrestal at this very moment is shown in Figure 1.

Before proceeding further, it is clear that Reference 1 mentioned in Part 1 of this article is amiss. Recall I quoted the following: "A Navy jet landing on the aircraft carrier U.S.S. Forrestal experienced the un-commanded release of munitions that struck a fully-armed and fueled fighter on deck."

The Forrestal was not configured at this moment in time to accept any landing aircraft, it's logistically and physically impossible. This reference is completely debunked.

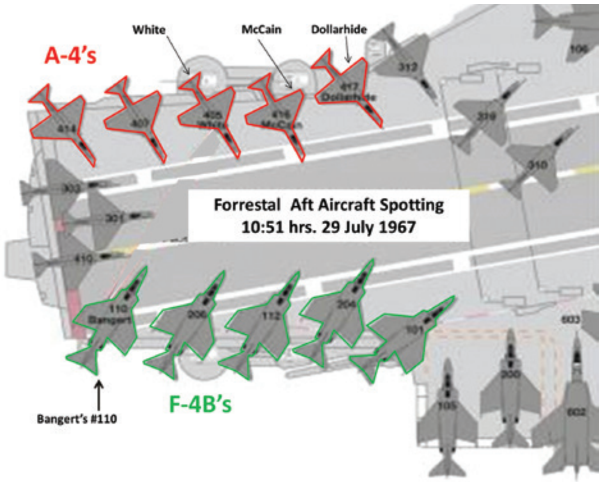

Figure 1: Forrestal aircraft at 10:51 am[25]
Please note: Reference numbers are continued from Part 1

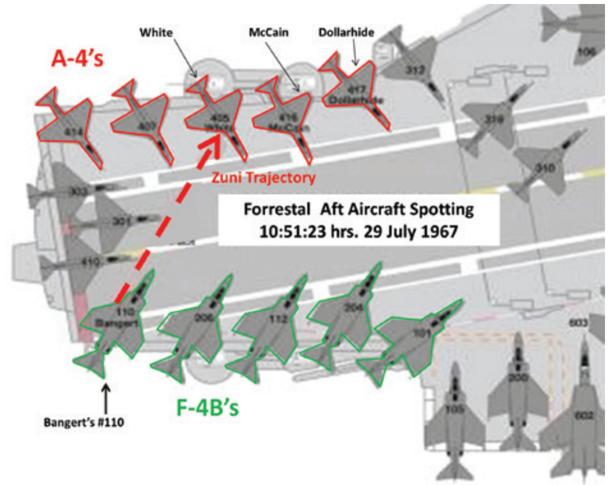

Figure 2: At 10:51:23, Bangert's F-4 fires a Zuni into Fred White's A-4[27]

The moment of the accident initiation is at hand. At this exact time, one may wonder what is currently stationed on Forrestal's flight and hanger decks. Fortunately, there is an exact USN accounting; let's take a moment to review all the flammables on the flight deck.[26]

There were 27 fully fueled and armed aircraft for the 1100 strike. These were armed with ten 1,000 lb. AN-M65A1 bombs, eight 750 lb. AN-M117 bombs, 64 MK82 500 lb. bombs, 144 5" Zuni rockets, each with a 125 lb. warhead, 24 Sidewinder and 23 Sparrow air-to-air missiles, and six Shrike missiles. All the aircraft on deck held a combined total of 40,000 gallons of JP-5 jet fuel. The "bomb dump" behind Forrestal's island on the flight deck held weapons for the planned 1500 strike. These included 34 750 lb. AN-M117 bombs, 22 MK82 500 lb. bombs, two LAL-10 launchers with eight more Zuni rockets, and nine more Shrike missiles. Below deck, the hanger bay #1 contained an additional 53 tons of munitions, including six more of the AN-M65A1 bombs, 73 750 lb. AN-M117 bombs, 35 Mk 82 500 lb. bombs, 16 of the 300 lb. Mk81 bombs, four CBU-24B 830 lb. bombs, two Sidewinders, and two Sparrow air-to-air missiles.

At exactly 10:51:23 am on July 29, 1967, Pilot Jim Bangert, following normal preflight procedures, switched his aircraft from ground start power to his internal left and right aircraft generators by switching the two switches shown in Figure 7 in Part 1 of this article. Throwing these switches sent a power transient throughout the jet, including to the LAL-10 plug and its Zuni payload. Bangert felt a Zuni rocket launching which struck an opposing A-4 Skyhawk with Lt. Commander Fred White in the cockpit (see Figure 2). He testified later his F4-B master ARM was off, his right hand was on the two power switches above, and his left hand was on the throttles and not on the F4-B control column.

Streaking across the flight deck, the Zuni took the shoulder off a Brown Jersey across the deck, then struck Fred White's external fuel tank, causing it to instantly explode and rupture. Shrapnel from the Zuni explosion penetrated two neighboring A-4 fuel tanks, spilling a total of 1200 gallons of burning JP5 on the deck. Furthermore, the jarring explosion from the Zuni knocked both of Fred White's AN-M65A1 bombs attached to his aircraft to the deck. While they didn't explode on contact because the arming spinner hadn't been activated, they were sitting amidst 1200 gallons of burning JP-5 fuel. Within five seconds of the Zuni strike, queued by the explosion, the PLATS camera operator Petty Officer Third Class Vince Ignizio turned his camera aft and begins to film the unfolding disaster.

FIRE ON THE FLIGHT DECK AFT!

Immediately across the entire flight deck, heads turned and instincts kicked in. Get the fire out, grab hoses, foam hoses, extinguishers, anything. Help the wounded, of which there were plenty. Those closest

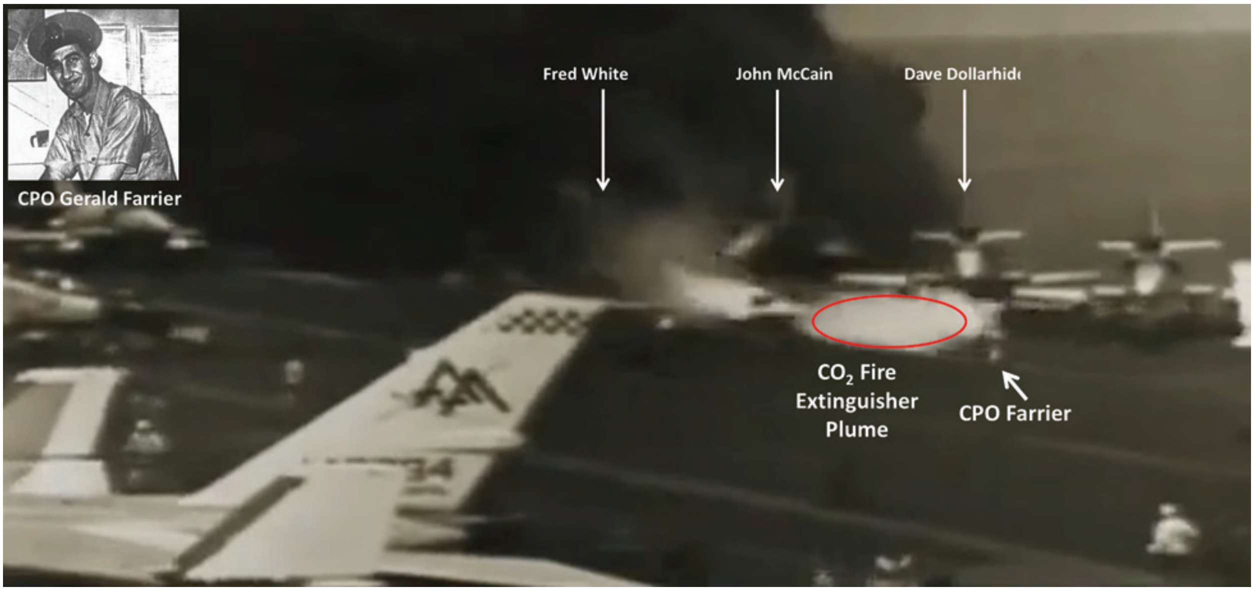

Figure 3: PLATS camera footage at 10:51:31 (t+12 seconds) as CPO Farrier dashes towards the fire[28]

to the fire recognized the dangers immediately. Away from the fire, plane directors and catapult operators immediately ceased operations and started evacuating pilots or moving aircraft forward and out of danger. Those wounded and on the deck cried for help, and sailors from all corners begin to converge. The fire must be stopped.

The Forrestal's Repair 8 squadron was chiefly responsible for aircraft crash, recovery, and fire control. Their leader, Chief Petty Officer Gerald Farrier (Figure 3, inset), was considered the finest trained firefighter in the entire Atlantic fleet. If a fully fueled aircraft caught fire, Repair 8's firefighting team was trained to quell JP-5 fuel fires within one to three minutes using a combination of foam and carbon dioxide (CO_2) fire suppressants. When Fred White's fuel tank exploded, CPO Farrier grabbed a CO_2 fire extinguisher and dashed out to White's burning A-4 within 30 seconds of the Zuni strike. Since the PLATS camera had now swiveled aft towards the fire, the entire accident scene was filmed within five seconds of the Zuni strike. Figure 3 shows the PLATS camera at 10:51:33 am, only twelve seconds after the Zuni. It shows CPO Farrier running and initiating the CO_2 extinguisher while his eight Repair 8 shipmates were seconds behind him, dragging foam hoses. Four nearby seamen were dragging a 2.5" saltwater fire hose, including Yellow Jersey Air Boss Aviation Boatswain Mate Dave Dickerson from Catapult 3.

Meanwhile, Brown Jersey plane captains tried desperately to get pilots out of their A-4s without having their 11-ft. cockpit exit ladders nearby. Lt. (j.g.) Dave Dollarhide jumps from his A-4 awkwardly and breaks his hip and elbow when he lands on his side. Flat on the burning flight deck with a broken hip and elbow, he is somehow dragged to safety by deck personnel. Next to him, Lt. Commander John McCain tightropes on his refueling probe and jumps to the deck in the middle of a burning JP-5, severely bruising his ribs and receiving multiple burns. He, too, escapes and heads to the sick bay to treat his injuries. Finding the sick bay overwhelmed, McCain runs to the hanger deck to help with firefighting and weapons disposal. Fred White is initially trapped but miraculously escapes with the help of his brave plane captain and Brown Jersey ground crew.

Now, under White's A-4, CPO Farrier immediately noticed something was seriously wrong. He spots the two AN-M65A1 bombs on the deck in direct contact with the fire, both split, sizzling, and leaking deadly explosives. Though he tries desperately to quench the two bombs with CO_2, he knows it's hopeless since these

AN-M65A1 bombs were not fire-rated. Turning around, he desperately tries to waive away the rest of the Repair 8 and the other firefighters because detonation is imminent.


Figure 4: PLATS camera records the first AN-M65A1 1000 lb. bomb explosion at 10:52:55[29]

At 10:52:55 am, 94 seconds after the Zuni strike, the first of Fred White's AN-M65A1 bomb explodes, instantly killing 28 sailors on deck, including the entirety of the Repair 8 firefighting team and CPO Farrier. The PLATS camera operator, Petty Officer Ignizio, records the catastrophic moment of detonation in Figure 4.

Aviation Boatswain Mate Dave Dickerson recounts the moment.

> *"I see the initial fire developing. I know the importance of getting a jump on the growing flames. I run aft to join up on a fire hose. Running on an angled path towards the starboard catwalk, I arrive at a saltwater fire station in the catwalk near the boat and aircraft crane just aft of the elevator. I helped break out the hoses and handing them up to the flight deck while the saltwater was charged."*
>
> *"On the flight deck, I climbed out of the starboard catwalk and join others manning a charged saltwater fire hose as it is advancing towards the fire. Then bam! The next thing I know, I've been blown backward along the deck by the first explosion. I jump back to my feet, and to my total surprise I was uninjured!"* [30,31]

Dave Dickerson's shipmates on the fire hose were all killed instantly.[31] Getting up again, Dave charged back into the blazing inferno, grabbing yet another fire hose.

The initial blast creates a ten-foot diameter hole in the armored flight deck. Beneath the gaping hole were sleeping berths where 60 sailors died instantly in their beds. With all the nearby damaged aircraft gushing JP-5 fuel, thousands of gallons of burning JP-5 now flow below, causing massive fires below deck. At 10:53:01 am, just 9 seconds after the 1st explosion, a second AN-M65A1 bomb explodes, again recorded by the PLATS cameraman PO Ignizio (see Figure 5).

Figure 5: PLATS camera records burning debris raining down after the 2nd explosion[32]

The third explosion shatters most of the windows in the Forrestal's island area called "PRI-FLY," where the PLATS camera operator PO Ignizio worked. While everyone else in PRI-FLY was hunkered below the steel window frames, PO Ignizio stayed behind his camera and continued to record. Over the next four minutes, four additional AN-M65A1 bombs exploded. Chaos now reigns on the deck, with burning aircraft, ordinance, fuel, and debris flying everywhere. It's 10:56 am and the desperate fire battle begins in earnest.

Captain John Belling (Figure 6) was just returning from his cabin when the fire started. Arriving at the bridge when the first explosions hit, he issued a series of critical orders. He reversed engines to slow the ship so that the deck fires were not fanned by 39 mph deck winds. He ordered condition "ZED" to close all watertight doors and to contain the fire in specific sections of the ship. While this did trap some sailors in burning spaces, it very likely saved the ship. He ordered deck crews by the bomb dump, on the flight deck, and on the hanger deck to throw overboard all ordinance and to push overboard as many burning aircraft as possible.

Figure 6: Captain John Belling[33]

Non-commissioned sailors throughout the ship mobilized thousands of sailors to attack various aspects of the fire. Many of these brave sailors were not trained to fight fuel-fed fires, and their use of saltwater hoses

Figure 7: The Forrestal at 10:57 AM[34]

frequently moved the burning fuel around instead of extinguishing it. But they learned fast and charged the maelstrom both above and below deck without regard for personal safety.

By 10:57 am, the overall situation was grave indeed. Thousands of gallons of JP-5 were pouring below decks in multiple flight deck holes (see Figure 7).

Meanwhile, below deck in damage control, Chief Engineering Officer Commander Mervin Rowland was dealing with several very serious issues. By 11:00 am, millions of gallons of seawater pumped below decks to fight fires cause the USS Forrestal to list significantly to port. Carriers are by nature top-heavy, and the ship rapidly approaches the point of capsizing, endangering the entire 5,400-man crew. Since this carrier is fuel-oil-powered instead of nuclear-powered, Captain Belling ordered Commander Mervin Rowland to pump all fuel oil to the port tanks. His quick execution of this order reduced the list and saved the ship from capsizing. Meanwhile, the USS Rupertus drew alongside and, in a feat of incredible seamanship, kept station with the moving USS Forrestal with only a few feet separating them while lending their fire hoses to the battle (Figure 8).

