METHOD FOR DERIVATION AND SYNTHESIS OF ELECTROMAGNETIC ENVIRONMENTAL EFFECTS REQUIREMENT LIMITS FOR ACHIEVING SYSTEM LEVEL ELECTROMAGNETIC COMPATIBILITY

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ABSTRACT

As humans endeavor to build large-scale complex systems, it will necessitate the integration of engineering practices and techniques to allocate many of the design aspects and responsibility across traditional boundaries. Many of today's large-scale complex systems, like commercial aircraft, satellite systems, and even automobiles use parts from all over the world. A recently completed airframe, largest commercial aircraft in the world, took nearly 30 years to build, required over 400 different suppliers from 20 different countries. These kinds of projects dictate a method for derivation and synthesis of electromagnetic environmental effects (E3) requirement limits for achieving system level electromagnetic compatibility (EMC).

If a system level EMC design is an assemblage of compliant subsystems, then the subsystems should be an assemblage of compliant module and component designs. This requires tailoring the system level requirements through to module or component level designs. The method discussed is applicable to a variety of designs across varying levels of complexity and importantly implementable early in the design process. The method provides rationale for derivation of limits while maintaining traceability to system level requirements.

Specific examples using the four common divisions of EMC requirements, conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility are included. An overall system engineering approach and formal methodology is included. Detailed comparison examples using commercial and military EMC requirements are also included. Lastly, a discussion is included on comparison and margin analysis of input filtering for verifying compliance to requirements at the system level.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS (or) ABBREVIATIONS

A	Amps
CE	Conducted Emissions
CS	Conducted Susceptibility
CS	Conducted Susceptibility
CTU	Command and Telemetry Unit
CW	Continuous Wave
dB	Decibel
E3	Electromagnetic Environmental Effects
ELU	External Lighting Unit
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMRO	Electromagnetic Radiation Operational
EMV	Electromagnetic Vulnerability
EP	Electronic Protection
ESD	Electrostatic Discharge
EUT	Equipment Under Test
HERF	Hazards of Electromagnetic Radiation to Fuel
HIRF	High Intensity Radiated Fields
HPM	High Power Microwave
Hz	Hertz
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
ILU	Interior Lighting Unit
LISN	Line Impedance Stabilization Network
MIL-STD	Military Standard
PCU	Power Conditioning Unit
PCU	Power Conditioning Unit
RE	Radiated Emissions
RF	Radio Frequency
RS	Radiated Susceptibility
SE	Shielding Effectiveness
TBR	To Be Resolved

V	Volts
V&V	Validation and Verification
VAC	Volts Alternating Current
VDC	Voltage Direct Current
W	Watts

CHAPTER 1 INTRODUCTION

As humans endeavor to build large-scale complex systems, it will necessitate the integration of engineering practices and techniques to allocate many of the design aspects and responsibility across traditional boundaries. Many of today's large-scale complex systems, like commercial aircraft, satellite systems, and even automobiles use parts from all over the world. The Airbus A380, largest commercial aircraft in the world, took nearly 30 years to build, required over 400 different suppliers from 20 different countries [1]. These kinds of projects dictate a method for derivation and synthesis of electromagnetic environmental effects (E3) requirement limits for achieving system level electromagnetic compatibility (EMC).

System level design for EMC frequently uses a hierarchical approach to requirements decomposition and "flowdown". This makes each subsystem design compliant to a lower order EMC requirement that when combined at the system level design is the assemblage of these lower level designs. Extending this approach further, if a system level EMC design is an assemblage of compliant subsystems, then the subsystems should be an assemblage of compliant module designs, and modules an assemblage of compliant components. This approach requires tailoring and deriving the system level requirements down to the lowest feasible design level. Simply reducing a level or limit and prescribing it progressively lower is not sufficient. This approach leads to unverifiable consequences and lacks traceability rationale.

Previous research has focused on tailoring requirements to specific environments or applications [1] [2]. Requirement standards often include brief discussions on rationale for potential tailoring such as limited allocation but do not extend to lower levels. Standards must self-impose a type of limitation; they cannot address all applications and levels. “Flowdown” is the process of allocating requirements progressively down to lower level designs, system to subsystem to modules to components. Inherent to the flowdown process is each requirement must have closure, be valid and verifiable at the level of allocated architecture. Designers, suppliers, verification, and qualification stakeholders need these requirements allocated at their perspective level to ensure a compliant design when escalated to the system level.

Compared to design techniques and methods, the amount of research on the challenges of extending EMC requirements to subsystems, modules, and components to achieve system level EMC compliance is minimal. Various design techniques, methods, and tools used to achieve EMC have had a substantial amount of research; these are seldom available to a system level designer. System level designers cannot allocate “How” a requirement is to be satisfied or request specific design methodology at subsystem, module, or component level without assuming responsibility for the design. For example, if a supplier is directed to use a specific component that fails to meet requirements. Allocating derived requirements and not design methodology avoids this problem.

Allocating system level susceptibility requirements beyond their applicability is particularly concerning because this results in unfeasible verification scenarios. Examples of this are power inputs that derive their waveform internally, these are beyond the applicability of most requirement standards or excluded outright. For example, MIL-STD-461 does not apply to secondary power output waveforms at all. Secondary power unit outputs may have significantly lower drive levels that cannot tolerate limits intended at a system level. In addition, requirements must trace with rationale to a parent requirement, demonstrating compliance. Requirement standards give no instruction on how to decompose applicable limits to a lower design level because secondary inputs are out of the requirement scope. Siefker in [3] provides a discussion with examples of requirements incorrectly prescribed and leading to unintended consequences or outright infeasibility but Siefker does not address the difficulty of allocating requirements from the system to subsystem, module, or component level in the “Flowdown” process.

This dissertation introduces a novel method for deriving electromagnetic environmental effects (E3) requirement limits from system level requirements for allocating to subsystems, modules, and components, thus extending the requirement beyond its initial level of applicability at system level. The method maintains consistency with the approach used to develop system level limits from requirement standards. This aspect is important because it maintains traceability and provides derivation rationale. An outline of the formal approach is given; then to highlight commonly encountered difficulties detailed examples using commercial and military standards are studied. The examples postulate sample system hardware to focus discussion.

