Full Load EMI Testing of Medium-Voltage,High-Power Systems

WHITE PAPER

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Executive Summary

The U.S. Navy's ongoing electrification of surface ships and submarines, including integrated power systems, energy storage systems (ESS), high-power inverters, and medium-voltage (MV) switchgear enables advanced propulsion, distributed loads, and dynamic mission systems. However, these technologies introduce significant electromagnetic interference (EMI) risks that, if unaddressed, can degrade mission effectiveness, compromise safety, and increase lifecycle cost.

This whitepaper illustrates the *benefits of comprehensive EMI qualification testing* for high-power, medium-voltage systems, explains current limitations in test capabilities nationwide, and describes traditional DoD qualification approaches along with the risk they pose. We present recommendations and highlight new EMI test services to ensure robust, timely, and cost-effective qualification for naval applications.

Introduction

Evolution of Naval Power and Energy Architectures

Modern U.S. naval platforms are undergoing a fundamental transformation in how electrical power is generated, distributed, and utilized. Historically, shipboard electrical systems were designed primarily to support hotel loads, auxiliary machinery, and relatively modest combat system demands, using low-voltage AC distribution. Propulsion systems were primarily mechanical, with electrical power playing a secondary role.

Over the past several decades, this paradigm has shifted significantly. The emergence of Integrated Power Systems (IPS) and Integrated Power and Energy Systems (IPES) represent a fundamental shift in naval ship design philosophy, in which all shipboard electrical generation and distribution are treated as a single, integrated resource rather than being partitioned into propulsion and ship-service domains. Integrated Power and Energy Systems (IPES) extend this concept further by incorporating energy storage, advanced power electronics, and dynamic energy management to support pulsed and transient loads. Unlike legacy ship designs, IPS enables full power sharing across the platform, allowing electrical energy to be dynamically allocated based on mission needs. Platforms such as the DDG-1000 (Zumwalt-class) destroyer exemplify the IPS approach, providing megawatt-class electrical power for propulsion and mission systems from common architecture.

Together, IPS and IPES architectures form the electrical backbone of modern and future U.S. Navy surface combatants and submarines, enabling high-power mission systems while improving efficiency, survivability, and operational flexibility. This transition is driven by increasing power demands from electric propulsion, advanced radar systems, directed energy weapons, high-performance computing, missions systems, and future combat capabilities, as well as the need for improved efficiency, survivability, and operational flexibility.

However, IPS and IPES architectures also inherently increase EMI risk. This is due to the concentration of high-power converters in propulsion and distribution systems, long MV cable runs connecting generators, motors, and loads, and shared buses that enable EMI propagation across traditionally isolated domains. In an IPS environment, EMI generated by propulsion drives or large converters can propagate throughout the platform, potentially affecting sensitive combat and navigation systems. This is a critical consideration in EMI qualification and system integration

Transition to Medium-Voltage Distribution

Low-voltage distribution architectures face inherent limitations as total shipboard power increases. As power levels scale upward, low-voltage systems suffer from excessive conductor size, weight, thermal losses, and reduced fault tolerance. To address these constraints, modern naval designs increasingly augment or replace low-voltage systems with medium-voltage AC (MVAC) and medium-voltage DC (MVDC) distribution which offer several advantages including reduced current for a given power level, lowering conductor size and resistive losses, improved efficiency over long cable runs, enhanced support for high-power, pulsed, and transient loads, and greater flexibility in power routing and reconfiguration following damage. MVDC architecture also can eliminate reactive power issues, simplify power conversion for DC-native loads, and supports rapid energy transfer between sources and loads. These benefits are well documented in naval power system research and form the basis for next-generation surface combatant and submarine designs.

Shipboard and Submarine Electromagnetic Environments

The convergence of advanced medium voltage-high power technologies fundamentally alters the electromagnetic environment aboard ships and submarines. These systems are often installed in close proximity to mission-critical RF, navigation, and communication equipment, within confined metallic compartments, which promote complex EMI coupling paths between sub-systems and equipment. EMI arises when electrical systems unintentionally emit electromagnetic energy that interferes with other electronic equipment. High-power, high frequency switching in converters and MV switchgear generates both conducted and radiated emissions, which can couple into other circuits or systems.

While these technologies are transformational in terms of performance and capability, they create dense, broadband, and highly dynamic EMI environments that cannot be adequately assessed using legacy low-power testing assumptions. Rigorous, full-load EMI qualifications are therefore essential to ensure safe coexistence, mission assurance, and long-term fleet readiness.