Commander Rowland also had two other catastrophic problems to contain. To prevent the JP-5 fuel lines from further contributing to the fire, he ordered the entire ship's fuel system purged with inert CO_2 gas. Next, he realized the intense fire on the hanger deck was rapidly advancing toward the ship's 750-gallon liquid oxygen (O_2) tank. This tank is used to fill the oxygen bottles of the ship's aircraft complement, and if the fire reached it, it would act like an accelerant and cut the ship apart. Normally, a crew of six sailors would take control of this O_2 tank, but because of the intense fire and condition ZED, only Sailor Robert Clark was able to get to his general quarters station by the O_2 tank.

Commander Rowland ordered Sailor Clark to empty the tank overboard, but this contingency was never planned for in the design of the tank. Sailor Clark found a valve on the tank's lower side. He scrounged up a 1" garden hose, hooked it up, and dragged the end of the hose to the edge of the hanger deck overboard. He then discharged the entire

Figure 8: Listing USS Forrestal with USS Rubertus (DD851) assisting[35]

750-gallon contents of the O_2 tank safely overboard, with the angry deck fire only 20 feet away from him!

The final big problem Commander Rowland faces involves the Forrestal's steering. The USS Forrestal was designed with redundant steering controls on the port and starboard aft end of the ship. Steering controls were normally relayed electronically from the bridge, but the intense fire on the hanger deck aft had cut off the port steering room from the rest of the ship. Three sailors were trapped in port steering, including Sailor James Blakis, who on that day had traded duties with his best friend, Sailor Robert Shelton. Robert was on the bridge recording commands from Captain Belling when he learned of his friend being trapped.

Commander Rowland knew the firefighters wouldn't reach port steering in time to save the sailors there, but he had to have the controls for port steering transferred to the starboard steering room. Despite injuries and the intense heat, James Blakis and his crew successfully transferred the controls. At this point, Captain Belling allowed Robert Shelton to phone down to port steering to say goodbye to his friend James before the fires overwhelmed the compartment.

Despite overwhelming odds, the deck crews extinguished the topside fires in about 2.5 hours. This is in spite of multiple additional ordinance explosions, including a Shrike missile, multiple 20mm cannon rounds, and belts of 50 caliber machine gun bullets going off in the burning aircraft. Below decks, the fires were more persistent and stubborn, but after 17 hours, the last of the flames were extinguished.

At this point, 134 sailors had perished, and another 161 were severely injured. Only 28 of the fatalities were on deck, the rest were below in the sleeping and working berths beneath the flight deck. Of the 73 aircraft on board, 21 were utterly destroyed, and

Figure 9: Devastation on the Forrestal's flight deck as the fires are extinguished[36]

another 40 were damaged, many permanently. In 2024 dollars, damage to the Forrestal exceeded $644 million dollars, with another $537 million of destroyed aircraft and lost ordinance. The scale of the post-fire devastation is evident in Figure 9.

SORTING THE CHAOS – THE POST-ACCIDENT INVESTIGATION

After quenching the fire, the USS Forrestal was initially ordered to Subic Bay in the Philippines. After being made seaworthy, the Forrestal was ordered to return to Norfolk for repair and refit. During the return voyage, an accident board chaired by Rear Admiral Forsyth Massey (Figure 10) was convened aboard the Forrestal.

Figure 10: Rear Admiral Massey[37]

During the long homeward voyage, Admiral Massey and his board interviewed nearly everyone on the flight deck and all the pilots, including Jim Bangert. Massey's surviving aircraft evidence was non-existent, as Bangert's F-4 and nearly all the A-4s were pushed overboard to quell the fire. Since the entirety of the Repair 8 firefighting crew was killed, he lacked much of the "hard evidence" an accident board would normally have.

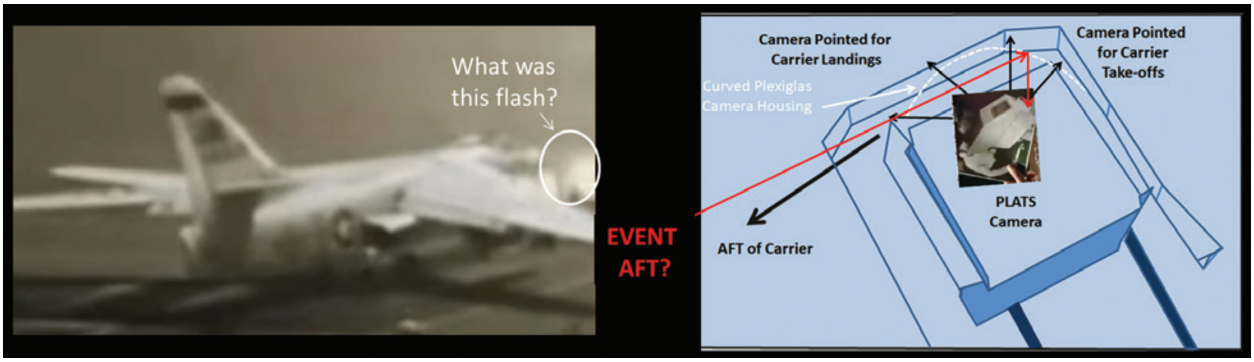

Figure 11: PLATS capture at 10:51:23 from A-3 Sky Warrior (L) Did the PLATS record something aft? (R) [38]

However, he did have the PLATS video data taken by PO Ignizio, and it turned out to be the key evidence of the root cause.

From the pilot and deck crew interviews, many testified seeing a bright flash from the fantail in the vicinity of Bangert's F-4 #110. As Bangert had miraculously survived, he testified that he felt a Zuni launch the moment he switched over his F-4B from the cart to aircraft power. Looking at other F-4Bs on deck that had survived the fire, Massey ordered that a Zuni Rocket be launched out to sea from an F-4 to see what "safety interlocks" had to be overridden to cause a LAL-10 paired with a Zuni launcher to "fire its weapon."

Several of the accident board members also inquired whether the Zuni launch event could have been triggered by the on-board radar. So, Massey checked the Combat Information Center's electronic records. He found that the AN-SPS 43 UHF radar main beam was pointed forward and slightly to starboard. He also found that prior to the Zuni launch, an S-3 Sky Warrior aircraft was on Catapult 2, awaiting the launch command. As the aircraft hadn't launched when the Zuni fired, the SPS-30 radar would have been pointing forward and in standby mode, awaiting the catapult trigger to turn on and measure the departure velocity. Since the SPS-30 was pointed forward, neither of these radar's main beams were pointed anywhere close to the location of Bangert's parked F-4B on the rear starboard side of the ship.

There was never hard evidence presented with data that implicated either of the onboard radar systems with the actual initiation event. The fact that Bangert stated that the Zuni firing was tied precisely to the moment of switching from ground start to aircraft power ruled out this possibility.

In reviewing the PLATS video, Massey had a complete visual record of everything that happened 10 seconds after the Zuni launch because the PLATS operator PO Ignizio had bravely filmed the entire scene. What about the actual initiation event itself? While reviewing the PLATS footage as it focused on the soon-to-be-launched A-3 Sky Warrior, a weird flash

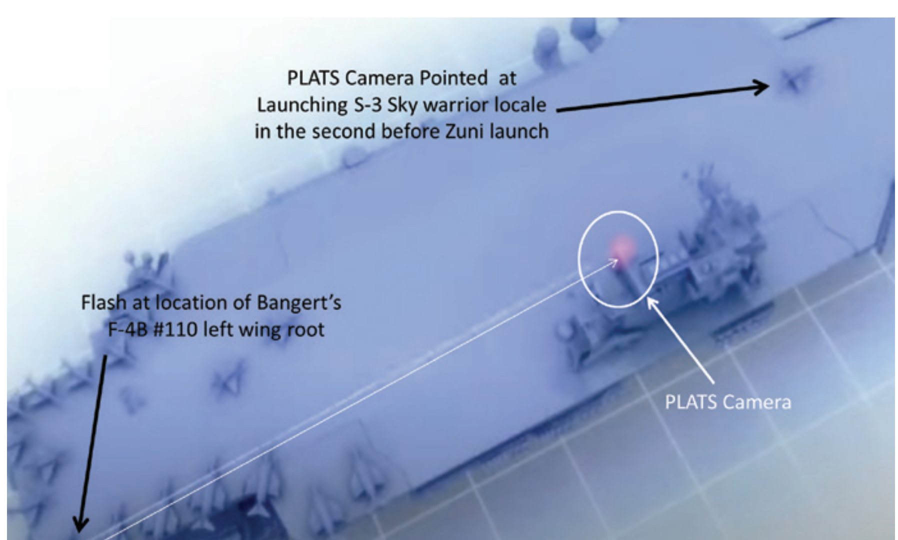

Figure 12: Strobe flash location at Jim Bangert's F-4B wing root recreates the flash in PLATS video[39]

appears forward of the A-3 in the video, as shown on the left side of Figure 11. (To see a 17-second film loop of this flash, go to https://youtu.be/0RiQUK89oug.)

Did the PLATS camera somehow capture the moment of initiation even though it was pointed forward and not aft? This is where Admiral Massey made a brilliant deduction. He remembered the interior of PRI-FLY, where the PLATS camera was located, had a curved Plexiglas housing. After having the housing repaired, he wondered if the PLATS camera looking forward had viewed a reflection of an event that occurred on the aft of the ship (see the right side of Figure 11).

To test his thesis, Massey conjured up an experiment on deck. He equipped a crew with a high-powered strobe flash unit and placed the crew at various positions on the aft of the ship. He had them "fire" the strobe while he was watching the PLATS cameras as it was pointed forward at Catapult 2 just as the day of the accident. When the deck crews went to the starboard side aft and positioned their strobe at the very position of Jim Bangert's F4-B wing root (Figure 12), the flash appeared on the PLATS display exactly as in Figure 11. Not only had Massey proved his thesis, the PLATS system gave him the exact time of the event.

ACCIDENT ROOT CAUSE AND INVESTIGATION CONCLUSIONS

1st Conclusion

The initial flight deck fire on July 29, 1967, at 10:51:23 am local time was caused by F-4B Phantom Jet #110 piloted by Jim Bangert inadvertently firing a 5" Zuni rocket which struck an A-4 Skyhawk #416 piloted by Fred White. The A-4 was loaded with a 400-gal external fuel tank and two AN-65A1 1,000 lb. bombs. The bombs were dislodged from the A-4 and fell to the surface of the flight deck, which was immediately engulfed in flames from 1,200 gallons of spilled JP-5 fuel from three damaged A-4s.

The Zuni fired precisely when Jim Bangert switched from a ground start cart power to his aircraft generator power. The LAL-10 launcher connector was plugged in, and the TER safety pin was pulled. The accident board noted that LAL-10 pigtails frequently had loose or bent pins, and several post-accident inspections revealed shorted or malfunctioning pins on other LAL-10 launchers. While there were technically six interlocks to prevent the firing command from reaching the LAL-10 launcher, there turned out to be little protection for the LAL-10 power line to jump a voltage surge directly to the firing command wire. F-4B voltage surges down the LAL-10 pigtail during ground cart switchover were reproduced in the field and in the lab on other USN F-4Bs. This was confirmed post-accident, as Bangert's F4-B was pushed overboard during the fire.

2nd Conclusion

The initial flight deck fire could have been controlled within 2-3 minutes if the A-4 munitions were standard MK 81/82/83 bombs, which had fire ratings of a minimum of four minutes and up to ten minutes in direct fire contact. Firefighter Gerald Ferrier had a CO_2 extinguisher on the two AN-65A1 bombs within 40 seconds, as confirmed by the PLATS video. His team was pulling foam lines right behind him. However, the original deck fire catastrophically spread after the detonation of seven AN-M65A1 "thin-skinned" bombs. Three additional AN-M65A1s could have been blown overboard in those explosions, otherwise, those certainly would have exploded as well. The first explosion occurred 94 seconds after the Zuni fire started. The second detonation occurred at 103 seconds, and the remaining five explosions occurred within four minutes of the Zuni fire initiation. Note that firefighting was hampered because the entire firefighting Repair 8 squadron was killed in the first explosion.

3rd Conclusion

The third series of findings surrounded the USS Forrestal's firefighting equipment and capabilities. Containing the large fires above and below deck was hampered by a lack of firefighting experience with fuel-fed fires due primarily to the loss of critical Repair 8 personnel killed early in the fire. Trained firefighters know that chemical foam sprayed on top extinguishes fuel fires while water goes underneath burning fuel and spreads it. Much of the burning fuel spilled through the ten-foot deck hole caused by the first explosion and flowed through several lower decks, which burned for the next 16+ hours before being contained.

Despite a lack of formal firefighting training, many of Forrestal's sailors pressed into service fearlessly battled fires and never retreated. Their heroic actions saved the ship from destruction. Furthermore, with all the additional water weight on the port side, Captain Belling's orders to Commander Rowland to shift oil weight to starboard prevented Forrestal from capsizing.

4th Conclusion

Captain Belling had the last statement to the accident board. His comment of record was as follows:

> *"The diagram shows that (a) massive effort to control the fire was under way and that the hoses from the starboard catwalk and forward were surrounding it. About one additional minute would have been required to bring enough hoses into action to affect the fire and they would have been ideally placed to contain it. I feel, therefore, that had the bomb not exploded, significant headway could have been made against the fire by about three minutes after its inception. However, I consider it utterly beyond the possibility that the fire could have been suppressed in ninety-four seconds by any group of men with the equipment available. We only needed three minutes. Just three (expletive) minutes and we could have controlled that fire….Yet (my) crew responded with consummate skill and bravery."*

All the primary deck explosions in the first five minutes were attributed to the AN-65A1 bombs. Even in the extended fire, not a single MK 83/84/85 on other aircraft detonated. They burned, they melted, but they didn't catastrophically detonate in the giant blaze that followed the original explosions. Other Zunis and Shrikes missiles did explode, but the crew never backed down nor retreated in their duties.

At this point, a little perspective is important. During World War II, the US Navy at the Battle of Midway sank four Japanese carriers by striking them with dive bombers using a single 1000 lb. bomb each. One 1,000 lb. bombs struck the IJN carrier Akagi, three or four bombs struck IJN carrier Kaga, three struck IJN carrier Hiryu, and three struck IJN carrier Soryu.