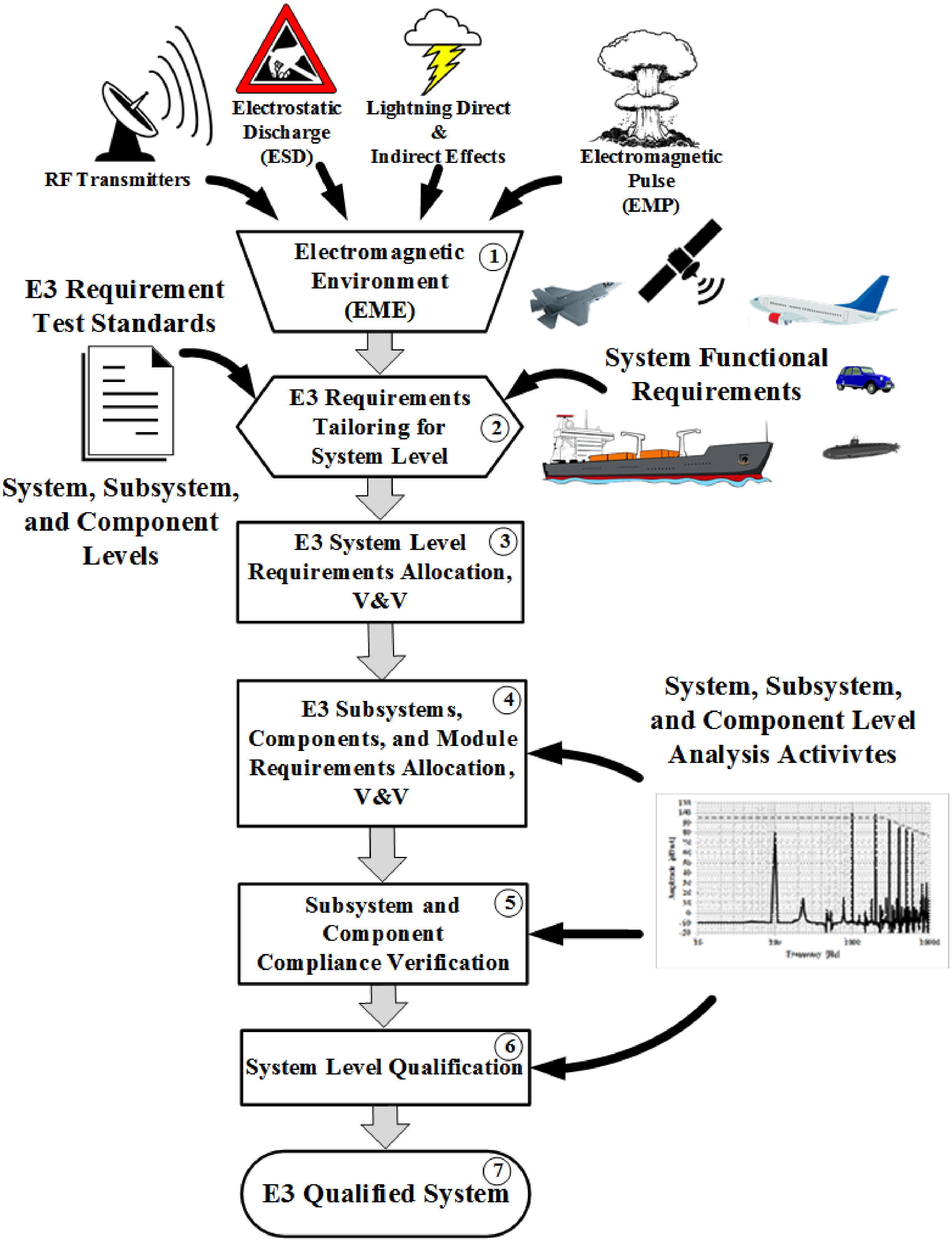


Figure 1 System Flowdown Process for E3

1.1 Key Terms Definitions

For the purposes of edification, to provide consistent understanding and avoid conceptual contradictions, this dissertation defines a few key terms particularly in relation to EMC. The term “System” means a high-level assemblage of subsystems or modules that must meet mission level requirements. For example, an airplane, satellite, or automobile is a system. The term subsystem means a self-contained part of a system that may be further divisible into a module or assembly. For example, a power converter unit within an airplane, satellite, or automobile is a subsystem. A module is a singular assemblage with a distinct function not capable of standalone operation, typically a collection of components. For example, a circuit card assembly contained within the power converter that produces a specific power waveform. A component is the lowest divisible element or part of a module. Differing industries may interpret these terms differently depending on their level of integration and designer’s point of view. Figure 2 shows this hierarchy.

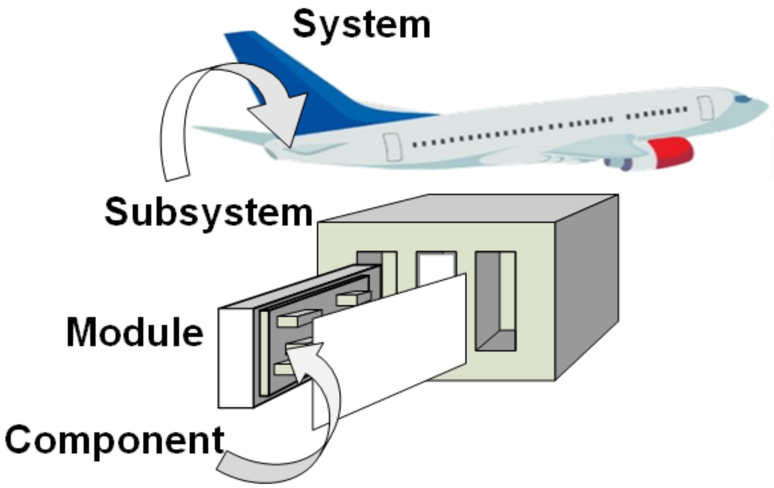


Figure 2 Flowdown Level Summary

For this dissertation “Tailoring” is defined as “The process by which the requirements of a standard are adopted (that is, modified, deleted, or supplemented) to accommodate the peculiarities, characteristics, or operational requirements of a specific equipment, system, or subsystem specification. The tailoring process does not constitute a waiver or deviation from the requirements of a standard.” [4]. For example, applying a requirement to a specific subsystem or portion of the system based on exposure or operation. For purposes of this dissertation, “Derivation” is defined as decomposing to a lower level of initial applicability than what the original requirement was applicable to or directly intended to address. Often the derived requirement should maintain the same dimensional units. From a system compliance perspective, each requirement must be traceable to a higher level or “Parent” requirement. This means assessing compliance rationale at each level for closure. Requirements allocated incorrectly can impede the flowdown process or end up deleted for being unverifiable.

1.2 Derivation

Starting from the allocated requirements that have been tailored and allocated to their lowest level of applicability, determine what aspect of the subsystem design is applicable. Subsystems are often composed of multiple modules/components. These lower level modules/components typically divide according to function, for example, power, signal, or telemetry. Only a portion of the allocated subsystem requirements will apply to specific modules/components. This is consistent with the system to subsystem flowdown.

Determine the most elementary module/component performance or design parameter to gauge compliance with the allocated requirement. For example, ask what happens in response to the electromagnetic environment, perhaps noise manifests itself on the cabling. Determine a direct correlation to the operational subsystem level parameter identified above and the module/component design. For example, what functional aspect of the design in effected, perhaps a signal protocol is corrupted, or sensor threshold voltage exceeded or bit error rate increases. This performance parameter is necessary for validation and verification, for determining pass/fail criteria. If the parameter deviates beyond a certain envelope then the subsystem will fail or likely fail. An example for emissions is current and power draw; these are consistent indicators of subsystem performance. For CS, voltage developed across input impedance is a consistent indicator.

Scale the E3 parameter following the technical basis used from system to subsystem, for example applicability, environmental limitations, or design aspects. This maintains consistency, validation, and traceability. For example, not allocating radiated emissions (RE) requirements to chassis enclosed modules/components may lead to insufficient requirement allocation. Another more thorough approach would be to allocate a shielding effectiveness requirement to the chassis and then allocate a reduced, corresponding to the SE, RE requirement to the module/component. Another example is if the subsystem has an input filter with a specified insertion loss, then a derived requirement would be the system level requirement reduced to the subsystem then reduced further, by the subsystem level input filter, so that it applies at the module/component level.