Energy Storage Systems (ESS)

Energy Storage Systems (ESS) have emerged as a cornerstone technology in modern naval power architecture. Large-scale battery systems, typically lithium-ion–based, are integrated with power conditioning units to provide improved power quality and system stability, load leveling and buffering of transient demands and support for pulsed power loads (e.g., radar, weapons), as well as enhanced survivability and ride-through capability during faults.

ESS units interface directly with MVDC or MVAC buses through high-power converters, introducing fast-switching electronics and high stored energy into the shipboard environment. These characteristics make ESS a significant source of conducted and radiated electromagnetic emissions, particularly during charge/discharge transitions, fault events, and dynamic load sharing. As ESS deployment increases, EMI qualification becomes critical to ensuring compatibility with adjacent combat and control systems.

High-Power Inverters and Converters

Power inverters and converters are the enabling link between diverse generation sources, storage systems, and loads. These devices perform DC–AC, AC–DC, and DC–DC conversion at megawatt-class power levels, often using high-frequency switching techniques to improve efficiency and controllability. From an EMI perspective, these devices present many challenges. The high amplitude, fast dV/dt and dI/dt switching transitions create high amplitude, broadband RF emissions which can couple between power and communications cabling and throughout the ship structure.

As the number and power rating of devices increase, their cumulative EMI contribution poses a significant threat to the platform electromagnetic environment, which equipment level EMI qualification requirements are based on. Without strict EMI control, and rigorous qualification requirements, these emissions can interfere with sensitive RF receivers, navigation systems, and digital control networks. The Navy and IEEE literature consistently highlight power electronics as one of the dominant EMI sources in modern ships today.

Medium-Voltage Switchgear

Medium-voltage switchgear forms the backbone of power distribution and protection in modern naval vessels. These systems manage fault isolation, load shedding, power reconfiguration, and system survivability. Increasingly, switchgear incorporates solid-state or hybrid technologies, replacing purely mechanical breakers with fast electronic controls. While these advances improve response time and reliability, they also introduce new EMI concerns including high-frequency transients during switching and fault clearing and coupling of transient energy into adjacent power and signal cables increasing the risk of susceptibility of protection logic to electromagnetic disturbances.

Switchgear subsystems have been found to be susceptible to EMI resulting in nuisance trips or delayed fault clearing and pose a direct risk to mission continuity and personnel safety. Consequently, EMI qualification of MV switchgear is essential not only for compatibility, but for core system reliability.

EMI Qualification Testing

EMI qualification testing evaluates whether electrical and electronic hardware can operate safely and reliably in the presence of electromagnetic disturbances relative to its intended installation platform electromagnetic environment (EME). Testing also establishes if the electromagnetic fields this equipment emits exceed levels that can interfere with other equipment in the same environment. In defense and aerospace environments, this is essential because systems are densely packed, operate in harsh electromagnetic environments, and often perform missioncritical functions. The U.S. Department of Defense (DoD) defines these requirements through two major standards: **MILSTD461** (Equipment/Sub-system level) and **MILSTD464** (System/Platform level).

For over 60 years, MILSTD461 shas been the EMI qualification standard for all electrical and electronic equipment procured by the DOD and installed on military platforms spanning across Land, Sea, Air, and Space environments. The intent of this testing is to ensure that every item placed on a military platform is electromagnetically compatible with its environment and does not interfere with the operation of other equipment located on the platform. MIL-STD-461 defines the applicable laboratory test methods and test limits for emissions and susceptibility test types based on the equipment, procuring service (Army, Navy, or Air Force), and platform it will be installed on. These requirements are often tailored by the government to address known mission EME's the equipment may be exposed to not specifically covered by standard qualification testing.

The MIL-STD-461 qualification test types are segregated into two categories (emissions, and susceptibility). Emissions testing measures the electromagnetic noise emitted for the device and compares it to control limits that have been established by the tri-service group for each applicable platform environment. Electromagnetic Emissions testing ensures that the equipment will not interfere with other equipment when fielded. Susceptibility tests expose the equipment to specific electromagnetic environments to ensure it is resilient and will continue to operate safely and reliably. Test levels and ranges are representative of those expected to be encountered on each platform.