The USS Forrestal survived the explosion and fire from no less than seven AN-65A1 1,000 lb. bomb explosions and multiple secondary explosions. In the midst of total disaster, Forrestal's brave crew saved her from sinking.

INVESTIGATION LESSONS LEARNED

Admiral Massey's 7,500-page classified report was sent to Admiral Ephraim Holmes, Commander of the USN Atlantic Fleet, who reported to the USN Chief of

Naval Operations, Admiral Moore. Admiral Massey's report essentially exonerated Captain Belling and the crew's response to the fire, putting the blame squarely on US Navy Systems Command. In addition to sending the original AN-M65A1 bombs to Forrestal in the first place, Massey identified many technical and safety shortfalls of carrier operations with live ordinance and identified specific faults with the F4-B arming system and LAL-10 launcher subsystem. Massey's report recommended a complete safety overhaul of weapons safety from design to implementation.

Admiral Ephraim Holmes disagreed with Massey's report only in one area – he held Captain Belling personally responsible for the fire and issued him a career-ending reprimand. When Admiral Moore, the CNO, reviewed the report and Admiral Holmes's dissent, he decided to rescind Captain Belling's reprimand. However, Admiral Moore wanted one more look at the root cause. He brought in now-retired Rear Admiral James Russell, his former Vice Chief of Naval Operations, to independently re-review Massey's report to confirm findings and follow any open leads.

Two months later, Admiral Russel returned to the CNO's office to provide his "final verdict" of the root cause. Out of courtesy, Captain Belling was invited to attend the half-hour debrief. Russell pulled out of his pocket a TER safety pin with its red "Remove Before Flight" streamer attached and a separate brass multi-contact slide switch. He stated that the underlying brass slide switch is what the TER pin disengaged. Russel stated that the switch design was flawed, and it regularly shorted out in bench tests, oftentimes regardless of whether or not the TER pin was fully engaged or removed. Ground tests proved beyond a doubt that a power surge could jump directly from the power pin to the firing pin during transients like engine start-up and power switch-over from ground power. "That's what caused the fire." Though exonerated by the CNO, Captain Belling never again commanded a ship.

So, how bad was the TER safety pin design? According to USN Systems Command, the "LAL-10 Launcher was 'impossible' to launch a weapon when all safety systems engaged and functional." Upon close inspection and reviewing many LAL-10 field units, multiple design deficiencies were uncovered: 1) the LAL-10 TER and shorting pin had to be fully screwed in to be properly seated. However, pins corroded in the salt air after multiple uses, preventing proper seating of pins and making the safety interlock unreliable; 2) the TER shorting device only needed to be 20% loose to potentially open a pathway from the power to firing pin, thereby effectively leaving the weapon system armed; 3) if the TER shorting device is "sprung" it never makes contact, which fails to "safe the weapon;" and 4) if the LAL10 mounting lugs are not fully seated, there is mechanical interference which prevents the TER pin from seating completely. This is why Russel states, "That's what caused the fire."

PERMANENT USN SAFETY CHANGES AFTER THE USS FORRESTAL FIRE

In 1967, there were hundreds of documented USN fires, mostly minor, in vessels across the entire Navy. The USN decided that, in basic training, every sailor and officer would be taught how to prevent and fight chemical, paper, and fuel-fed fires. The US Navy's Fire Fighting School was greatly expanded, and every recruit today gets fully certified fire training. The Fire Training School is named after Chief Petty Officer Gerald Farrier.

Over the years, every single US Aircraft carrier was retrofitted with a "Carrier Wash-down Firefighting System." Basically, this is a giant chemical foam inverted sprinkler system that could wash an entire carrier deck in foam suppressant with the pressing of a button on the bridge in minutes. (To see a three-minute demonstration of a wash-down system on a Royal Navy ship, go to https://youtu.be/Guo4aQq9uSM.)

Figure 13: Aviation Boatswain Mate Dave Dickerson (1967) (L), and Dave in 2024 with Becky Fischer (R) [40]

Lastly, the US Navy established a brand-new program called insensitive munitions. The purpose of the program was to ensure a weapon carried on any ship would never go off, deploy, or explode unless it was supposed to. Safety interlocks were upgraded, EMI/EMC-related power transient suppression systems were added, and arming procedures were changed. While insensitive munitions did spawn far-reaching electromagnetic compatibility requirements, including hardening from RF interference, the root cause of the Forrestal accident was a power-switching event and not a radar induction event. Hence, my introductory referrals to References [1] and [2] in Part 1 blaming the shipboard search radar are clearly incorrect.

So, were the radars seriously examined as a possible cause of the USS Forrestal accident? Yes, that thread was explored, and preliminary (not final) findings stated the threat needed to be considered. But a deep dive into the problems with the F4-B power subsystem and the inadequacies of the LAL-10 launcher TER safety pin were clearly identified as the accident's root cause. Contributing to the accident was the presence of ordinance that never should have been brought on board (AN-M65A1 bombs) and the procedural short-cuts to connect weapons connectors prior to arriving at the catapult.

ACKNOWLEDGMENTS

The author would like to thank the US Naval Heritage Command, the USS Forrestal Organization, Dr. Mike Nowak (USAF F-4 combat pilot), Aviation Boatswain Mate Dave Dickerson, and the multiple people who contributed to or reviewed this work.

I am especially grateful for Dickerson's referral to Kenneth V. Killmeyer's outstanding book *Fire, Fire, Fire on the Flight Deck Aft; This Is Not a Drill*, arguably the definitive word on the actions of thousands of sailors and their collective experiences in saving the USS Forrestal on July 29, 1967. This 831-page book shows there were thousands of stories as compelling as Dickerson's own experience. I am so honored to have learned about these heroes whose stories I never knew but truly appreciated.

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33. Photo courtesy: https://en.wikipedia.org/wiki/1967_USS_Forrestal_fire#/media/File:RADM_John_Beling.jpg

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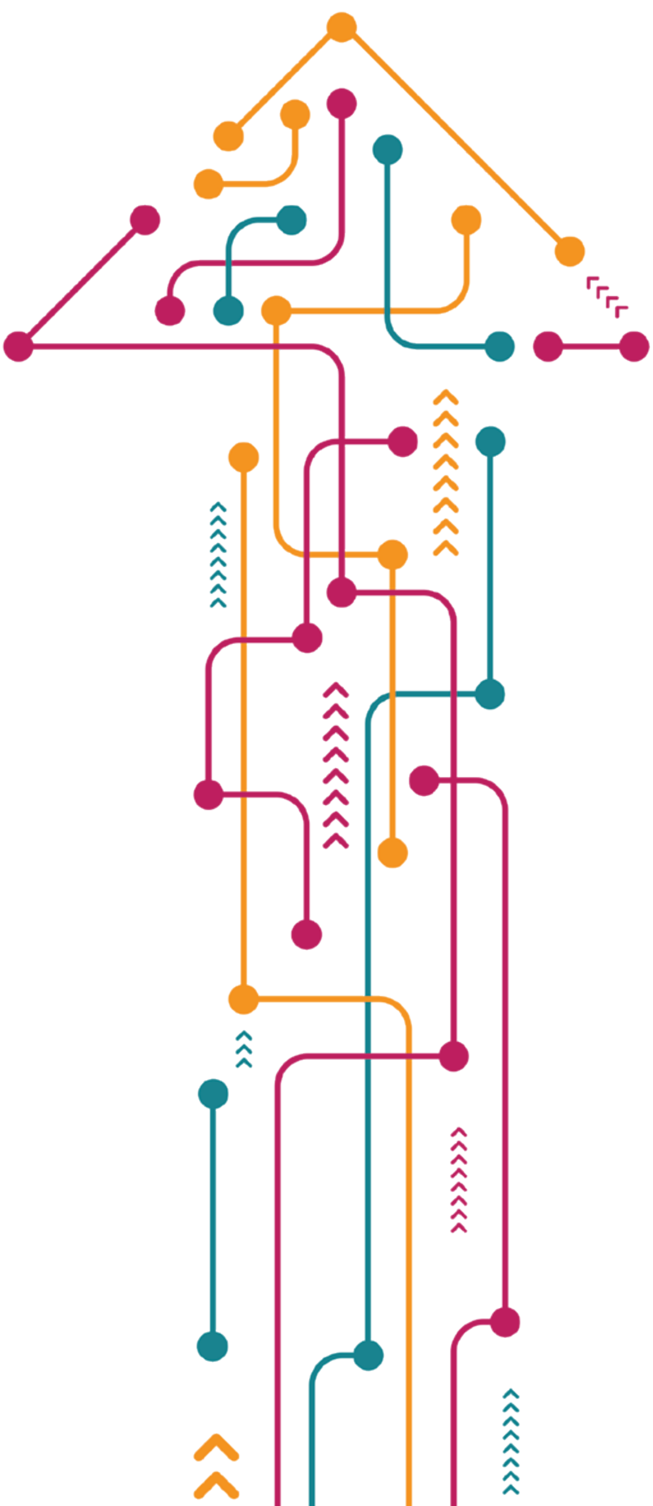
39. National Geographic History Channel, Single Frame Grab from "Seconds from Disaster Aircraft Carrier Explosion," Original Broadcast 9-1-2021

40. Personal Photograph taken by Brian Fischer, used by permission, taken in Cincinnati, Ohio, August 2024

ACHIEVING AND SUSTAINING MEDICAL DEVICE COMPLIANCE

A Product Life-Cycle Compliance Model



The journey of bringing a new medical device to market is littered with potential pitfalls and obstacles that need to be overcome. A common challenge facing innovators is how to navigate regulatory pathways. Typically, this is a topic that is low on people's to-do lists.

Irrespective of the regulatory pathway that applies to your product, you will have to demonstrate that your product has valid scientific evidence of adequate safety, performance, and efficacy throughout its product lifecycle. Failure to provide this information is a common reason for delays and rejection of regulatory documentation by regulators such as the U.S. Food and Drug Administration (FDA) and conformity assessment bodies such as EU Notified Bodies. This often leads to increasing costs and failure to obtain market access of a device that may have a positive health outcome and better safety profile.

Therefore, taking time to evaluate regulatory pathways early in the development of a product will mean that you understand evidence requirements and minimize the likelihood of issues during regulatory approval processes. It will also mean that you have a better understanding of regulatory costs and timelines.

Once a positive regulatory decision has been made and your device is on the market, that is not the end of the journey. No medical device is infallible. So, plan to expect issues to arise. Each year, regulators such as the FDA and the United Kingdom's Medicines and Healthcare Regulatory Agency (MHRA) receive thousands of adverse incident reports about medical devices each year. The harm or potential to cause harm to patients and users caused by device or manufacturing failure, user error, or new unidentified hazard can result in recalls, changes in design, further validation and verification, and reputational risk.

A product life cycle approach, underpinned by a proactive and reactive regulatory and compliance strategy, helps to

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By Nicole Small, Michael Kipping, and James Pink

ensure that you consider all of the key steps, from first having your idea to placing a medical device on the market and then maintaining that market access.

This approach requires the involvement of a range of subject matter experts, such as those with technical, quality, and commercial expertise, to analyze a broad scope of requirements, standards and guidance. It is critical to know what applies and when, know how to keep abreast of changes, and plan how to obtain the evidence necessary to fulfill requirements. For start-ups and small businesses in particular, it is not always feasible to have all these in-house capabilities.

Nonetheless, a robust regulatory and compliance strategy is the key to success.

INVEST IN DEVELOPING A REGULATORY AND COMPLIANCE STRATEGY AND KEEP IT UP TO DATE

Regulatory Strategy—Background and Approach

A regulatory strategy is an essential document that helps you to understand the likely legal compliance requirements that will determine the path to market of your medical device. Before a regulatory strategy can be developed, a clear understanding of the product description, its intended purpose, and, of course, its key technological characteristics that impact safety must be derived. Device manufacturers with market acceptance in other markets may not realize the evidence requirements differ in a new market that they want to access. Therefore, documenting and aligning these three aspects, coupled with defining your target market(s), are critical steps in understanding the likely regulatory route and developing the regulatory framework that needs to be navigated.

It is important that all those involved in the design and development of the product description, intended purpose, and key technological characteristics also understand the medical conditions to be treated, diagnosed, or prevented and what medical/clinical and performance claims are to be made. They also need to have an understanding of the technological characteristics that may impact safety, such as invasiveness, energy, principles of operation, and the key aspects of the product's design and construction.

Another important point is that those involved need to be aware of how regulatory authorities and regulations define those terms. Therefore, it is often valuable to seek external help from clinical, regulatory, and technical professionals familiar with medical device regulation, compliance, and conformity assessment.

Once these inputs are identified and agreed upon, it is then possible to work through the following aspects of a regulatory strategy within each target market(s):

1. Does your device qualify as a medical device? If so, you can then review the legal definition of a "medical device" in the regulations of your target country.
2. If yes, what is the likely regulatory risk classification, and how does this change based on the product description, intended purpose, and key technological characteristics?

   For example, Class I = low risk, Class III = high risk. This will narrow down the conformity assessment/submission route options. Depending on the classification, you will then start to gain an understanding of the pre-clinical and clinical, as well as non-clinical, evidence you need to collect, analyze, and report, including, in some cases, demonstrating how your new device is equivalent to a legally marketed device. It is a substantial proportion of your submission/technical documentation.
3. Based upon the regulatory risk classification, what are the conformity assessment options available to us in order to receive market approval?

A regulatory strategy may change based on the choices an innovator makes around product claims, intended purpose, and technological characteristics. In some instances, simply choosing to remove claims, particularly around clinical or medical purposes may mean that the product is no longer meeting the definition of a medical device in the chosen market. Similarly, the regulatory classification (and conformity assessment option) may change based on choices around the type of medical purpose, intended purpose, and/or technological characteristics.

Compliance Strategy—Background and Approach

A compliance strategy is another essential document that helps you to understand the likely technical and regulatory compliance requirements that will require demonstration of conformity throughout the product lifecycle. Compliance throughout the product life cycle begins with determining in advance of detailed design and design verification and validation exactly what regulatory and technical requirements will need to be addressed. Before a compliance strategy can be developed, it is important to understand the technical frameworks in place regarding the safety and performance of your particular product. This includes product- and process-based standards, as well as specifications and technical norms published by industry experts, national standards bodies, conformity assessment bodies, and regulatory bodies under a highly structured framework of consensus.