1.3 Closure

Closure is showing that satisfying lower level requirements will guarantee, or with a high likelihood of satisfaction, satisfying the higher-level requirements. From the RE example, if an enclosure acts like a Faraday cage providing SE over a known frequency range assuring compliance to the requirement. Closure is often difficult to show at any level of decomposition. For example, compliance to a subsystem level requirement may not guarantee compliance at the system level once combined together. Another difficulty with closure at system level is it often requires additional testing to make a direct correlation to performance parameters. For module/component level, showing closure is innate because the process reduces to a specific parameter, where system level performance relies on numerous parameters. This is because as the E3 effect is flowdown it manifests itself more directly, like a voltage threshold across a component. Fewer parameters also make it easier to quantify uncertainty at the module/component level. Uncertainty bounds closure and then is reduced through verification. By deriving and allocating the requirement to modules/components, verification may occur earlier than system level.

1.4 Heritage Techniques

There are no established or standardized methods for deriving EMC requirements to components or module level. The alternative is to stop requirements allocation at the subsystem level and assume the risk of noncompliance or devise another method. Some standards suggest tailoring but not derivation. Standards offer some tailoring guidance but none establishes derivation techniques beyond their scope of applicability. Mil-Std-461 suggests limiting the rise time or repetition rate to mimic the EUT; this requires detailed design aspects that may not be available. The method in this dissertation is proactive; it allocates requirements to the stakeholders who are capable of influencing the design. Being consistent with the flowdown process keeps the verification approach feasible and maintains traceability and accountability in the design process.

1.5 Sources of Uncertainty

Uncertainty of this method divides along lines of aleatory and epistemic uncertainty. Aleatory (or stochastic) uncertainty is irreducible and present throughout regardless of derivation. An EMC related aleatory uncertainty example could be the Shielding Effectiveness (SE) due to the seam gap tolerance in a chassis build or the variance in the flatness of mating metal to metal contact points or how a conductor's resistance varies due to temperature variations.

Parameters effecting EMC introduce epistemic uncertainty during derivation and when their linked to parent requirements. Epistemic Uncertainty or "Reducible Uncertainty" is from a lack of knowledge; examples are inaccurate models, measurement methods, and analysis. This step requires inherent design knowledge that may not be available. Address uncertainty by enveloping and iteratively reducing or varying the unknown quantity to ascertain its effect.

1.6 Composing an Effective Requirement

Effective requirements meet specific needs; they are a statement of a need not a want. The need can be a product, solution, service or function for a colleague, company, or customer. Even though a requirement is verifiable, attainable, and well stated, a requirement that is not necessary is no good. Good requirements are attainable, technically feasible, within budget and on schedule. Requirements for items that are impossible to build are a waste of time and effort. Requirements should be clearly understandable and express a single concise, simple, well thought out and measurable goal. Effective requirements use short simple sentences with consistent terminology; more plainly worded the better. Positively word requirements to be most effective; it is extremely difficult if not impossible to test that something does not happen. This type of testing is circuitous, expensive, and time consuming. Effective requirements do not seek to constrain the solution space.

Effective requirements are consistent; never contradict one another or other requirements. Similar requirements should be grouped together to maintain consistency, and avoid redundancy. Effective requirements are always verifiable, typically by inspection, analysis, test, demonstration or some other means. Think about how a designer will prove the product meets the requirement. Determine the specific criteria for product acceptance, this will ensure verifiable requirements. Effective requirements are grammatically correct; this is not only good practice it is essential for correct understanding. Correct sentence structure ensures the implementer or tester understands the task; it keeps lines of responsibility obvious and well defined.

1.7 Value of Results

Results of this method benefit EMC compliance programs in the near and long-terms, by identifying valid E3 requirements early, flowing down to design stakeholders, and tying them across design aspects. System level EMC requirements are inherently distant in the requirement hierarchy from the design process. For example, E3 requirements are different from other environmental requirements; they can range from nuisance to critical and are not always readily evident. Fire sensors maybe set off indicating a false alarm due to E3. This method introduces module/component level requirements into the flowdown process. This step bridges the gap and introduces design stakeholders early in the process by providing them an objective that will allow their design to meet system level requirements. It ties system level compliance to module/component level parameters and brings the work necessary for compliance into proximity to design stakeholders. This highlights the extent each design relates to another and uncovers discontinuities. For example, knowing the consequence of a module or component failure on the system allows for assessment. In the long term, this method provides verifiable requirements and feasible test methods with rationale and traceability. It disseminates accountability for design compliance and identifies risks early. Testing a subsystem or module at its corresponding level without system level hardware can happen early. Also having subsystem, module, and component levels to compare, provides substantive data for assessing potential design change impact. If a future design changed due to obsolescence, a comparison performed at the corresponding level would have a higher confidence it would continue to comply than initially implementing at system level.

CHAPTER 2 METHOD ELEMENTS

Major components used, as inputs to the overall methodology for E3 requirements tailoring and derivation are included in this chapter. Prior to discussing the fundamental building blocks of the method itself, it is important to define clearly the base elements used along the method's process. This aspect is important because it gives the reader a frame of reference to use the overall formal approach for utilization on any system, subsystem, component, or module. The purpose is to give the reader a clearer idea of the structure used in the formal approach, outlined in chapter one and Figure 1 System Flowdown Process for E3 and is not intended to be an algorithmic or heuristic approach but adaptable to both.

2.1 Electromagnetic Environment (EME)

Electromagnetic environment (EME) is a broadly interpreted term. The IEEE definition is "The electromagnetic field(s) and or signals existing in a transmission medium" [5] and [10] gives another. For the purposes of this dissertation, EME is the resultant electromagnetic radiated or conducted emission and susceptibility levels that a system, subsystem, component, or module may encounter. Units of the electromagnetic environment are in terms of power, voltage, or current and distributed over time or frequency ranges. Functional roles and operational phases of the exposed system, subsystem, component, or module heavily influence how EME applies. For example, the EME may change depending on whether the system is in transportation, storage, handling, or assembly stage of its operational life. Radars illuminate airplanes in flight, this creates a radiated susceptibility environment while flying over airports but not during maintenance. While the airplane is being assembled or having fueling operations performed, ESD is a possible electromagnetic environment.

These examples highlight how the electromagnetic environment may change depending on the phase of the operational life cycle. In addition, a system, subsystem, or module may only have one operational stage, thus limiting the EME. One example is the use of a onetime use Electrically Initiated Device (EID).

The EME is not a verifiable test requirement that needs demonstrated directly. Instead, the EME must be derived to an applicable level. This is because the EME is applicable at the system level. To verify the EME directly would require an entire system. For example, an airplane communications system is not allocated a direct lightning strike requirement, even though a direct strike is a part of the airplane EME. Instead the direct strike lightning requirement would be tailored and derived to an applicable level, maybe conducted, radiated, or both. Verify applicable levels at the appropriate level, in this case the communications system, and therefore the EME functional requirement as well. Keeping these two requirements linked is validation.

Many test standards associate EME with specific events directly responsible for its realization. For example, lightning and HEMP environments are due to lightning and nuclear events. This can lead to confusion because often-different events may create similar effects, for example lightning and HEMP both can create conducted transients. Event-induced effects influence the system architecture.