MILSTD461 Test Requirements

It includes both conducted and radiated Test criteria

Category	Examples of Test Methods	What It Evaluates
Conducted Emissions (CE)	CE101, CE102	Noise emitted from power lines
Conducted Susceptibility (CS)	CS101, CS114, CS115, CS116, CS117, CS118	Ability to withstand injected noise, transients, and RF currents
Radiated Emissions (RE)	RE101, RE102	Fields emitted into the environment
Radiated Susceptibility (RS)	RS101, RS103, RS105	Ability to withstand external electromagnetic fields

** List excludes Antenna port specific tests*

In addition to performing these tests, MIL-STD-461 specifically requires that the equipment must be tested in operating modes and conditions that will produce maximum emissions during emissions testing and are considered most susceptible to EMI during susceptibility testing. Additionally, for equipment with several available modes (including software/firmware controlled operational modes), a sufficient number of modes must be tested to ensure that all circuitry is evaluated.

For example, Power converters, variable frequency drives, or switch-mode power supplies, would likely be configured to operate at its highestfrequency switching mode, communicating with a maximum data throughput on digital interfaces, and operated at fullload operation. Each of these conditions are expected to maximize the electromagnetic emissions signature of the equipment under test.

MIL-STD-464 Requirements

MILSTD464 addresses the DoD's systemlevel Electromagnetic Environmental Effects (E3) requirements which covers aircraft, ships, ground vehicles, space systems, and associated ordnance. Power systems are a major part of these environments, but they are addressed at the *system level*, not the equipment level. MIL-STD-464 defines how the *entire platforms'* power generation, distribution, grounding, and loads must behave in the electromagnetic environment, while MILSTD461 governs the individual power components. Therefore, MILSTD464 encompasses and relies heavily on MIL-STD-461 test results during the E3 risk assessment process.

Test Infrastructure Limitations

As power systems become larger and more powerful, their maximum power loading requirements for MIL-STD-461 compliance testing become far reaching. EMI power handling capabilities, especially for medium-voltage, high-power (MW) equipment nationwide are severely limited, which can force alternative EMI compliance approaches to be explored.

Most commercial EMC/EMI test labs are optimized for *low-voltage (≤1 kV), low-power* electronics testing. While there are a few facilities like Element U.S. Space & Defense that are able to support low-voltage high-power systems operating at voltages up to 440 VAC and power levels up to 1 MW, it is very rare for EMI/EMC to be readily equipped to handle medium-voltage inputs at (e.g., 4610 -28.2 kV) at high power loads >5 MW, which is common Naval power systems.

In addition to power source limitations, high-power equipment typically requires a large, complex water-cooling support system which most test laboratories are generally not equipped to handle. The cooling infrastructure typically employs cooling loop that delivers filtered, deionized (DI) water directly to the electronic equipment to ensure electrical isolation, corrosion mitigation, and stable thermal performance. Continuous monitoring of conductivity, pH, flow, and temperature ensures water quality remains within operational limits are also generally required. Large centrifugal pumps, often equipped with variable frequency drives, are often used to maintain the required high flow rate and pressure while providing resilience to equipment failure. These systems are often controlled through integrated automation and instrumentation packages that manage pump operation, temperature regulation, flow control, and fault interlocks. Expansion tanks, air separators, and leak-detection systems provide additional protection and operational stability. The facility layout typically includes dedicated pump and treatment rooms, service access clearances around heat exchanger banks, non-metallic DI piping runs, and vibration-isolated mounting for major equipment.

Full load EMI testing of medium-voltage, high power equipment and systems will also require large resistive load banks that are rated for the output voltage (AC and/or DC) at the maximum power output. MW Power outputs can easily exceed current test capabilities of commercial EMI test labs.

It should also be pointed out that the size and weight of medium-voltage, high-power equipment and systems can easily exceed conventional EMI chamber dimensions, and maximum floor load ratings. For example, many multi-cabinet power system test setups can exceed a test setup boundary length of 50 ft, with cabinets reaching 100,000 lbs.

Lastly, there are several applicable tests specified in MIL-STD-461 that are simply not intended for high power medium voltage systems and require careful tailoring with consensus from the manufacturer and government. Tailoring activities can include modification of standard test limits, specifically related to high currents far exceeding a few hundred amps. Also, unique test setups, measurement equipment, and measurement techniques may be required to safety and accurately meet the MIL-STD-461 requirements. This demands expertise that spans power engineering and EMI/RF testing that many test laboratories have limited cross-disciplinary expertise, which at the very least will slow test execution and analysis.