The input to a compliance strategy again begins with the detailed product description, the intended purpose, users, use environment, and technological characteristics. However, this differs from a regulatory strategy as there is a much more detailed assessment of the actual technical regulations, standards, specifications, and norms that will shape the expectation of conformity. A good way to distinguish the difference is that the regulatory strategy enables you to ensure you identify and follow the right regulatory requirements and pathway, whereas a compliance strategy enables you to demonstrate that your product now conforms to the necessary "state of the art,"[1] ultimately helping address how to comply.

In developing a compliance strategy, it is critical that relevant product safety and technical specialists are involved in its development and implementation so that the correct standards, specifications, and norms are identified and ultimately defined. It is often the case that technical-based innovators exhibit bias around their technical specialization, such as electronic and electrical design, materials, software, etc., but do not necessarily understand the technical requirements of less familiar areas, such as packaging, human factors, sterilization, and connected technologies.

Many regulatory frameworks applicable to medical technologies have safety and performance requirements that need to be addressed, and these requirements cover multiple characteristics that impact safety or deliver essential performance. These requirements may be generally referred to as essential principles of safety and performance.

Ultimately, the compliance strategy is composed of:

1. The safety and performance requirements and the characteristics that determine them, as applicable
2. A comprehensive evaluation of the technical regulations, standards, specifications, and norms that need to be complied with through design, manufacture, installation, servicing, and use (a product life cycle approach)
3. A detailed overview of what requires full compliance, partial compliance, or options for compliance and
4. The method of achieving compliance, such as risk management, design solutions, manufacturing controls, packaging systems, information for safety, and human factors.

Once a compliance strategy is identified, it is possible then to determine the likely evidence requirements necessary and now can focus your teams on the detailed design and development requirements that will need verification and validation.

The importance of having a good compliance strategy throughout a product's entire lifecycle cannot be overstated. It is specifically to minimize the risk of market access delays caused by conformity assessment bodies or regulatory agencies requiring technical evidence that was not originally planned for or budgeted. Examples would include having to undertake unexpected electrical safety testing, material safety studies, or tests that are representative of a product's lifetime or worse-case environments.

Document reference and source	Date of applicability	Applicable because	Regulatory considerations
Electromagnetic Compatibility (EMC) of Medical Devices, Guidance for Industry and Food and Drug Administration Staff FDA online guidance database	June 6, 2022	• Our product is electrically powered or • Has functions or sensors that are implemented using electrical or electronic circuitry AND • We intend to place our medical device on the US Market.	US FDA regulatory guidance (non-binding guidance)

Table 1: Sample categorization of FDA guidance documents and their applicability

In some circumstances, market access has simply been denied or interrupted either due to the complete lack of evidence or a total loss of confidence from the regulator or conformity assessment body that the product can be brought into compliance within reasonable timeframes.

IDENTIFYING RELEVANT REQUIREMENTS AND SOLUTIONS FOR SAFETY AND PERFORMANCE

The Need

In an environment where change is the only constant, there is a need to have a system that is able to evaluate the legal requirements against the product characteristics and intended purpose in real time. Through advanced algorithms and data analytics, identifying the key requirements defined within relevant standards, legislation, applications, and guidance gives assurance that certain legal requirements are not missed.

Ultimately, regardless of how medical technologies are brought to market and the regulations that apply, we all need to work smarter rather than harder, using digital tools to augment evidence gathering for conformity assessment activities and generating faster yet reliable data/results to bring safer medical devices to market that improve patient outcomes.

The How

Regulatory Intelligence Digital Tools

Preparing a regulatory strategy requires an in-depth knowledge of the databases, publications, and regulatory and technical information necessary to comply for particular jurisdictions. Often, these sources are not well publicized, are not easily searchable, or simply exist behind paywalls.

Be sure to keep a library of applicable regulations, including their date and type, and create labels or tags that outline the reason for applicability. Table 1 provides an example of how to categorize FDA guidance documents related to EMC considerations.

Creating a database of the identified guidance, standards, technical regulations, specifications, or norms will then ensure that not only do you obtain, evaluate, and decompose requirements within those documents but that you can also periodically search for updates and evaluate whether they remain current and applicable. Often, these documents also define exactly what must be designed and tested to demonstrate conformity.

In addition, regulatory intelligence management systems (RIMS) may help you track regulations and key technical requirements and provide you with updates that may impact your regulatory strategy.

Compliance Strategy Digital Tools

Preparing a compliance strategy requires a careful alignment of the device's intended purpose with its technological characteristics that potentially impact safety and performance and then ensuring you describe why a technical publication is relevant to inform your compliance efforts.

Document reference and source	Date of applicability	Compliance considerations	Key compliance tasks required
Electromagnetic Compatibility (EMC) of Medical Devices, Guidance for Industry and Food and Drug Administration Staff FDA online guidance database	June 6, 2022	• EMC-related device characteristics • EMC Risks • EMC Consensus standards • Essential Performance immunity pass/fail criteria • EMC Testing	• Determine if we want to comply with the non-binding requirements • Incorporate within our design requirements • Create necessary test plans • Identify testing providers or develop in-house testing capability • Confirm compliance

Table 2: Sample categorization of compliance documents

As we discussed in the previous section, it is important to align chosen regulatory and technical standards, specifications, and norms with why they are relevant to your compliance strategy. Table 2 provides an example.

By documenting in this way, you can now utilize internal and external tools to identify, evaluate, and monitor regulations and compliance requirements across the lifecycle. Further, by using various product lifecycle management software, it is possible to document the sources of requirements that will inform your product design and evidence generation for conformity assessment.

ENSURING ROBUST SCIENTIFIC DATA THROUGH DESIGN VERIFICATION AND VALIDATION TESTING

Confirming within your organization exactly with which requirements you wish to comply creates a series of design and development activities that ultimately lead to verification and validation activities. Verification confirms that the medical device has been designed correctly, and validation confirms that the right medical device has been designed. This is a critical nuance within all aspects of medical device development, which means that compliance requirements derived from your compliance strategy will require verification and/or validation testing.

In order to ensure robust scientific data has been gathered from testing, it is important that you undertake the following steps:

1. Confirm the compliance strategy and how you wish to comply with regulations and requirements detailed in applicable standards
2. Identify the requirements within applicable regulations and standards that require verification testing
3. Evaluate whether testing can be conducted internally. If so, ensure that it can withstand regulatory scrutiny associated with internal testing and self-assessment and
4. If internal testing is not feasible, identify appropriate third-party testing partners and begin discussions as early as possible.

Identifying what testing is needed is carried out by considering relevant essential principles of safety and performance against product characteristics. These safeguarding principles are generally adopted in many pieces of legislation and provide assurances the device is safe and performs as intended. They set out broad, high-level expectations for design, production, and postproduction (including post-market surveillance) throughout the product lifecycle.

There are many methods to generate evidence to verify your device meets relevant principles and requirements defined in applicable regulations and requirements. This includes bench performance testing methods, such as in vitro, in vivo, and in silico, based on consensus/recognized standards or validated methods. The voluntary use of certain product and process standards can give a presumption of conformity to relevant requirements. Standards generally satisfy only a portion of a submission/documentation but play a significant contribution to evidence of compliance to relevant principles. You also have the option to provide alternative data or information along with a scientific rationale for why the alternative addresses the principle.

Standards also give confidence that you are applying "state-of-the-art" requirements. They help you understand that a high level of protection has been achieved, giving increased predictability and easing the premarket process. With a large number of recognized standards in each country (about 1600 FDA consensus standards and about 200 China National Medical Products Administration (NMPA) national and industry standards), identifying relevant standards applicable to your device to meet essential principles can be a challenge. Keeping up to date with changes to standards adds to that challenge.

Once you have identified the relevant standard, you will want to achieve a level of confidence in the test results. One rationale for the refusal of premarket application (PMA) by the FDA is whether the collection of pre-clinical data has been conducted in compliance with good laboratory practices and supports the validity of the data generated. Selecting third-party testing providers early in your journey enables you to adapt your design verification and validation plans and gain confidence that what you are doing is correct and that the results are more accurate, helping to ensure that your device is safe and performs as intended.

Before deciding on which test provider to use, it is prudent to review the website of a national accreditation body in the country where you want to conduct testing to verify that the test provider is accredited and has the competency to undertake the testing you require. Accreditation certificates for every testing provider are freely available to download and list the standards to which they are certified to test. Test providers may also be able to undertake testing for which they are not certified, but you need to consider the impact of any deviations that could impact the results and overall conclusions.

Testing undertaken to standards achieved by consensus is strongly encouraged by regulatory bodies and will make the regulatory conformity assessment process much smoother. Testing to recognized standards is also valuable when entering into commercial discussions, as end users gain confidence that standards of quality, safety, and performance have been met.

Third-party testing partners are exactly that. They help you understand the test requirements, sample and conditioning requirements, variability and uncertainty within the test, the impact of deviations, and how to ensure robust scientific results that are impartial and free from bias. Check regulations on the use of in-house and third-party testing facilities.

SUMMARY

A robust regulatory and compliance strategy is the key to success. It is critical that relevant product safety and technical specialists are involved in its development and implementation.

Regardless of how medical devices are brought to market and the regulations addressing conformity, we all need to work smarter rather than harder, using digital tools to augment strategies and evidence gathering for conformity assessment activities and producing faster yet reliable data/results that help us to bring safer medical devices to market.

ENDNOTE

1. IMDRF/GRRP WG/N51 provides the following definition: Developed stage of technical capability at a given time as regards products, processes and services, based on the relevant consolidated findings of science, technology and experience. (ISO/IEC Guide 2:2004)

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FILTER DESIGNS FOR SWITCHED POWER CONVERTERS: PART 2

Every Noisy Component You Need to Know in a Switched-Mode Power Supply

In Part 1 of this series of articles[1], we provide an overview of EMI filter design for switch-mode power supplies (SMPS). In this part, we will examine specific aspects of switched power converters. The goal is to help readers understand:

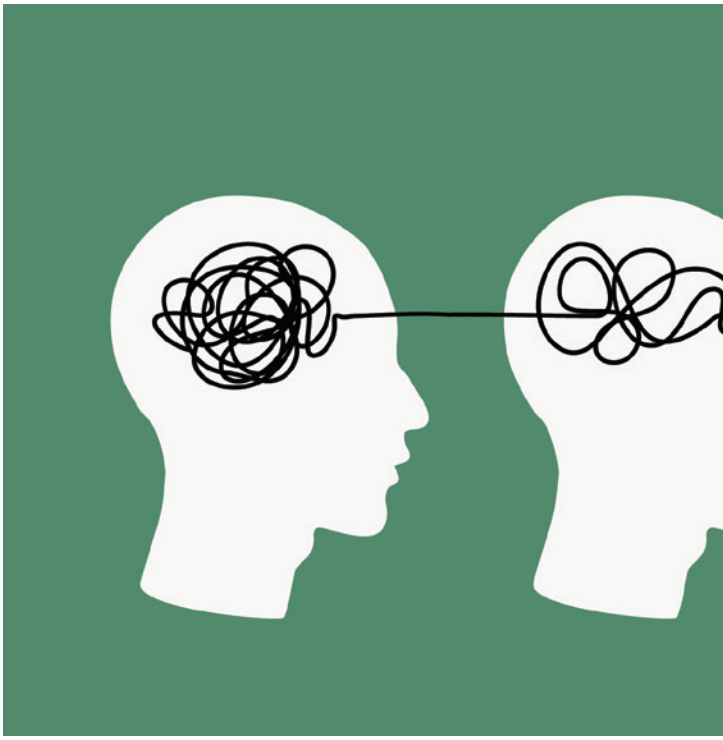
1. Emission spectrum of an SMPS
2. Noise sources in a typical SMPS
3. Coupling mechanisms of noise in an SMPS
4. Grounding considerations in switched-mode power supplies and
5. Input and output capacitors

Some readers may notice that this discussion does not directly address filters. However, years of experience in the field have shown that a deep understanding of these topics is essential to truly solving EMI issues. While filters are required for most switched-mode converters, failing to address points 1–5 makes designing an effective filter strategy inefficient, if not impossible. In this article, we will focus on the converter itself, with special emphasis on grounding, input, and output capacitors, as these often determine whether a filter will be effective.

EMISSION SPECTRUM OF A SMPS

Figure 1 shows a typical emission spectrum for two fixed-switching frequency converters. The primary source of SMPS noise emissions is the switching frequency and its harmonics. Due to the asymmetry of the switching waveform—determined by the PWM duty cycle—both odd and even harmonics are typically present.

If the fundamental switching frequency is stable and well-defined, the resulting emissions form a narrowband spectrum that can extend well beyond 30 MHz, particularly when transition times are fast. Measurement bandwidth settings



also influence how these harmonics appear in EMC testing (e.g., 9 kHz RBW from 150 kHz to 30 MHz, and 120 kHz RBW from 30 MHz to 108 MHz). This means that at lower frequencies, individual harmonics are clearly distinguishable.

In contrast, in the tens of megahertz range, they become harder to resolve, especially when the fundamental switching frequency is below 100 kHz. Designs in which the frequency is not stable will normally show modulation due to input or output ripple which has the effect of broadening individual harmonic lines so that an emission "envelope" is measured. Peaks in the emission profile are typical and can be caused either by resonances in the coupling path or by ringing on the switching waveform.