2.1.1 Electromagnetic Environmental Effects

A thorough definition of E3 from [10] reads “The impact of the electromagnetic environment (EME) upon the operational capability of military forces, equipment, systems, and platforms. E3 encompasses the electromagnetic effects addressed by the disciplines of electromagnetic compatibility (EMC), electromagnetic interference (EMI), electromagnetic vulnerability (EMV), electromagnetic pulse (EMP), electronic protection (EP), electrostatic discharge (ESD), and hazards of electromagnetic radiation to personnel (HERP), ordnance (HERO), and volatile materials (HERF). E3 includes the electromagnetic effects generated by all EME contributors including radio frequency (RF) systems, ultra-wideband devices, high-power microwave (HPM) systems, lightning, precipitation static, etc." This definition does not encompass all of the E3 there is still High Intensity Radiated Fields (HIRF), and EMRO. It is debatable if these are all distinct environments or just nomenclature but for the purposes of this dissertation, the definition is sufficient to show the wide variety.

Distinguish EME as the source of E3 and the latter as the manifestation of EME. There are a myriad of distinct E3 effects across multiple EME environments, so much that E3 effects may cross EME boundaries. For example, conducted transients may be due to lightning and ESD, two completely different EME. For now, it is important to know that even though strongly linked, EME and Electromagnetic Environmental Effects (E3) are two distinct entities.

2.2 E3 Requirements Tailoring for System Level

This is the second step in the overall process. Inputs to this step are the EME environments, E3 requirement standards, and system functional requirements. System functional requirements are typically to perform a particular function or high-level operation without degraded performance. Generally, these are high-level system type functions for the end user. Examples are following global positioning guidance, relaying transmissions, or maintaining communications, etc. EME is the system's environment while it is functioning. E3 requirements are prescribed test standards allocated all through the process. These requirements are flowed to system, subsystem, and module and component levels.

2.2.1 E3 Requirement Test Standards

The use of requirement test standards is essentially an appeal to authority [16]. Test standards by definition are a standard criterion for gauging performance, often with clearly defined and measurable objectives. Standards may also define the pedigree of equipment under test (EUT) as well as test configuration setups, performance guidelines, modes of operation, and more. Standards are widely accepted methods for comparing various equipment; they are a universal measuring stick that gives the designer a means of comparing performance across manufacturers. Often a consensus of manufacturers, certification authorities, government agencies, and industry experts sponsor and endorse standards.

Generally, E3 test standards at the primary level divide into four groups: conducted emissions (CE), conducted Susceptibility (CS), radiated emissions (RE), and radiated susceptibility (RS). Each group can be decomposed further, for example, CS requirements divide into radio frequency noise and transient noise tests. CS transient requirements relate to an event associated with operation, examples include turn on transients, load switching, but there are also external event CS transients. For example, lightning and Electromagnetic Pulse (EMP) are external induced transients. Radiated emissions divide into electric field and magnetic field emissions test. Not all test standards draw a distinction at the boundaries none the less they do exist, for example DO-160 section 20 test is both a radiated and conducted radio frequency test. While MIL-STD-461F has, RS103 radiated susceptibility for radio frequencies and CS114 conducted susceptibility for radio frequencies. The idea is that each EME has a corresponding electromagnetic environmental effect, which should in turn have a corresponding E3 test. This mapping from EME to E3 test is traceability and closure.

2.2.2 System Functional Requirements

System functional requirements are operational or mission objectives of the system defined in terms of functionality. These requirements apply at the system level; some can and cannot be decomposed or derived further. For example, an airplane may have a requirement to have the ability to climb to a certain altitude within a specific time. This requirement is difficult if not impossible to demonstrate compliance without a full up airplane. The requirement may be decomposed and lower level requirements derived, for example, allocating a requirement for total engine thrust. From the total thrust requirement, each individual engine is flowed a thrust requirement; a quantifiable value for the required engine thrust of each engine is determined; from that, the requirement can be prescribed a test standard for verification.

2.3 E3 System Level Requirements Allocation, V&V

Here the first E3 requirements are flowed to the system level. Consequently, this is also, where the initial validation of requirements begins and then requirements provide verification. This is important to do early on in the process to reveal large dichotomies if they exist, thus necessitating wholescale corrective actions. For example, interfaces allocated a requirement to survive an ESD discharge when the real objective is to protect the circuitry downstream; this type of design oversight often requires significant last minute design changes. The real requirement is Section 3.6 defines validation and verification.

2.4 E3 Subsystems, Module, and Component Requirements Allocation, V&V

In this step, the E3 requirements are flowed to the subsystems, modules, and component levels. This is where the second validation of requirements occurs, only after this step is verification possible and only if feasible. Because of the steps leading up this stage, a large divergence from the intended design is not likely. However, less impactful oversights may still be lurking. Uncertainty or lack of design knowledge often conceals these types of oversights. For example, not specifying measurement units to a flight altimeter; this lead to the crash of an explorer mission to Mars.

2.4.1 System, Subsystem, and Component Level Analysis Activities

System level analysis differs from subsystem and component level analysis obviously in complexity but also according to the success criteria. For example, a subsystem is not likely to have redundant capability to overcome an event while a redundant subsystem may be capable at system level. Redundancy to resolve a system level anomaly is allowable but not at subsystem level. At subsystem level the criteria is clear and distinct, for example, the subsystem's response when the voltage level exceeds a certain level. System level criteria can be mission dependent, for example, an automotive entertainment system would experience an upset requiring intervention and reset. System level analysis must lend itself to the principle of "Sum of all parts", that is if all of the subsystems, components, and modules are compliant then when they are assembled the system should be also.

In a similar fashion, the subsystem level analysis should do the same only with itself in the role of the system and the component in the former role of the subsystem. For example, a wireless communications link would be analyzed at system level to determine its response to an in band emitter. A system level analysis would identify the subsystems likely to experience susceptibility, and then evaluate the subsystem as a whole, then specific components within the subsystem and back out to the system level to determine its response. Lastly compare how the susceptibility would affect mission objectives. This same approach is flowed down to the component and module levels. The analysis activities answer the question of “Sum of all parts”.

2.5 Subsystem and Component Compliance Verification

In this step actual test, analysis, measurement and testing to verify compliance to the prescribed requirements takes place. Examples of this would be the Mil-Std-461 or DO-160 testing to the derived levels. Because each of these requirements is a subsystem requirement, they will have different methods and in particular different compliance criteria. Subsystems provide an operation or input for to the system to use in achieving its objectives. For example, an altimeter subsystem relays location to the system for use in navigation when an airplane is flying.

2.6 System Level Qualification

This step is the combination of the subsystem and component level verification efforts. This step maybe achieved by demonstration, test, or analysis using the verification data from the previous step. Specify a method of verification beforehand or as early as possible. At system level, much of the compliance and performance criteria tie to each other. For example, operational performance while exposed to the requirement environment would be an example; maintain a communications link while exposed to radiated susceptibility without dropping communications.

2.7 E3 Qualified System

This is the final step in the process; it is the overall objective. Each requirement has been flowed down, each parent requirement has one or more children requirements that when combined at the system level show full compliance to the parent requirement and closure. Future design revisions may use the flowdown to evaluate the impact of a design change and its likely significance. For example, evaluate a design change to a module against its flowdown requirements, then maybe at the subsystem level to demonstrate compliance. Figure 3 shows the general process.