Testing mediumvoltage, highpower systems at a government facility can be incredibly valuable as these sites often have capabilities that simply don't exist in the commercial world. However, the scheduling process can be surprisingly difficult as there are only a limited number of government test facilities that support mediumvoltage or megawattclass power testing and demand is high. As a result, test windows may be booked months or even years in advance, Priority is often given to highvisibility or urgent DoD programs, and rescheduling is difficult once a slot is assigned which can create major programlevel delays if testing is on the critical path.

Traditional DoD Qualification Approaches & Associated Risks

Due to the challenges and limitations addressed above, subsystem EMI testing has traditionally been performed at reduced power levels or with surrogate loads. Attempts are then made to extrapolate these partialload results to predict the electromagnetic emission levels expected at maximum operating conditions. While convenient, this practice introduces a substantial risk of mischaracterizing the system's true electromagnetic behavior. Switching noise, harmonic content, and transient phenomena do not scale linearly with load; instead, they tend to intensify disproportionately as components approach their electrical, thermal, and magnetic limits. Effects such as increased switching overlap, magnetic core saturation, altered controlloop dynamics, and increased transient responses can all emerge only at or near fullpower operation. As a result, relying on reducedpower data can lead to significant underestimation of actual emission levels, potentially masking compliance issues that will only become apparent when the system is subjected to its true operational stresses.

Deferring full electromagnetic interference (EMI) assessment to large platformlevel events such as Builder's Trials offers the advantage of evaluating system performance under realistic, fully integrated operating conditions, where all subsystems function at their true power levels and interact through actual cabling, grounding, and structural return paths. This environment provides the most accurate representation of realworld electromagnetic behavior and can reveal coupling mechanisms or installationdependent issues that are impossible to replicate during isolated bench testing. However, relying primarily on these latestage trials introduces significant programmatic risk. Any unexpected emissions, susceptibility problems, or crosssystem interactions discovered at this point are difficult to diagnose, costly to correct, and often require intrusive rework or schedule delays. The limited diagnostic access available on a fully assembled platform further complicates rootcause analysis, increasing the likelihood that issues will persist or require operational restrictions. As a result, while platformlevel testing is essential for final verification, deferring major EMI discovery to this phase can jeopardize cost, schedule, and system performance.

Analytical assessments and benchlevel testing offer valuable early insight into expected electromagnetic interference (EMI) behavior by allowing engineers to evaluate designs, run simulations, and validate subsystem performance long before fullpower hardware is available. These methods are costeffective, repeatable, and highly flexible, enabling rapid iteration and early identification of design weaknesses without the logistical and safety challenges associated with highpower testing. However, relying heavily on analysis and lowpower bench data introduces meaningful risk. Models are only as accurate as their assumptions, and many EMI mechanisms, such as nonlinear switching behavior, magnetic saturation, loaddependent harmonics, and fullpower transient events cannot be reliably captured without physical testing at operational power levels. As a result, predictions based on limited highpower data may underestimate real emission levels or overlook installationdependent coupling paths, leading to latestage surprises during integrated platform testing.

Risks Associated with Traditional Approaches

Risk Category	Description	Impact
Incomplete Coverage	Low-power tests don't reveal high-power conducted emissions	Missed EMI issues until late integration
Late Discovery of Faults	EMI problems detected only during shipboard integration	Costly rework, schedule delays
Standard Mismatch	MIL-STD-461 limits not tailored to MV power electronics	Underestimates actual emissions/susceptibility
Cost & Schedule Delays	Deferred issues inflate project cost	Mission readiness impacted
Operational/Safety Risks	EMI can affect combat systems and safety interlocks	Potential mission failure or unsafe events

These challenges and compliance risks highlight a critical need for specialized EMI test facilities, infrastructure, and technical support of mediumvoltage, highpower system qualifications. Full Load testing offers substantial benefits by providing a far more accurate understanding of how these systems behave under realistic electromagnetic stresses.

By validating performance in representative electromagnetic environments, programs gain stronger mission assurance and confidence that systems will operate reliably even in dense or contested EM conditions. This level of qualification also strengthens overall system safety and reliability by confirming that protection, control, and safety mechanisms remain stable and immune to EMIinduced perturbations, reducing the likelihood of nuisance trips, misoperations, or cascading failures during highpower operation.