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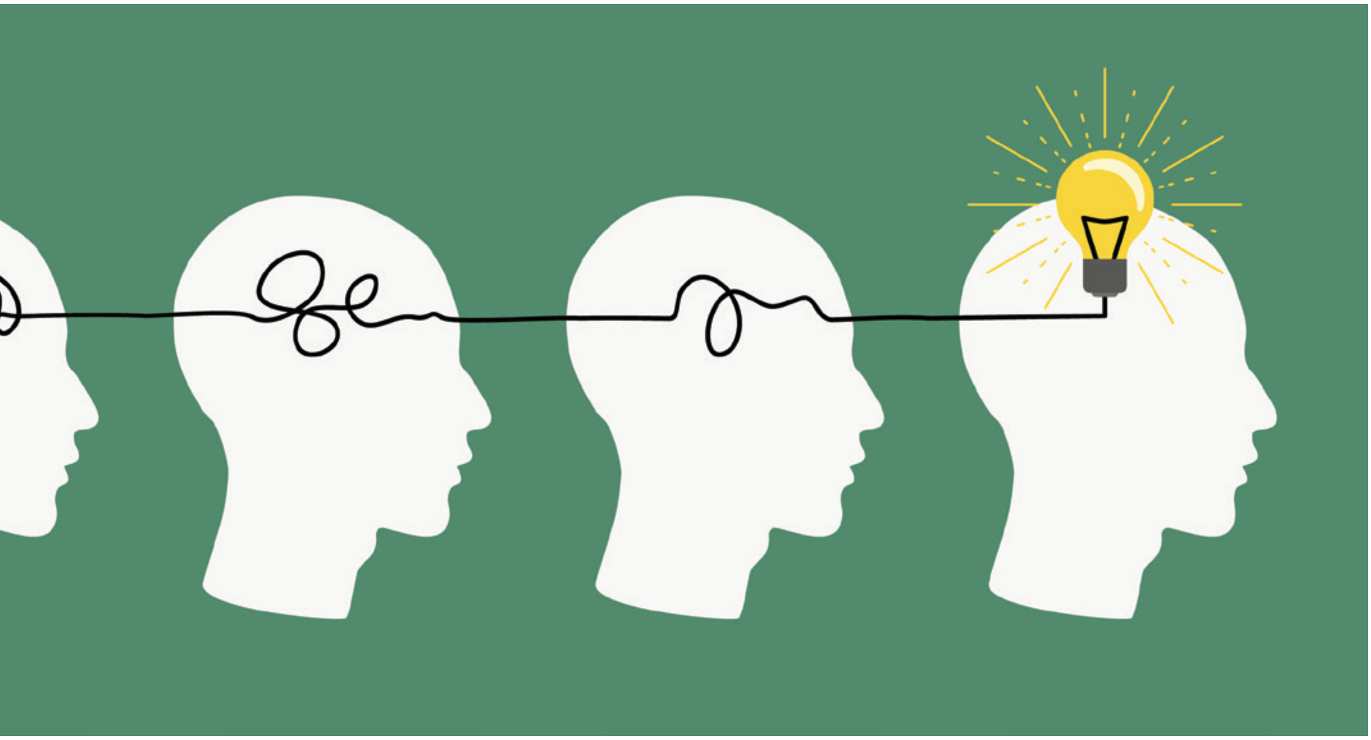


For low-power converters operating at 200 kHz switching frequency or higher (such as the 2.2 MHz converter in this case), emissions in the higher frequency range still appear in the narrowband. For example, in Figure 1, the blue trace demonstrates narrowband noise extending into the FM range.

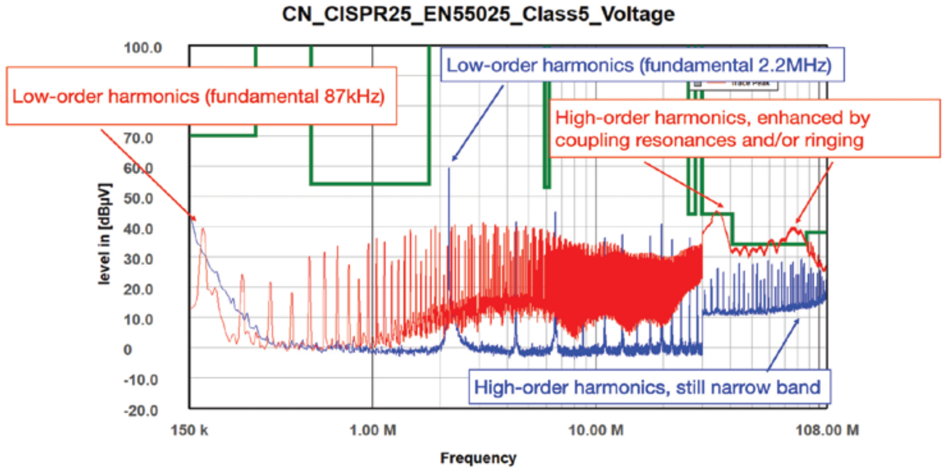


Figure 1: A typical emission spectrum from a CISPR 25 conducted emissions test, comparing two switching power supplies, one operating at 87 kHz (red trace) and the other at 2.2 MHz (blue trace)

NOISE SOURCES IN A TYPICAL SMPS

In our previous article, we discussed hot loop areas and the switched node, which are typically associated with near-field magnetic field loops and electric field antenna-like structures. In this article, we will examine all key noise components in a typical SMPS.

Types of Power Electronics Switches

Silicon-based MOSFETs are the most common choice for SMPS, used in voltage ranges from 3.3V to 800V. Before the introduction of SiC MOSFETs, silicon-based MOSFETs dominated power applications.

One of the most critical factors affecting EMI performance is rise and fall time. The shorter the rise and fall time, the worse the EMI performance, as shown in Figure 2. These transition times can be controlled via gate drive resistors connected to the MOSFET gate. By using a diode in series with the fall time control resistor (R_{G_off}), designers can individually control rise and fall times. Increasing the resistor value slows down switching, reducing high-frequency EMI (particularly common-mode noise) but at the cost of increased switching losses.

P-N diodes, including the MOSFET body diodes, are another significant noise source due to reverse recovery charge (often referred to as Qrr in the component's datasheet). In the time domain, this manifests as an overshoot during switching, while in

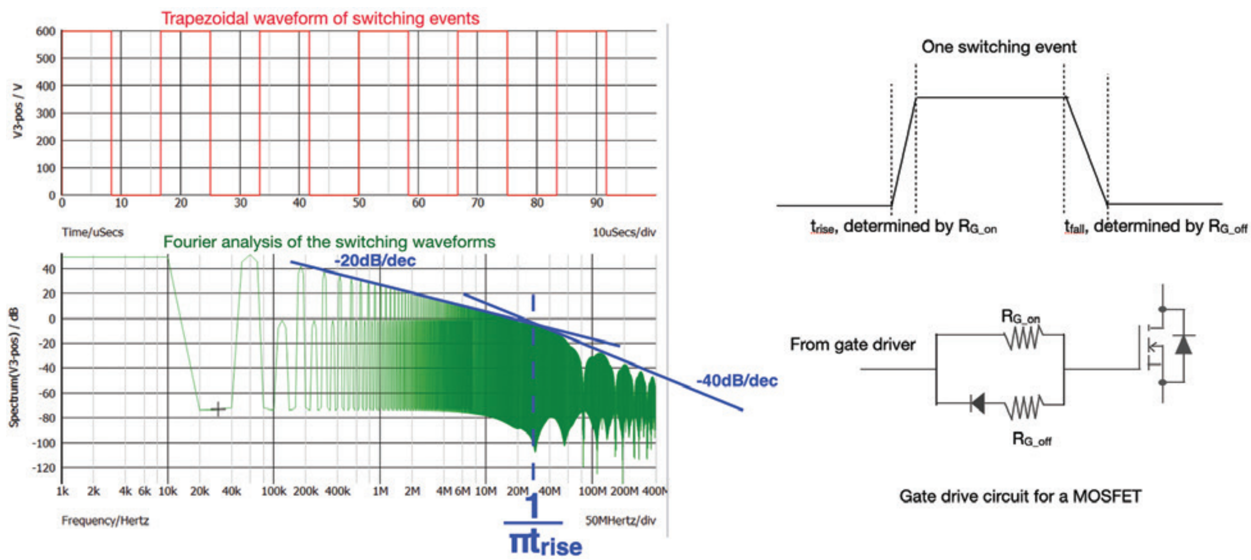


Figure 2: How gate driver determines emissions of an SMPS

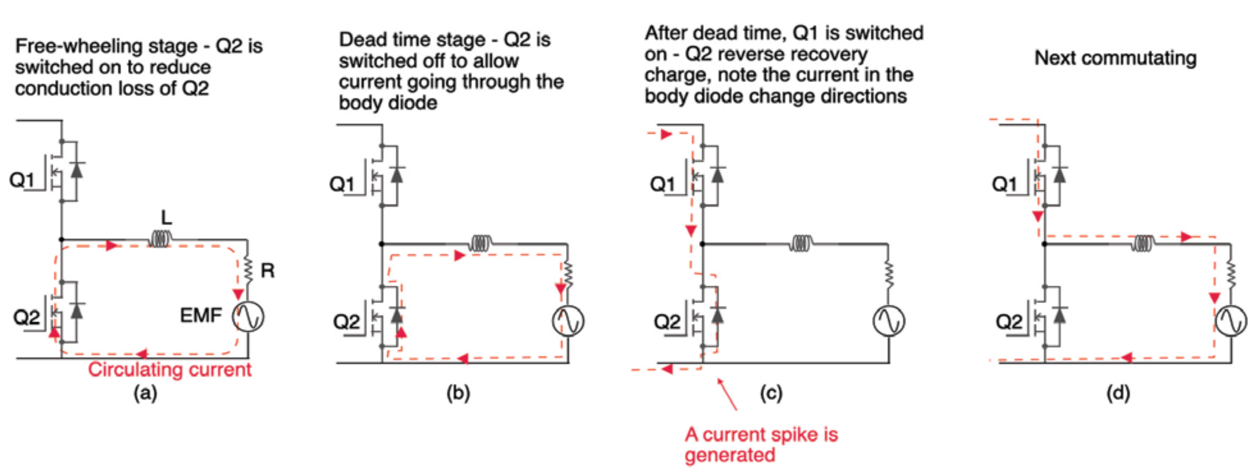


Figure 3: Reverse recovery charge leads to current spikes in motor drive applications.

the frequency domain, it contributes to high-frequency noise. Figure 3 illustrates this in a motor drive circuit.

To mitigate reverse recovery issues, Schottky diodes or fast-recovery diodes are often placed in parallel with MOSFETs. Since Schottky diodes do not have a PN junction, they theoretically eliminate reverse recovery charge (switching is essentially "instantaneous" with only a slight capacitive loading, which is much less of a concern). However, as we will discuss later, Schottky diodes are not always a perfect solution.

IGBTs, on the other hand, switch more slowly than MOSFETs and can withstand higher power, making them more suitable for high-voltage, high-power applications.

GaN and SiC transistors are becoming increasingly popular but introduce significant EMC challenges (again, due to the fact that they can be switched on and off much faster). We previously covered these topics in another of our articles[2]), and readers are encouraged to revisit that discussion.

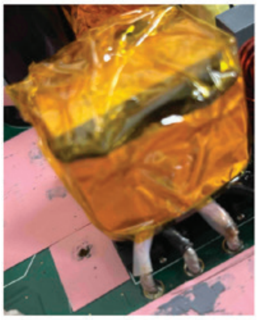
PARASITIC EFFECTS IN SWITCHING DEVICES

Parasitic Capacitance and Resonance with Nearby Magnetic Component

Parasitic capacitance in switching devices is often overlooked, even though it is clearly specified in device datasheets. Engineers typically focus on R_{DS}(on), rise/fall times, and voltage/current ratings, but ignoring parasitic capacitance can lead to unexpected EMI issues.

The primary concern with parasitic capacitance is that it resonates with inductance in the system. A switching device can self-resonate, but, more commonly, it resonates with inductance from PCB traces and tracks. A proper PCB layout can minimize inductance caused by traces, but another significant resonance source is the isolation transformer, used in nearly all isolated power supply designs. The leakage inductance of the isolation transformer can strongly resonate with the parasitic capacitance of the switching device due to its close physical proximity. This often results in resonance peaks in the emission spectrum.

Figure 4 illustrates how placing a flux band around the transformer reduces leakage inductance, improving EMI performance.



A flux band was applied on the isolation transformer

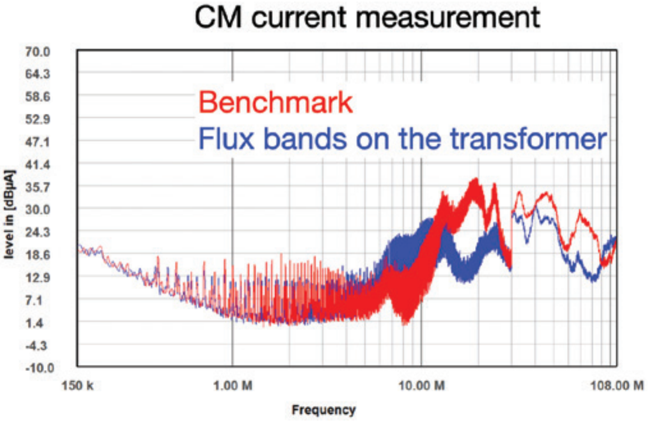


Figure 4: Common mode current measured when a flux band was applied on the transformer of an SMPS

If power switches are already chosen, design engineers have no control over the parasitic capacitance of the device itself. Instead, they must optimize the layout and minimize the inductance of PCB traces and magnetics to reduce noise.

Another issue with parasitic capacitance is its impact on EMI when mounting switching devices on heatsinks. The larger the parasitic capacitance, the greater the common-mode current coupled into the heatsink. Additionally, the larger the heatsink, the greater the common-mode noise. In most cases, the dominant factor may be the heatsink size rather than the switching device itself. This highlights the importance of proper grounding and EMI mitigation techniques when integrating heatsinks.

Parasitic Inductance and Self-Resonance of Devices

Now that we understand parasitic capacitance, we turn our attention to parasitic inductance in switching devices. Just like in all EMC-related topics, geometry plays a crucial role in inductance.

One common package option of a power electronics switch is the through-hole device (such as TO-247). The long leads of these devices introduce significant inductance, which can negatively impact EMI performance. Engineers often prefer these packages because they allow for mounting on the PCB edge with heatsinks attached. However, if the heatsink is not properly grounded, it can worsen EMI issues. Additionally, mounting these devices at the PCB edge may exacerbate EMI problems due to unexpected return current paths. We have covered a detailed case study on this in another article[3].