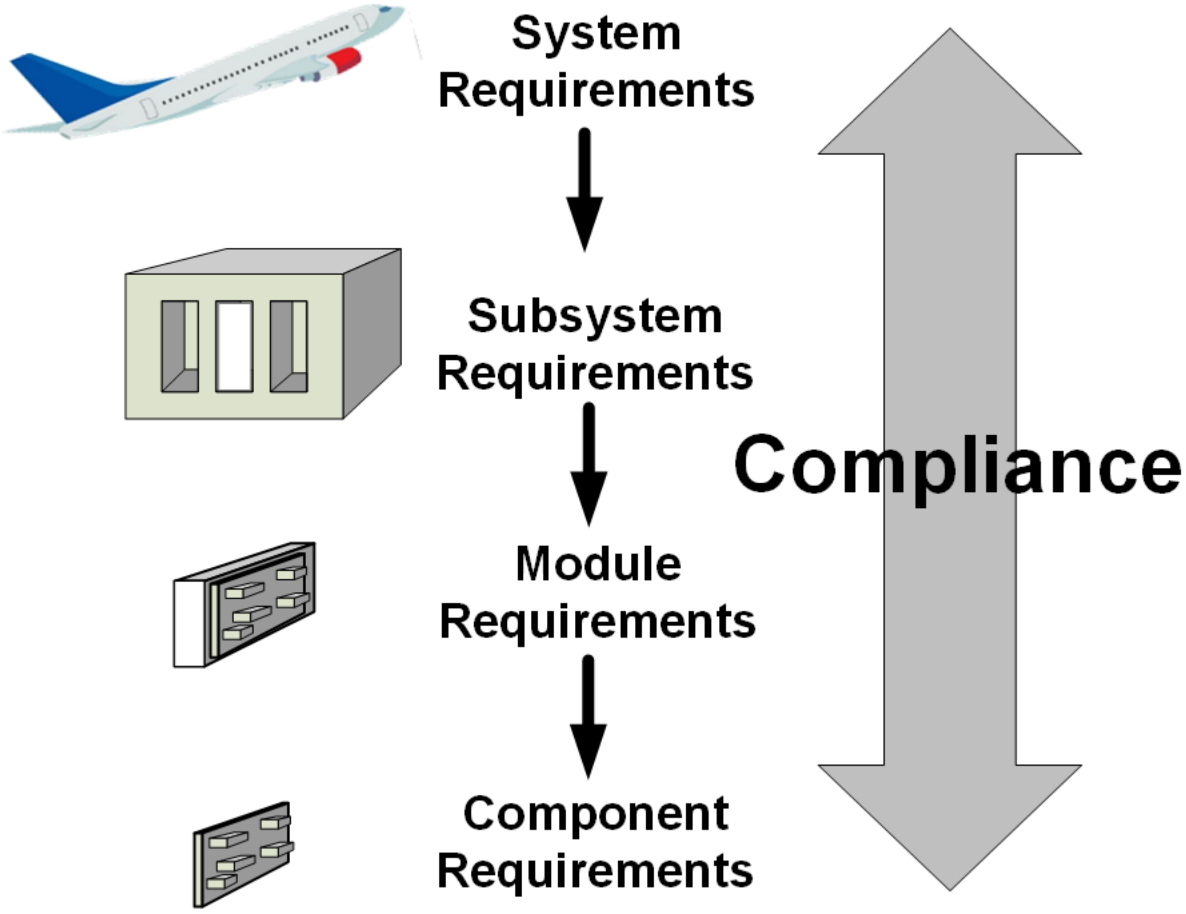


Figure 3 Compliance Summary

CHAPTER 3 FORMAL APPROACH

3.1 Hierarchical Requirement Decomposition and Flowdown

Requirement decomposition and flowdown follow a hierarchical structure. Mission requirements at a high-level are decomposed and allocated to the system. These make up the functional, performance and environmental requirements at system level. Subsystem level requirements are decomposed further. Each requirement at each level must be validated, verifiable, and traceable to a high-level requirement. Most EMC requirements by definition are environmental requirements that apply at system level, for this reason EMC requirements need tailoring. Often tailoring is only performed system to subsystem level. This dissertation establishes a method to extend the requirement decomposition further by derivation, to the module/component level while maintaining validation, verification, traceability and providing technical rationale and closure.

3.2 EMC as Environmental Requirements

Because EMC requirements are environmental requirements that apply at the system level, a natural decomposition occurs according to which parts of the system that are exposed to the EMC environment and which are not. For example, external antennas are exposed to externally generated fields while internal cabling shielded by a chassis is not. Allocating these requirements according to which is applicable is a form of tailoring. This approach is not always correct, for example shielding effectiveness is not absolute and can vary according to frequency and may only be provided to portions of the system. Another approach would be to reduce the limit level to account for a specific design benefit; this is also a form of tailoring not derivation, because the allocated requirement has only reduced in scope and still applies but only to particular portions of the design.

3.3 Flowdown and Tailoring before Derivation

The flowdown process must decompose or tailor system and subsystem EMC requirements to their lowest applicability level before allocation. To be consistent this step must take into account applicability, environmental limitations, and inherent design aspects at a system level. MIL-STD-464 applies at system level, but not all portions apply, for example depending on whether the service type is land, sea, air, or space. Tailoring through applicability is reducing the number of requirements by reviewing which requirements apply based on system functionality, for example, an airplane requirement would not apply to a surface ship; this is an example of applicability tailoring.

MIL-STD-464 defers to MIL-STD-461for subsystem applications but does not specify which portions apply. Mil-STD-461 consists of many different tests. All or none may apply, some are excluded based on applicability, environmental limitations, or inherent design factors. This is another example of tailoring not derivation. An example of tailoring due to environmental limitations would be not applying a test that is specific to airplane platforms because the equipment tested does not operate while on an airplane. An example of tailoring due to inherent design factors would be not allocating a test because it only applies to secondary power lines, those lines that provide external power, because it has none in the design. After reaching the lowest level of decomposition by tailoring through applicability, environmental limitations, and design factors, derivation begins.

3.4 Electromagnetic Environmental Effects Requirements Tailoring for Systems

Ultimately, requirements apply at the system level; unfortunately, you cannot test all requirements at the system level. Systems are costly, airplanes for example, and another reason is the system may not exist until late in the program, therefore waiting until the last minute to verify requirements would be extremely risky. Another reason is the catastrophic potential, for example, loss of life due to lack of safety or the first flight of an aircraft or weapons system is another.

Grady [ref 14] argues this “Cart before the horse” type scenario where requirements need verifying before the system can be built is the nature of modern systems engineering. That it has occurred out of necessity as humans endeavor to build more and more complex large-scale projects. Here we examine the E3 aspects of this scenario.

3.5 Electromagnetic Environmental Effects System Level Requirements Allocation

System level E3 requirements are developed in conjunction with system level functional requirements and electromagnetic environments. Functional requirements mean the intended function or operation of the system. For example, an airplane taking off, flying and landing safely is an example of functional or operational requirements. Another example is an automobile driving and stopping safely. These examples are high-level functional requirements of a system, for example airplanes, and automobiles. These requirements naturally decompose into lower level requirements, some still at a system level but most at subsystem levels.