Beyond operational assurance, Full Load EMI testing plays a crucial role in early design maturation of medium voltage, High power systems, by exposing weaknesses in filtering, grounding, shielding, and layout practices long before fullscale integration, enabling engineers to correct deficiencies when changes are still inexpensive and manageable. This early insight reduces rework, shortens development timelines, and minimizes the risk of discovering critical issues during late-stage platform trials.

Element U.S Space & Defense, through commercial partnerships, has developed a state-of-the-art medium-voltage, high-power EMI test facility located in the Milwaukee WI area to address the current industry-wide limitations described earlier. This facility is equipped with a very large semi-anechoic EMI chamber measuring 74' x 36'x 16', lined with high performance poly styrene RF absorber material which meets the MIL-STD-461 minimum absorber criteria. The chamber is equipped with a large 12' x 12' double leaf door and a "low profile" steel ramp specifically designed to heavy weight equipment moving systems. The chamber floor has also been customized with ¾" steel plates to increase its floor weight rating to 100,000 lbs. Another unique feature is the 2" cooling water pipe (feed and return) penetrations mounted in the chamber wall. These pipes are designed to support a chilled water-cooling system that support flow rates up to 186 GPM. The pipes are equipped with custom designed waveguide inserts to maintain 80 dB of chamber shielding effectiveness at 18 GHz. The chamber is also equipped with custom built low and medium-voltage low pass EMI filters designed to support voltages from 440 VAC to 13.8 kVA > 5 MW, and 1500 VDC up to 4000 amps. In addition to this, the facility is equipped with selectable resistive load banks and metering services as a complete turn-key solution to equipment manufacturers.

The facility is accredited to ISO 17025 to perform EMI testing to MIL-STD-461 specific to Navy shipboard and submarine applications. However, it has the capability to support all test methods and test levels defined by the standard and extends it comprehensive E3 test and analysis services in accordance with MIL-STD-464 as well.

Element U.S> Space & Defense is highly experienced in developing standardized test plans tailored to medium-voltage, high-power architectures with a goal is to improve consistency and technical rigor across the industry. The Element team is skilled in both highvoltage/power engineering and RF/EMI disciplines, and able to support an incremental qualification approach from prototype through integration, to further strengthen program outcomes and reduce technical risk across the acquisition lifecycle.

To learn more about our unique test capabilities, please reach out to Jeff Viel, Chief Engineer EMI/E3 at Element U.S. Space & Defense (jeffrey.viel@elementdefense.com), or contact your designated sales representative.

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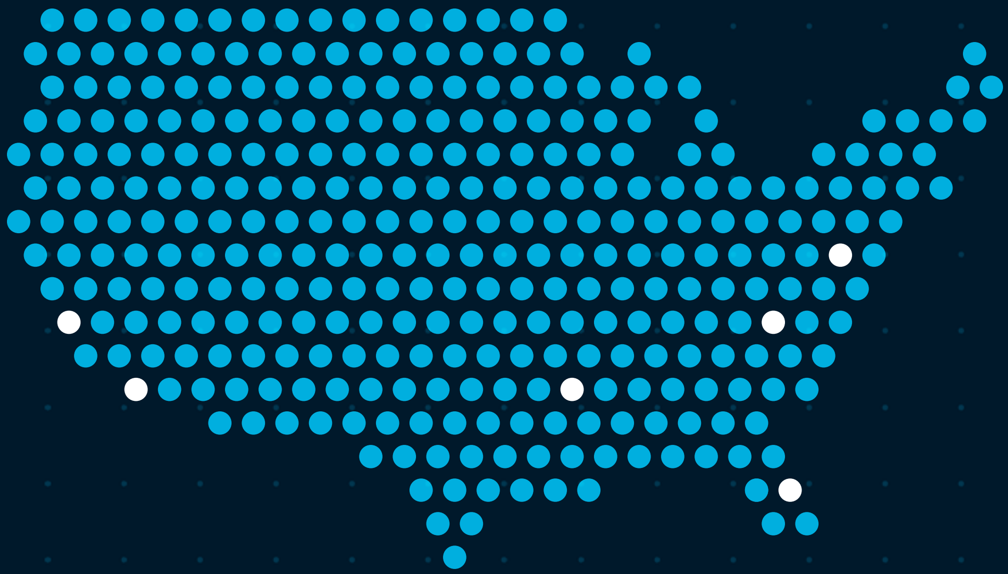

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