Another example of parasitic inductance affecting EMI is with Schottky diodes. In one case, an external Schottky diode introduced radiated emissions due

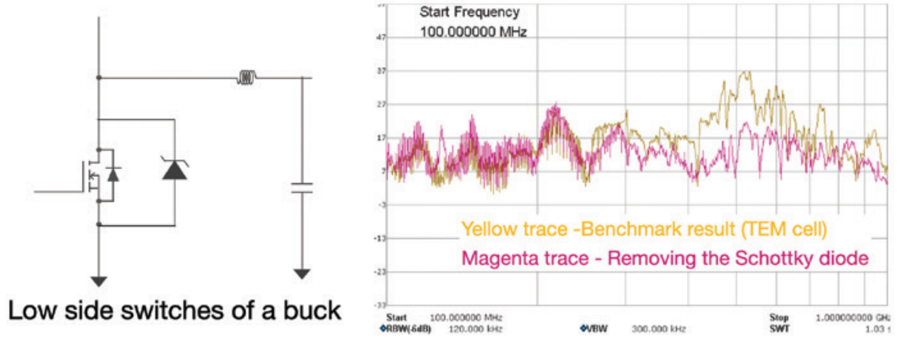


Figure 5: A parallel Schottky could lead to worse EMC performance

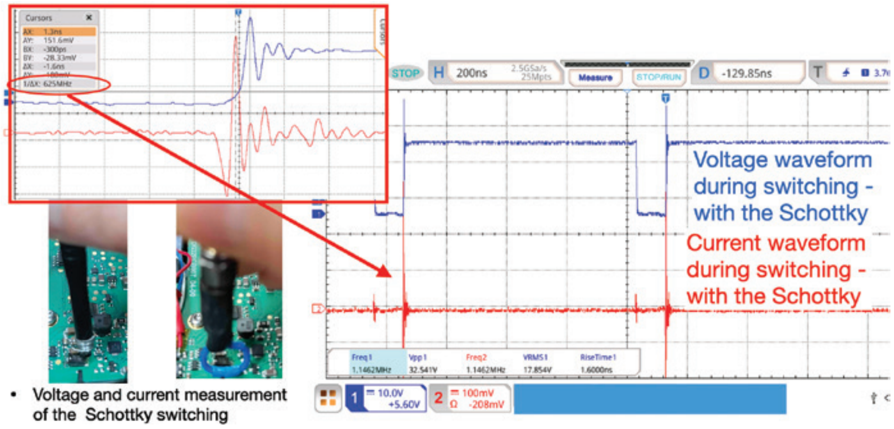
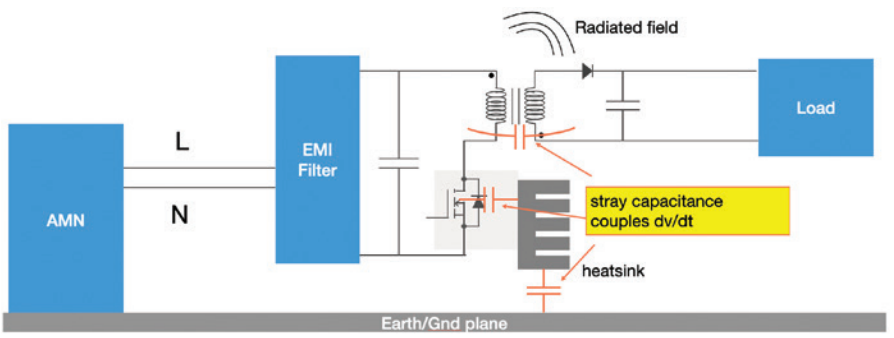


Figure 6: Time domain measurement of the Schottky diode



to a high-frequency resonance between the diode inductance and the combined capacitances of both the Schottky and MOSFET. Since both MOSFET and diode capacitances vary with voltage, analyzing and mitigating these interactions can be challenging.

Figure 5 illustrates this scenario, showing the frequency-domain measurements of the resonance phenomenon. A near-field loop probe placed close to the Schottky diode revealed the resonance issue described in time domain (Figure 6).

COUPLING MECHANISMS IN A SMPS

Using an isolated SMPS as an example, noise can couple into a system through multiple paths:

1. *Conducted coupling:* Noise propagates via conductive paths through power and signal lines. While input and output filters provide some suppression, they often cannot block noise completely, allowing noise to directly couple into other connected systems. In EMC testing, a LISN is used to measure conducted emissions.
2. *Near-field coupling:* This occurs through magnetic and electric field coupling. One common issue is noise coupling onto input and output cable leads, effectively bypassing the filters, and reducing their effectiveness. This is a frequent reason why filters fail to work efficiently.
3. *Radiated coupling:* The power stage of the SMPS can radiate noise directly, which can be detected by far-field antennas in EMC testing.
4. *Common impedance coupling:* This occurs when an SMPS shares the same ground connection with another circuit. A star grounding scheme can sometimes introduce common impedance coupling.

For the reasons previously mentioned, it is advantageous to place the high-frequency components of an EMI

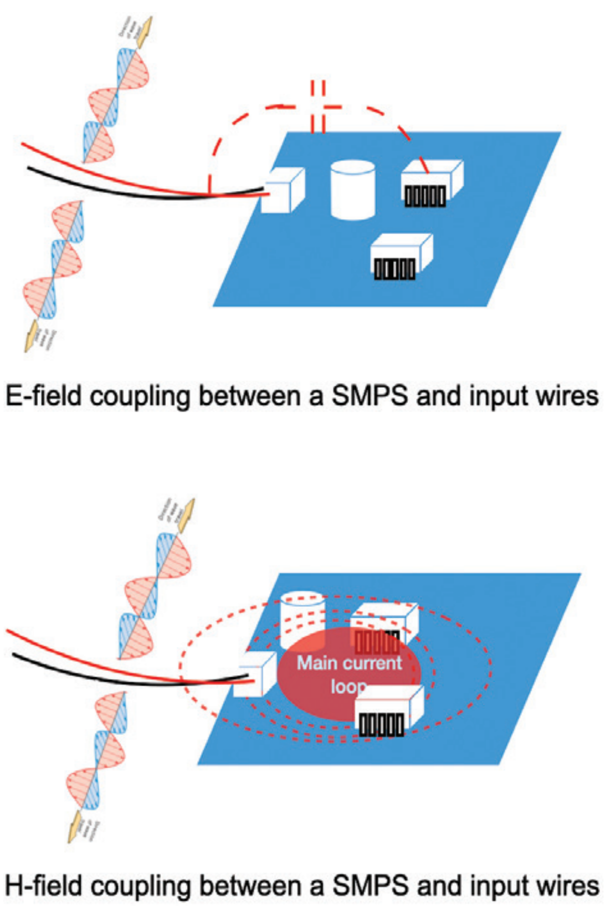


Figure 8: Near-field coupling between an SMPS and input wires

filter near the power connector rather than on a PCB. In military applications, such filters were traditionally implemented in an "EMI doghouse,"[4] but modern commercial/industrial designs increasingly incorporate shielded enclosures to enhance performance. We will explore this topic in greater detail in future articles.

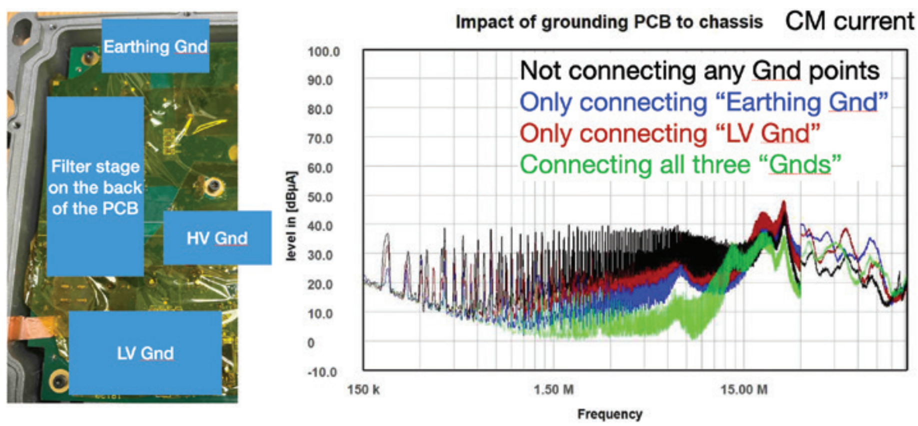


Figure 9: Grounding of an SMPS can affect the filter performance

As briefly mentioned earlier, mounting power electronics devices on a floating heatsink can introduce EMI challenges. Due to its size, the heatsink can act as an unintended antenna, coupling common-mode noise and either conducting or radiating EMI out of the system.

To mitigate this issue, it is highly recommended to ground the heatsink at multiple points to provide a low-impedance return path and minimize unwanted noise coupling. (More detailed recommendations on heatsink grounding strategies can be found in the sources referenced in endnotes 5, 6, and 7). A heatsink can unexpectedly couple noise into the common mode path. We will dedicate an article to this topic in a future publication to address this issue in greater detail.

GROUND POTENTIAL DIFFERENCE IN ISOLATED SMPS

For non-isolated SMPS, the ground design strategy is relatively simple, as there is only one common ground. However, isolated SMPS inevitably create multiple ground potentials. If these different grounds are not properly connected in RF terms (e.g., using appropriately placed capacitors), a high common-mode voltage can develop between them. This voltage can drive common-mode currents across the isolation barrier, typically through the primary-to-secondary capacitive coupling of the isolation transformer.

This is a common cause of unexpected EMI emissions in isolated designs. In our Part 1 article, we demonstrated the impact of capacitors linking these isolated grounds.

It should be noted that filter performance often depends on both the grounding of the filter circuits and the grounding of the switched-mode power supply itself. In the following example, a design contains four switching converters, with the manufacturer incorporating three PCB mounting holes to electrically connect the board to the chassis. Ignoring whether three mounting holes are sufficient (the

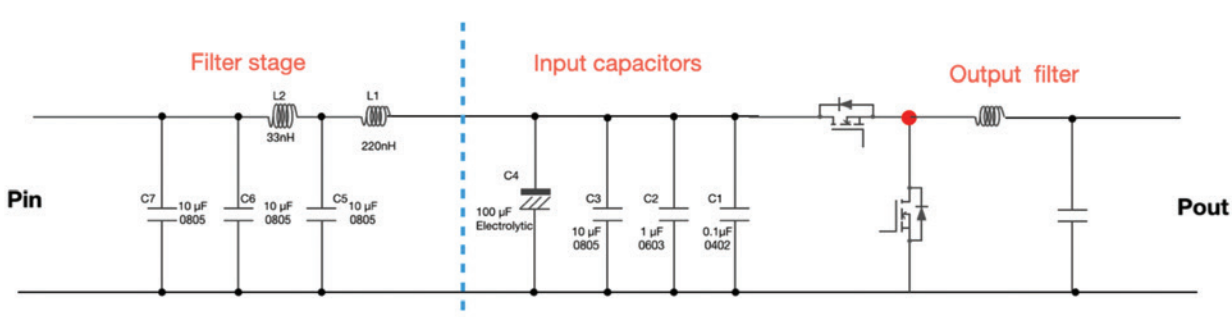


Figure 10: Input filter and input capacitors of a buck converter

answer is no, they are not), the common-mode current behavior changes significantly depending on which combination of mounting holes is used for grounding. Despite using the exact same filter, the EMC performance varies greatly.

This highlights the importance of proper grounding in SMPS design. When a seemingly well-designed filter fails to perform as expected, one of the first areas to check is the system grounding.

INPUT AND OUTPUT CAPACITORS IN SMPS

One of the most frequent mistakes in SMPS EMI design is confusing EMI filter capacitors with input/output capacitors.

For example, in Figure 10, we illustrate a buck converter where C1–C4 are best understood as input capacitors rather than components of an EMI filter. While these capacitors do interact with the inductor (L1) part of a multi-stage filter, their primary role is to provide a stable voltage source for the converter. A common issue arises when engineers insert an inductor between the input capacitors and the switching devices, mistakenly believing an L-C filter is necessary for switching noise, or place the input capacitors too far from the converter, following an application note that suggests locating the filter away from the main stage to minimize coupling. These mistakes stem from a fundamental misunderstanding of the distinction between input capacitors and the filter stage.

SUMMARY

This concludes Part 2 of our discussion on SMPS filters. As we explained in this article, understanding converter noise and coupling mechanisms is crucial before designing and laying out a filter. A solid grasp of these fundamentals also enhances simulation accuracy for those using a simulation-based approach to filter design.

Additionally, as we emphasized, filters are an essential part of SMPS design, but they cannot solve all noise issues. A key takeaway from this article is to first focus on good EMC design at the power stage before addressing the filter design.

In our next article, we will provide a step-by-step guide on designing effective filters.

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4. K. Javor, online resource, "EMI Radiation Coupling in SMPSs." https://www.mail-archive.com/emc-pstc@listserv.ieee.org/msg22573.html
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INDUCTOR IMPEDANCE EVALUATION FROM S-PARAMETER MEASUREMENTS

Part 1: S_{11} One-Port Shunt, Two-Port Shunt, and Two-Port Series Methods

By Bogdan Adamczyk, Patrick Cribbins, and Khalil Chame

This is the first of two articles devoted to the topic of *inductor* impedance evaluation from the *S* parameter measurements (*capacitor* impedance evaluation from the *S* parameter measurements was described in [1] and [2]). This article describes the impedance measurements and calculations from the S_{11} parameter using the one-port shunt method, two-port shunt, and two-port series methods. The next article will discuss impedance measurements and calculations using S_{21} parameters with two-port shunt and two-port series methods.

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Patrick Cribbins is pursuing his Bachelor of Science in Electrical Engineering at Grand Valley State University. He currently works full time as an Electromagnetic Compatibility Engineering co-op student at E3 Compliance, which specializes in EMC and high-speed design, pre-compliance testing and diagnostics. He can be reached at patrick.cribbins@e3compliance.com.

Khalil Chame is pursuing his Bachelor of Science in Electrical Engineering at Grand Valley State University. He currently works full time as an Electromagnetic Compatibility Engineer co-op student at E3 Compliance, which specializes in EMC and high-speed design, pre-compliance and diagnostics. He can be reached at khalil.chame@e3compliance.com.

ONE-PORT SHUNT METHOD

One-port shunt configuration is shown in Figure 1.

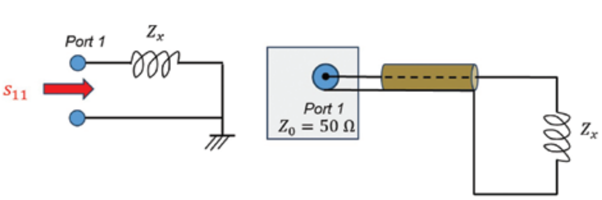

Figure 1: One-port shunt configuration

For this configuration, the inductor’s impedance in terms of the S_{11} parameter was derived in [1] as

$$Z_x = Z_0 \frac{1+s_{11}}{1-s_{11}} \tag{1}$$

TWO-PORT SHUNT METHOD

The two-port shunt configuration is shown in Figure 2.

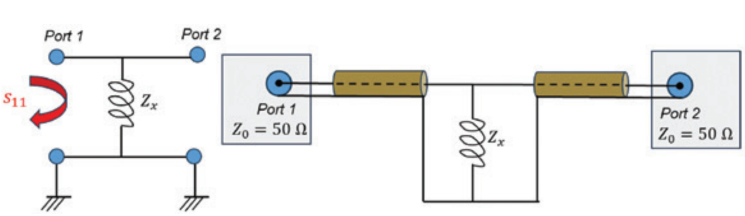

Figure 2: Two-port shunt configuration

For this configuration, the inductor’s impedance in terms of the S_{11} parameter was derived in [1] as

$$Z_x = -Z_0 \frac{1+s_{11}}{2s_{11}} \tag{2}$$

TWO-PORT SERIES METHOD

The two-port series configuration is shown in Figure 3.