These high-level system functional requirements coupled with electromagnetic environments are the origin of the E3 requirements. For example, an airplane must take off, fly, and land safely; couple these requirements with the environment, specifically the electromagnetic environment and the requirement becomes “airplane must take off, fly, and land safely when exposed the electromagnetic environment”. The next step is to characterize the electromagnetic environment; typically, done by surveying the operational sites, like airports, aircraft carriers, assembly and maintenance areas, etc. For example, perform field strength measurements and from the data recorded develop the requirement limits. This is the genesis of many E3 requirement test standards. For example, MIL-STD-464 is the current electromagnetic environment for DoD systems and is updated every few years after an exhaustive survey of many sites.

3.6 Validation & Verification

A definition of validation given in [14] is “a process carried out to demonstrate that one or more requirements are clearly understood and that it is possible to satisfy them through design work within the current technological state of the art”. A definition of verification given in [14] is “a proof process for unequivocally showing that a particular design will or does satisfy the corresponding requirements upon which it is based”. Simply stated alternatively, validation is “proving the right system is being or has been built” while verification is “proving the system build is right”. The two are mutually inclusive and often referred to entirely just as V&V. Tailoring and deriving requirements requires considering V&V at each level to maintain traceability and closure to the parent requirement. Accounting for V&V is not necessary at every step just beneficial to address V&V early on.

3.7 System Level Electromagnetic Qualification

System level qualification is the ultimate objective. Showing compliance at the system level from lower levels is a sum of all parts effort. This requires close correlation of each lower level to the next higher, up to the highest level of compliance. Each lower level requirement must show a direct correlation to the parent requirement or environment. For example, conducted power line transients disseminated across all connected power interfaces. Each interface in turn is flowed a tailored or derived level of the original parent requirement conducted power line transient. To demonstrate compliance each parent requirement conducted power line transient needs validated and verified with rationale. For purposes of this study system level is by definition the highest level needed for qualification.

CHAPTER 4 CONDUCTED SUSCEPTIBILITY RADIO FREQUENCIES

4.1 Commercial and Military

Commercial and military CS requirements have two common forms, transient and continuous wave. Examples of transient CS requirements are MIL-STD-461:CS106 and DO-160 section 17[9]. Examples of CW requirements are CS101 and section 18 [8] each of these is applicable to power lines. These are singular examples, not an exhaustive list. Both give injection limits in terms of voltage and each has a max power limit. DO-160 section 18 specifies a 100W power limit; CS101 specifies an 80W power limit. Calibration of each power limit is into a known load, this establishes a max current limit. CS101 specifies 80W into 0.5-ohm load, this equates to a current limit of 12.65A, DO-160 section 18 equates to 36.51A pk-pk. This power (or current) limit is an absolute at no time during test should it be exceeded; otherwise damage or over testing may occur. There are two ways to meet the test requirement: developing the voltage limit at the EUT input (case of high input impedance) or reaching the calibrated max power (current limit) whichever comes first. Input impedance of the EUT determines which.

Figure 4 shows the CS101 voltage, max current, and power limits. From the CS101 calibration procedure at 12.65A, 0.5-ohm impedance is required to develop the voltage limit. Higher impedance allows voltage to develop using less injection current. Using lower current is less likely to stress components, for example common mode components that may sink current. Common mode components are only one example. Though injected differentially, susceptibility currents can manifest as common mode current and most often do. These factors are critical to gauging performance at the subsystem/module/component level and avoiding over stressing the EUT.

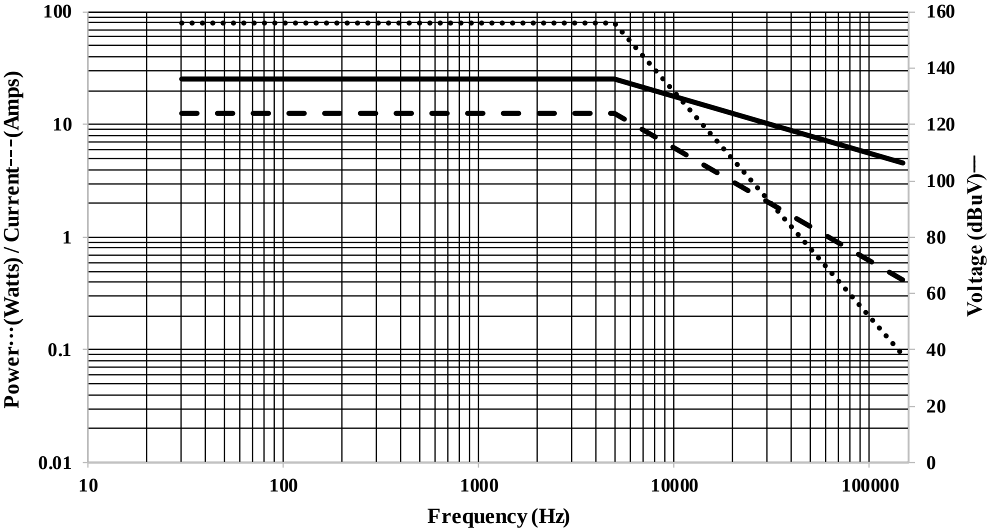


Figure 4 Voltage Limit, Max Current, and Power

The EUT impedance minimum determines the current limit necessary to develop the voltage limit.

4.2 Tailoring and Derivation of CS Injection Limits

EMC compliance requires disseminating requirements across varying levels of architecture to avoid noncompliance. Distributing the risk of noncompliance reduces the likelihood of a single point failure in the overall system design. To accomplish this, requirements must be “Tailored” to the most applicable level. Tailoring allows for test and verification at a lower equipment level, derivation goes one-step further by allowing test and verification at the module/component level. Reference [9] defines the system level as “A composite of equipment, subsystems, skilled personnel, and techniques capable of performing or supporting a defined operational role. A complete system includes related facilities, equipment, subsystems, materials, services, and personnel required for its operation to the degree that it can be considered self-sufficient within its operational or support environment." MIL-STD-464 decomposes the EMC environmental requirements to those defined in MIL-STD-461, which supports further tailoring but provides no instruction. The concept presented in Figure 5 is for the architecture detailed in Figure 6.

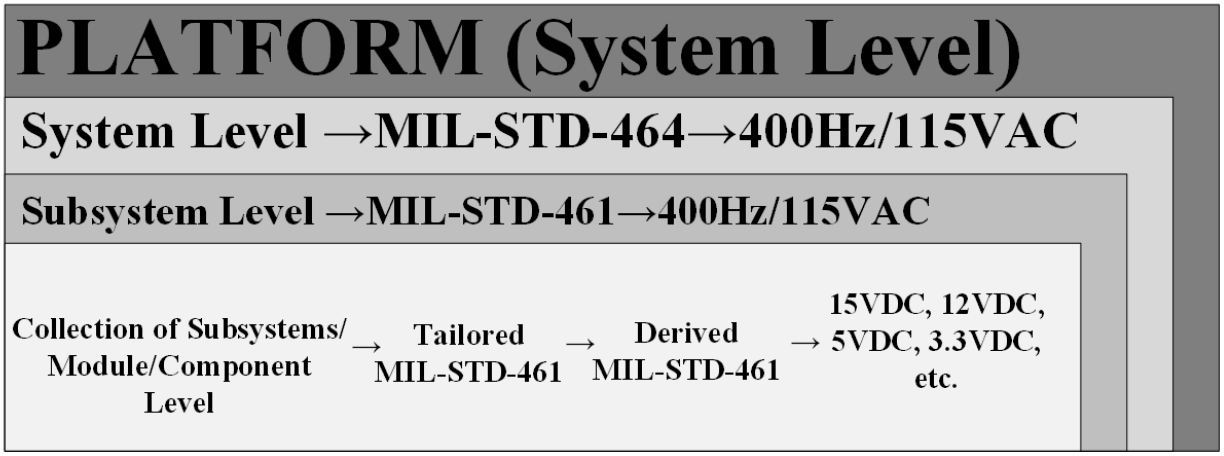


Figure 5 System to Component Flowdown Process for Sample Architecture

Subsystems may have platform power or system level waveforms (400Hz/115VAC) applied directly. These waveforms need conditioning before applied at the module/component level. For module and component level testing in accordance with MIL-STD-461, the corresponding susceptibility limits require derivation because full or tailored 461 levels (i.e. 12.65A) may cause damage at the module/component level. For example, 12.65A maybe more than the full load power draw of module power units.