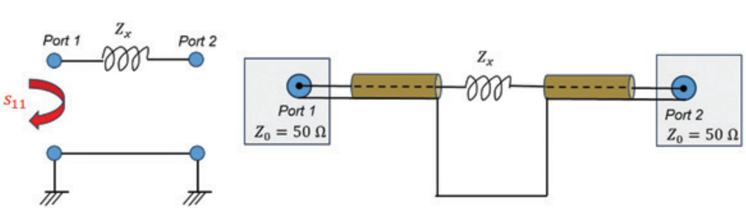

Figure 3: Two-port series configuration

For this configuration, the inductor's impedance in terms of the S_{11} parameter was derived in [1] as

$$Z_x = 2Z_0 \frac{s_{11}}{1-s_{11}} \quad (3)$$

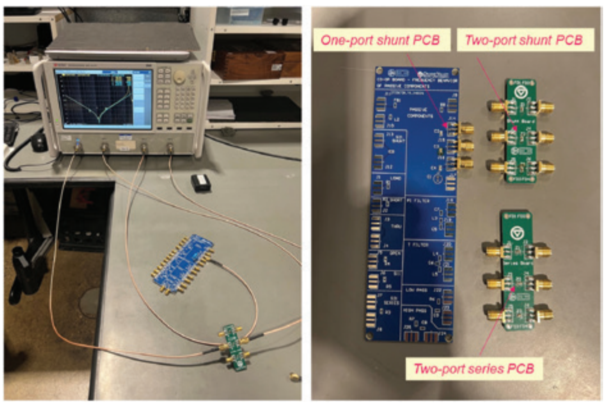

Figure 4: Measurement setup and PCBs

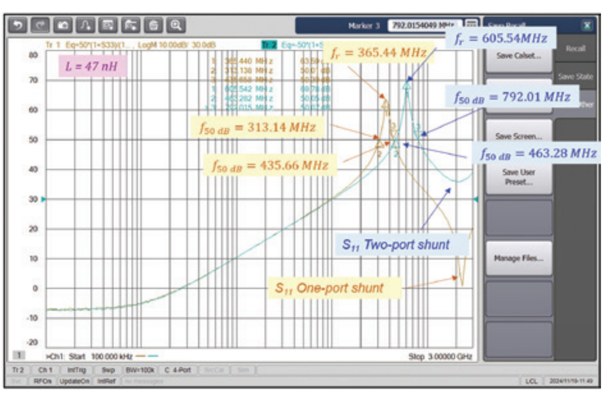

Figure 5: S_{11}-based impedance curves - one-port shunt vs. two-port shunt ($L = 47\ nH$)

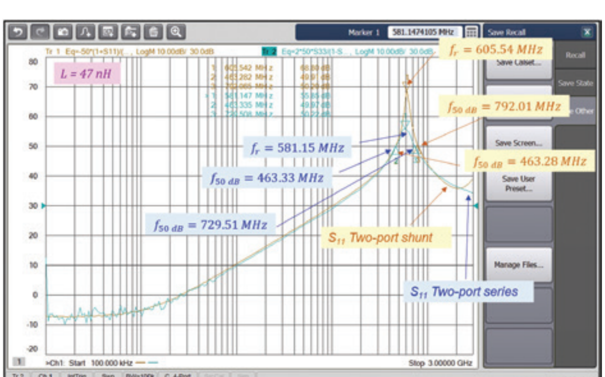

Figure 6: S_{11}-based impedance curves - two-port shunt vs. two-port series ($L = 47\ nH$)

IMPEDANCE MEASUREMENT SETUP AND RESULTS

The impedance measurement setup and the PCB boards are shown in Figure 4. The boards were populated with Murata RF inductors, LQG18HH47NJ00, LQC18HH15J00, LQG18HH27J00, of the values *47 nH*, *150 nH*, and *270 nH*, respectively.

Figures 5 and 6 show the impedance curves for a *47 nH* inductor based on the S_{11} parameter measurements. Figure 5 compares the one-port shunt and two-port shunt configurations, while Figure 6 compares the two-port shunt and two-port series configurations.

Figure 7 shows the inductor impedance curve obtained from the Murata Design Support Software "SimSurfing." [3].

The one-port shunt, two-port shunt, two-port series, and Murata measurements at 50 dB and at self-resonant frequencies are shown in Table 1.

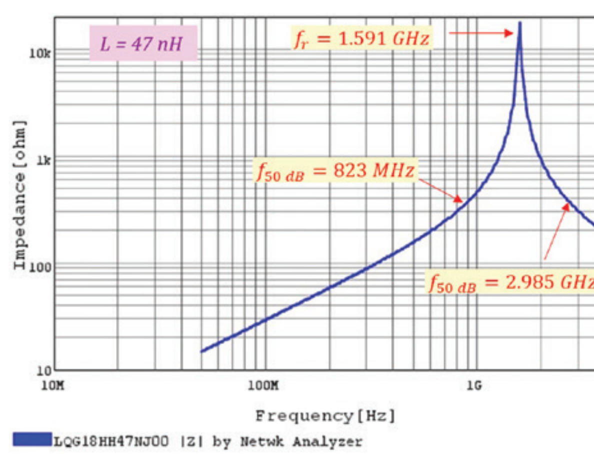

Figure 7: Murata "SimSurfing" impedance curve for *47 nH* inductor

L = 47 nH	*One-port shunt*	*Two-port shunt*	*Two-port series*	*Murata*
1st 50 dB frequency	313.14 MHz	463.38 MHZ	463.33 MHz	823 MHz
Resonant frequency	365.44 MHz	605.54 MHz	581.15 MHz	1.591 GHz
2nd 50 dB frequency	435.66 MHz	792.01 MHz	729.51 MHz	2.985 GHz

Table 1: Impedances at 50 dB and self-resonant frequencies (S_{11} methods)

The overall conclusion is that the inductor's impedance evaluation from the S_{11} parameter measurements is not accurate. The next article will discuss the inductor's impedance estimation from the S_{21} parameters and show its superiority over the S_{11}-based methods.

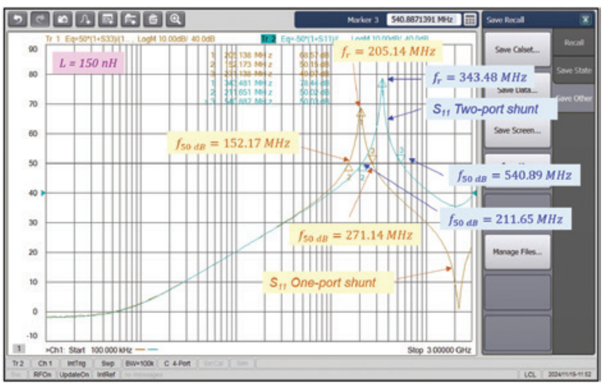

Figure 8: S_{11}-based impedance curves - one-port shunt vs. two-port shunt (L = *150 nH*)

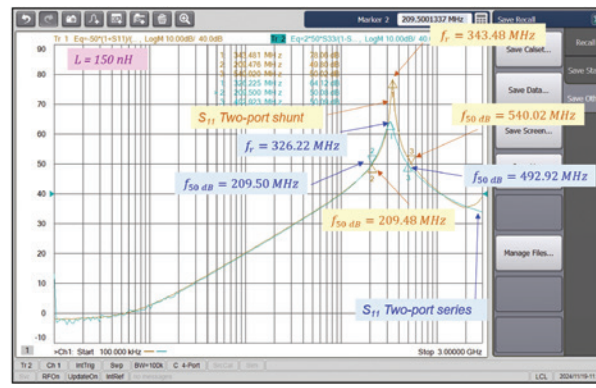

Figure 9: S_{11}-based impedance curves - two-port shunt vs. two-port series (L = *150 nH*)

Clearly, the one-port shunt, two-port shunt, and two-port measurements do not agree with the Murata values.

Figures 8 and 9 show the impedance curves for a *150 nH* inductor based on the S_{11} parameter measurements. Figure 8 compares the one-port shunt and two-port shunt configurations, while Figure 9 compares the two-port shunt and two-port series configurations.

Figure 10 shows the inductor impedance curve obtained from the Murata Design Support Software "SimSurfing."

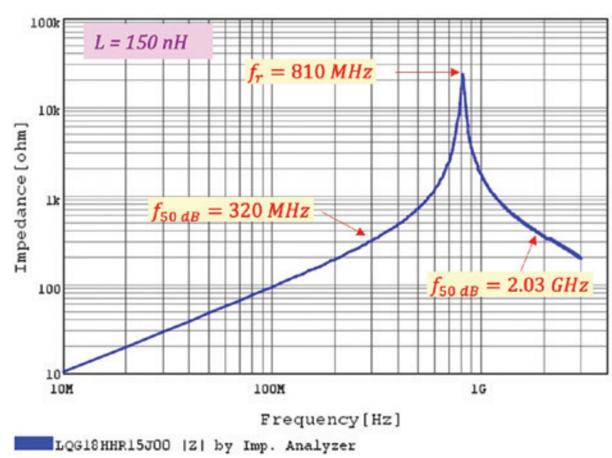

Figure 10: Murata "SimSurfing" impedance curve for *150 nH* inductor

The one-port shunt, two-port shunt, two-port series, and Murata measurements at 50 dB and at self-resonant frequencies are shown in Table 2.

L = 150 nH	*One-port shunt*	*Two-port shunt*	*Two-port series*	*Murata*
1st 50 dB frequency	152.17 MHz	211.65 MHZ	209.50 MHz	320 MHz
Resonant frequency	205.14 MHz	343.48 MHz	326.22 MHz	810 MHz
2nd 50 dB frequency	271.14 MHz	540.89 MHz	492.92 MHz	2.03 GHz

Table 2: Impedances at 50 dB and self-resonant frequencies (S_{11} methods)

Again, the one-port shunt, two-port shunt, and two port measurements do not agree with the Murata values.

Figures 11 and 12 show the impedance curves for a *270 nH* inductor based on the S_{11} parameter measurements.

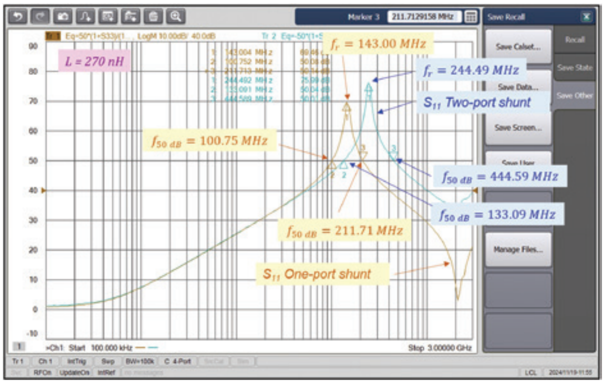

Figure 11: S_{11}-based impedance curves - one-port shunt vs. two-port shunt (*L = 270 nH*)

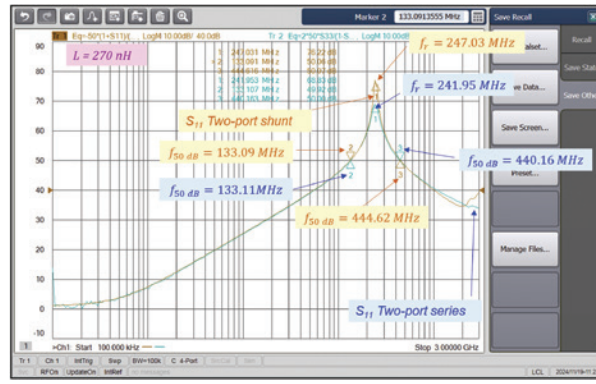

Figure 12: S_{11}-based impedance curves - two-port shunt vs. two-port series (*L = 270 nH*)

Figure 11 compares the one-port shunt and two-port shunt configurations, while Figure 12 compares the two-port shunt and two-port series configurations.

Figure 13 shows the inductor impedance curve obtained from the Murata Design Support Software "SimSurfing."

The one-port shunt, two-port shunt, two-port series, and Murata measurements at 50 dB and at self-resonant frequencies are shown in Table 3.

Once again, the one-port shunt, two-port shunt, and two-port measurements do not agree with the Murata values.

The overall conclusion is that the inductor's impedance evaluation from the S_{11} parameter measurements is not accurate. The next article will discuss the inductor's impedance estimation from the S_{21} parameters and show its superiority over the S_{11}-based methods.

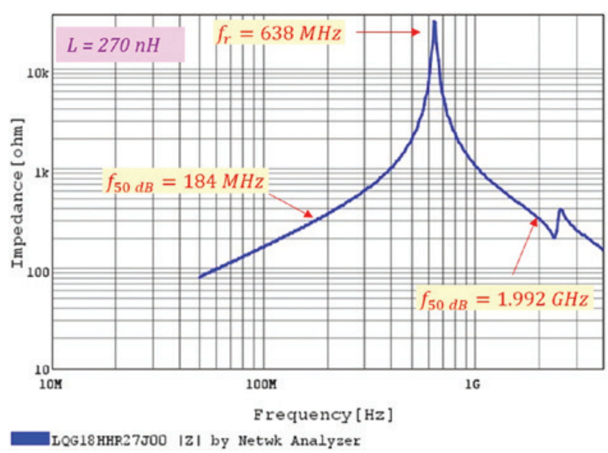

Figure 13: Murata "SimSurfing" impedance curve for *270 nH* inductor

L = 270 nH	*One-port shunt*	*Two-port shunt*	*Two-port series*	*Murata*
1st 50 dB frequency	100.75 MHz	133.09 MHz	133.11 MHz	184 MHz
Resonant frequency	143.00 MHz	244.49 MHz	241.95 MHz	638 MHz
2nd 50 dB frequency	211.71 MHz	444.59 MHz	440.16 MHz	1.992 GHz

Table 3: Impedances at 50 dB and self-resonant frequencies (S_{11} methods)

REFERENCES

1. Bogdan Adamczyk, Patrick Cribbins. and Khalil Chame, "Capacitor Impedance Evaluation from S Parameter Measurements – Part 1: S_{11} One-Port Shunt, Two-Port Shunt and Two-Port Series Methods," *In Compliance Magazine*, February 2025.
2. Bogdan Adamczyk, Patrick Cribbins, and Khalil Chame, "Capacitor Impedance Evaluation from S Parameter Measurements – Part 2: S_{21} Two-Port Shunt and Two-Port Series Methods," *In Compliance Magazine*, March 2025.
3. Murata Design Support Software "SimSurfing"

AC AND DC IONIZATION, THE WHOLE STORY

By Iad Mirshad and Ed Oldynski for EOS/ESD Association, Inc.