4.3 Specific Architecture Example

This example details an approach to allocating MIL-STD-461 CS101 requirements from system level to subsystems to module/component level including derivation. For purposes of discussion, assume a supplier or another secondary designer designed lighting subsystem for use aboard military aircraft.

The platform (aircraft) power is at system level, the lighting subsystem receives system level power (400Hz/115VAC) directly. Several modules/components make up the lighting subsystem, some receive power directly from 400Hz/115VAC others require conditioning. Figure 6 shows the example architecture and MIL-STD-461 applicability.

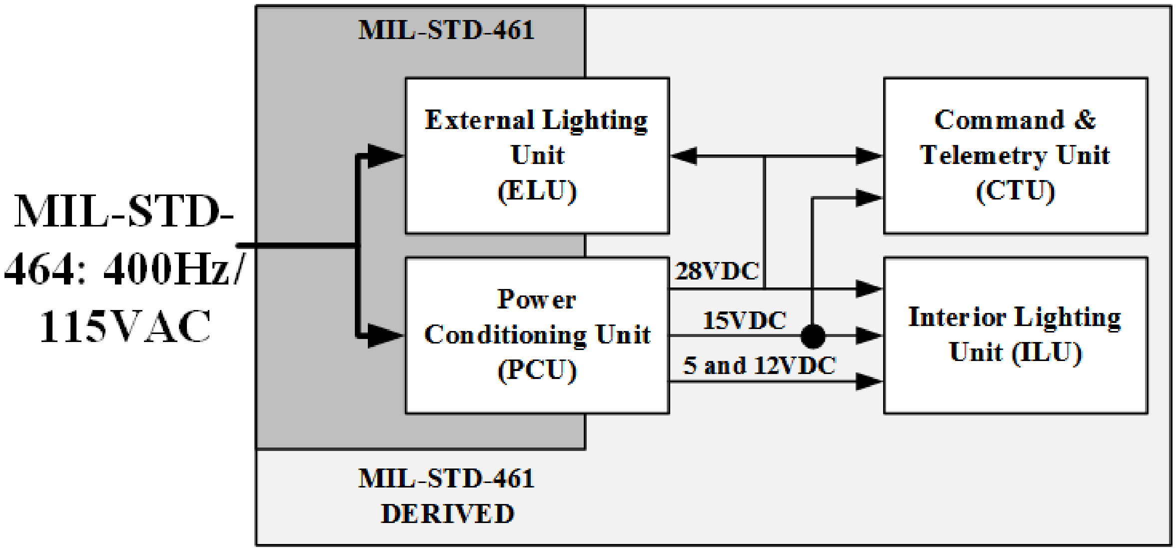


Figure 6 Example Architecture and MIL-STD-461 Applicability

The example lighting system has four major components: External Lighting (ELU), Power Conditioning (PCU), Command & Telemetry (CTU), and Interior Lighting Units (ILU); a separate supplier designs each. Requirements allocation begins at system level for each unit and continues through to modules and components. Figure 6 shows that since the PCU provides conditioning it would be incorrect to prescribe full MIL-STD-461 requirements to its outputs. MIL-STD-464 and 461 both exclude secondary output lines. To achieve compatibility it is necessary to allocate derived versions of MIL-STD-461 to each module separately. Figure 6 shows the full MIL-STD-461 limits allocated to PCU and ELU inputs. This is because these inputs interface directly to the system level power. The CTU/ILU inputs and the PCU/ELU outputs limits are derived and allocated.

4.4 Detailed Example using CS101

The following example uses a 28VDC power waveform but methodology approach is the same and can be adapted to accommodate any power waveform VAC or VDC. The PCU output provides 28VDC power to the ELU, ILU, and CTU; it does not connect directly to system power. For this reason, outputs of the PCU 28VDC are allocated derived limits. In this example, the 28VDC limit should be lower because it is an input to the lower level CTU/ILU modules. These modules by definition draw less power than the PCU, which must connect to system power and supply the ELU, so the derivation is a reduction.

4.4.1 Procedure for Requirement Derivation

The following method details how to perform derivation of the MIL-STD-461 CS101 limit for applicability at the module/component level so the requirement maintains rationale and traceability to the system level compliance assessment. Other requirement limits may use the same method.
Step one; determine a starting limit from which to derive the module/component level limit. From MIL-STD-461, determine the untailored subsystem level requirement for the specific waveform, in this case 28VDC given in Figure 4 and Table 1. This is important because it must be directly traceable to a parent requirement, it will establish the maximum limit threshold.

Table 1 Subsystem Level IAW MIL-STD-461

Frequency Range	Limit (dBuV)	Limit (Volts)	Power Limit (Watts)	Max Current (Amps)
30Hz to 5 kHz	136	6.3	80	12.65
150 kHz	106.5	0.211	80	12.65

Step 2; determine the correct subsystem, module or component level design parameters for limit comparison. Ripple voltage as defined in [10] is most applicable to the CS101 limit; similar specifications for transient and emission limit derivations may also be used. Depending on the derived requirement, different parameters may be used. For example, parameters for transient limits could be power input transient voltage spikes, turn on transients, or load switching. Often the location where the procurement process allocates requirements will determine the best approach. If the ELU is an existing product, it will have existing maximum ripple specifications for power input. If both units are new designs then it is necessary for each PCU output requirement to mirror the ELU's input requirement for consistency between the two. This is because the ELU design exists so to maintain consistency across each must be the same. Assume for this example the PCU is an existing product that has a ripple voltage requirement of no greater than 0.20V on the 28VDC output line. Assume for this example emissions do not contribute significantly.

Step 3; Verify subsystem, component, or module level requirements are consistent and provide compatibility across the entire interface. In this example the PCU output ripple requirement must be less than or equal to the maximum allowed input ripple for the ILU, ELU and CTU units. Assume for this example none of these units has an existing design, so their input ripple voltage requirement should be the assumed PCU output ripple requirement of 0.20V.

Step 4; derive the max power limit using the derived ripple voltage level. For this example, figure CS101-1 of MIL-STD-461[6] shows the 28VDC system level is applicable at the PCU input. The PCU output ripple requirement is no greater than 0.20V, thus the PCU must reduce the CS injected on its input to no greater than 0.20V on its output for the ELU, ILU, and CTU units to operate within specification. Table 2 shows specifying a constant ripple over the entire frequency range ensures the input ripple will be within specification and will provide margin in the higher frequency region where the CS101 limit reduces. Apply the same reduction to the power limit.