Iad Mirshad has a PH.D. in Physics from the University of California, Davis. He has worked as an Applications Scientist/Engineer in semiconductor metrology and inkjet printing technology for advanced displays. He is a Senior Applications Engineer at Simco-Ion, Technology Group.

Ed Oldynski holds a BS in Electrical Engineering from California State Polytechnic University at Pomona and BS in Industrial Technology from California State University at Long Beach. He is a Senior Electrical Engineer at Simco-Ion, Technology Group, holding this position for the last 25 years.

Placing a target too close to an ionizer, whether AC or DC, may increase the risk of negative effects, such as localized charge buildup, electrical stress, or minor material degradation. To prevent adverse effects and potential damage, maintain an appropriate distance from the ionizer. While AC ionizers can generate higher electric fields than DC ionizers, their impact on the target must be considered in the context of the target's impedance, size, and the ionizer's operational frequencies. When these factors are accounted for, the potential risks posed by AC ionization to the target are not significantly greater.

TEST SETUP

The experimental setup consisted of two ionizers, Model 5645 MP (AC) and Model 5225 (DC) ionizing bars, suspended above a perforated table, as shown in Figure 1.

The test sample in Figure 2a was designed to simulate the exposure of targeted devices and structures of various sizes. The experiment used four pads: a 1.0-inch square, a 0.5-inch square, a 0.25-inch square, and a 0.018 x 0.057-inch rectangle. Each pad was connected to a Lecroy WaveSurfer 64Xs oscilloscope using a 10 MW (9.5 pF) probe. A Faraday Cage was used to shield the probes from the electric field and minimize measurement contamination.

MEASUREMENTS

We already understand that a DC ionizer presents minimal risk due to its nearly negligible electric field (E-Field). Therefore, our focus is on the results from AC ionization. At various distances, our test sample was exposed to two output levels from the 5645 MP bar. As expected, the electric field strength--and consequently the induced peak-to-peak voltage--decreases rapidly with increasing distance. Notably, the ionization or "pusher" frequency was not prevalent in the data. The MP (Modulated Pulse) architecture consists of a high-frequency excitation voltage (around 20 kHz) and a lower "modulation" or pusher frequency (ranging from 0.3 Hz to 60 Hz) that drives ions toward the target when purging air is not employed. Figure 3 shows the peak-to-peak voltage results for the 1-inch square test sample, with similar outcomes observed for the other sample sizes.

It is this excitation voltage that is responsible for inducing the voltage on our test sample, as illustrated in Figure 4. This figure shows that as the sample size decreases, the induced voltage also decreases. It is important to note that as the test sample size reduced, interference from the sampling connection increasingly affected the measurement accuracy. Consequently, obtaining a precise measurement for a 0.018 x 0.057-inch square sample became challenging.

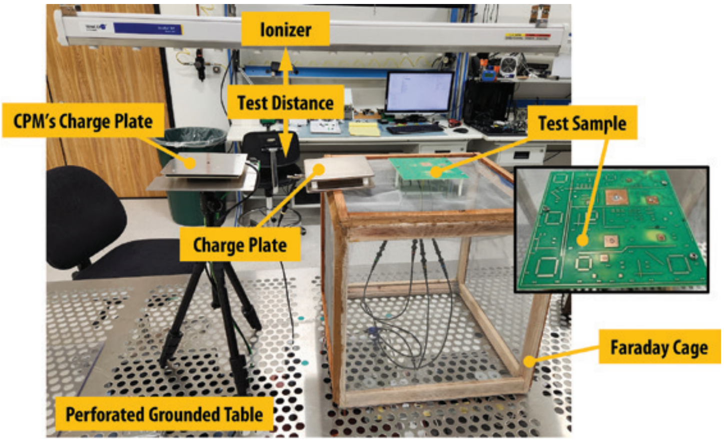

Figure 1: Test setup showing CPM's charge plate, charge plate, Faraday Cage, and test sample

WHAT DOES ALL THIS MEAN?

First, for comparison, Figure 5 illustrates the induced voltage on a standard, 20 pF 6x6-inch square, charged plate (Figure 2b). This reflects an observation when using a charged plate monitor (CPM) to evaluate ionizer performance. However, this can be misleading as typical devices would not experience such high voltage levels. Additionally, real devices have impedance, which would result in significantly lower voltage levels than those shown in Figure 4.

Second, all the voltages measured in this experiment are relative to a ground reference. However, in practice, a device is not damaged by Electrostatic Discharge (ESD) because of its voltage relative to ground, but rather from the interaction with nearby charged areas within the device or contact with other non-grounded objects.

It is important to note that the frequencies generated by AC ionizers are in the range of tens of Hertz, with a median wavelength of about 5,000 km. The 5645 MP also includes a 20 kHz component with a wavelength of 15 km. This means at such wavelengths all objects within the ionizer's range are subjected to the same instantaneous voltage at the same moment. Therefore, if we compare the voltage between two objects at equal distances from the ionizer, the voltage difference (differential voltage) will be zero or near zero. Since a significant differential voltage is required to trigger an ESD event, no event can occur when the differential voltage is zero.

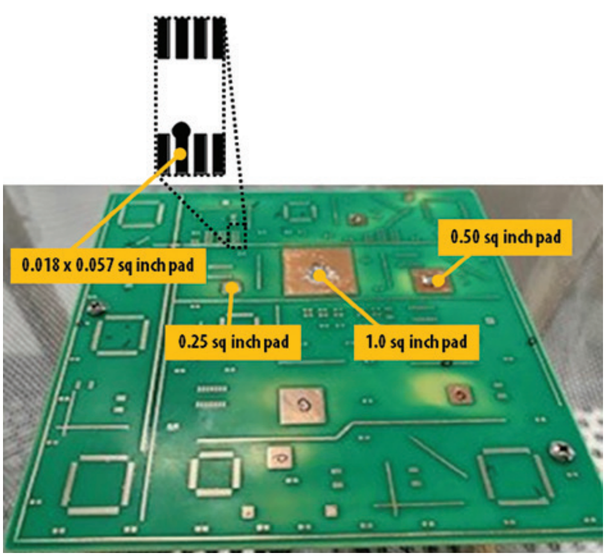

Figure 2a: Test sample

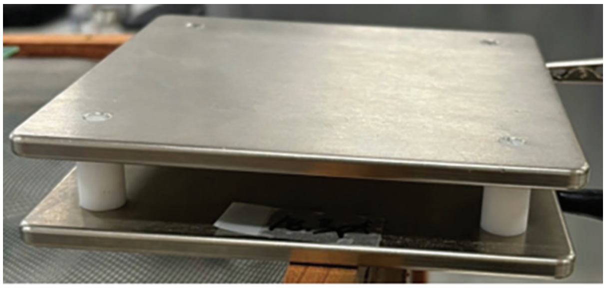

Figure 2b: Standard charged plate

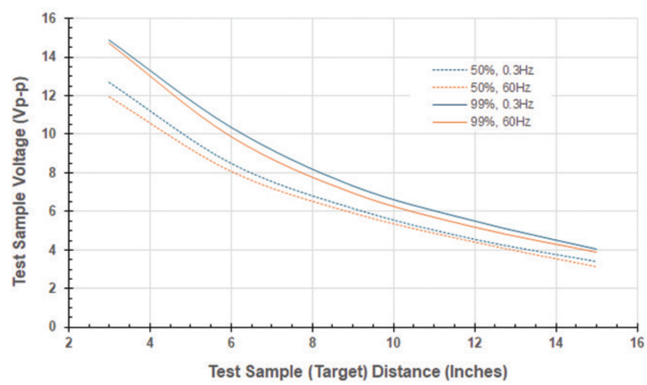

Figure 3: Ionizer Model 5645 MP on the 1.0-inch sq test sample with output of 50 and 99% and ionization (pusher) frequency of 0.3 and 60 Hz

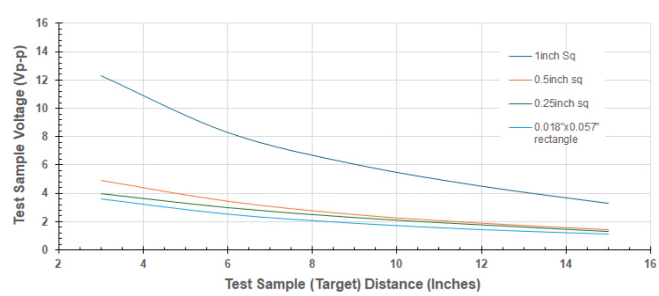

Figure 4: 5645 MP test sample size vs. test sample distance with output of 50 and 99% and ionization (pusher) frequency of 0.3 and 60 Hz

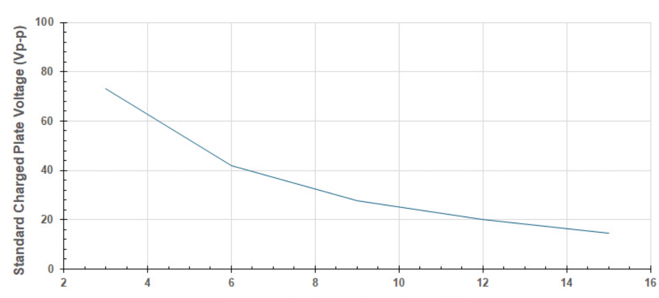

Figure 5: 5645 MP 20pF, 6 x 6-inch sq plate vs. test sample distance with output of 50 and 99% and ionization (pusher) frequency of 0.3 and 60 Hz

Consider this: Why do sparks (ESD events) occur when you place a metal object in a microwave oven? Many microwave ovens operate at a frequency of around 2.45 GHz, corresponding to a wavelength of 12.2 cm, and generate high power (about 1 kW)[1]. At this short wavelength, regions of high differential voltage are created. On the surface of the metal object, points only 6 cm apart experience instantaneous voltage differences, with the differential voltage corresponding to the peak-to-peak variation induced by the magnetron tube. This results in sparks jumping between those points.

In a microwave oven, any object within 6 cm experiences a significant differential voltage. In contrast, for a typical ionizer to generate a similar voltage difference, the object separation would need to be λ/2, or about 8 km (8000 meters). This is far from the case in semiconductor devices, where the separation is typically on the scale of nanometers (nm).

Third, what happens when a non-grounded object comes into contact with a semiconductor device under an operating ionizer? As the object approaches the device, it enters the same "zone of influence" created by the ionizer and experiences the same electric field as the device. This rapidly reduces the differential voltage between the object and the device to near zero, eliminating any threat to the device.

OTHER CONCERNS

During the experiment, it became clear that as the test sample was moved closer to the ionizer, additional frequencies unrelated to ionization were detected. These frequencies (characterized by long wavelengths) pose no risk but are worth noting. These "other frequencies" arise from the high voltage (HV) generation inside the ionizer, which is necessary for ion production. The HV generation (illustrated in Figure 6) typically involves either a fly-back or resonance circuit powering a step-up transformer. This creates an electric field that becomes noticeable when the device is within approximately 3 inches (or less) of the ionizer. Any ionizer, whether DC or AC, which uses high voltage generation will produce this effect.

CONCLUSION

It appears that the frequencies generated by both DC and AC ionizers are so low (with wavelengths much greater than millimeters) and of such minimal power that they cannot produce significant differential voltages capable of causing catastrophic damage to the device. Even when other tools are introduced into the ionizer's "zone of influence," the resulting differential voltages remain insignificant and pose no risk of damage to the device.

Additionally, placing a target too close to an ionizer, whether AC or DC, can increase the risk of negative effects, such as localized charge buildup, electrical stress, or minor material degradation. To avoid these issues and potential damage, it's recommended to maintain a safe distance from the ionizer.

ENDNOTE

1. "Introduction to RF Solid State Microwave Heating," Slipstream Design.

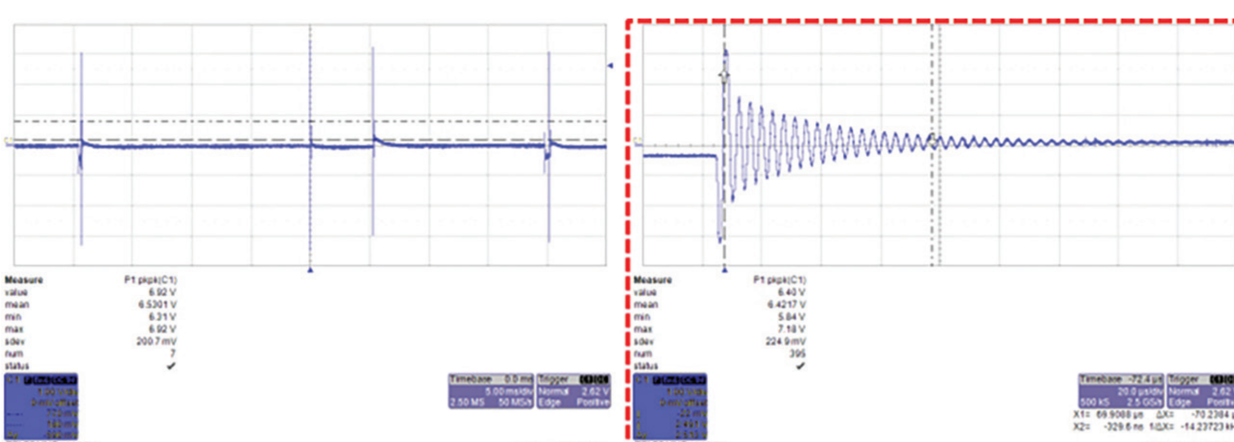

Figure 6: Signal artifact of high voltage generation. The signal from the ionizer Model 5225 in steady-state mode (DC ionization)

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2025 International Applied Computational Electromagnetics Society (ACES) Symposium

May 19-21
EMC & Compliance International Exhibition & Workshops

May 19-22
2025 IEEE International Instrumentation and Measurement Technology Conference

May 19-23
2025 Asia-Pacific International Symposium and Exhibition on Electromagnetic Compatibility (APEMC)

May 20
★ AMTA 2025 Regional Meeting

June 3-6
WPTCE 2025IEEE Wireless Power Technology Conference and Expo

June 15-20
★ IMS 2025 – IEEE International Microwave Symposium

June 26
Cybersecurity Maturity Model Certification for Federal Government Procurements