Table 2 CS101-1 limit Derivation

Frequency Range	Limit (dBuV)	Limit (Volts)	Power Limit (Watts)	Max Current (Amps)
30Hz to 5 kHz	106.2	0.2	0.08	0.4
150 kHz	106.2	0.2	0.08	0.4

When calibrated into a 0.5-ohm load the 2.13W power limit reduces the max current limit to 2.06A down from 12.65A for 30Hz to 5 kHz. From 5 kHz to 150 kHz the power limit reduces to 0.08W and the current limit to 0.4A. This CS101 example highlights a common discontinuity between voltage ripple requirements and CS injection levels. If the voltage ripple requirement specifies a constant amplitude over the entire CS frequency range, this causes the design to have significant margin for CS over the high frequency range of the requirement. The CS101 requirement reduces from 5 kHz to 10 kHz. If the CS101 derived limit does not exceed the input ripple at unit level, there is no deficiency between the two. Figure 7 shows the derived limits.

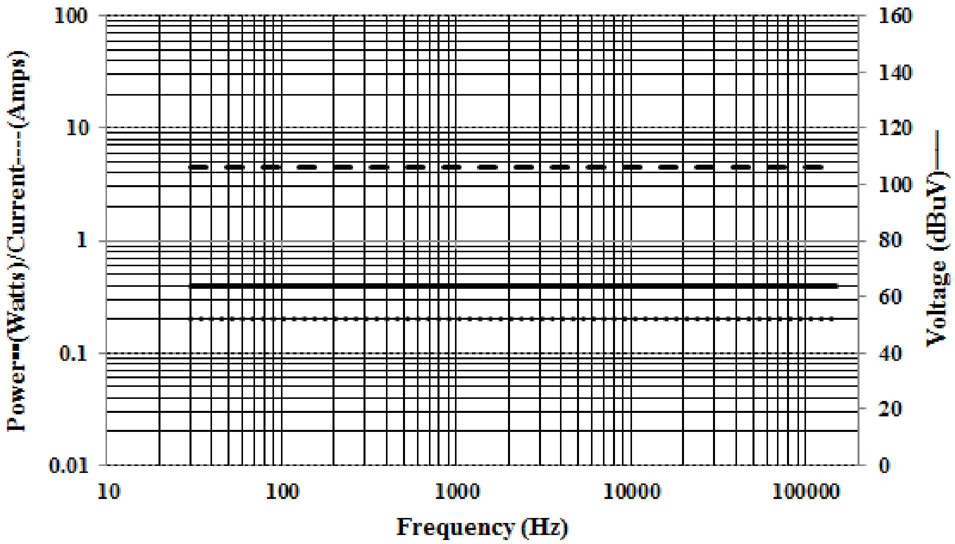


Figure 7 Derived Voltage Limit, Max Current, and Power Limits

4.5 Example using DO-160 section 18 and Applying Design Margin

MIL-STD-461 CS101 and DO-160 section 8 are similar requirements; low frequency power input requirements. DO-160 section 18 [9] has a power limit of 100W calibrated into a 0.06-ohm load that equates to 36 amps pk-pk.

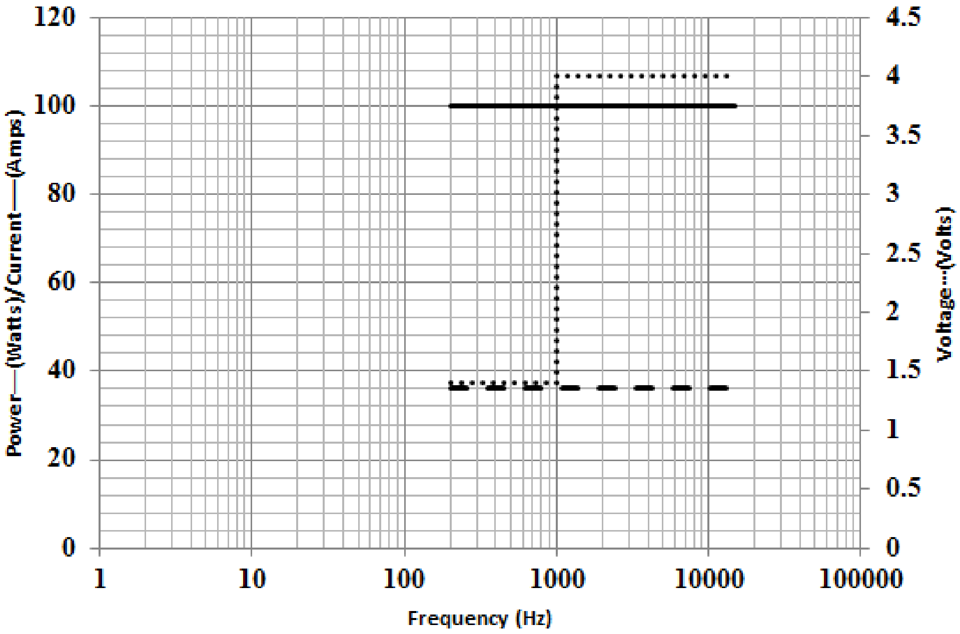


Figure 8 DO-160 Section 18 Voltage Limit, Max Current, and Power

Figure 9 shows the system architecture. This example derives CS requirements on the 15VDC power input for the Interior Lighting Unit (ILU) and assumes the ILU and CTU inputs have a power ripple specification of no greater than 0.30V. From the architecture in Figure 9 the PCU derives its 15VDC output from the 28VDC. The PCU must reduce the 28VDC ripple to 0.30V.

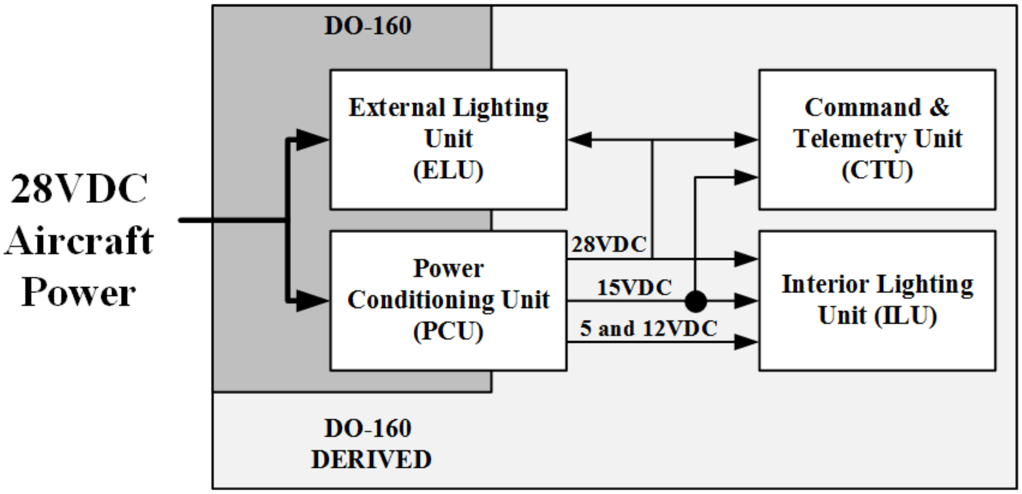


Figure 9 Example Architecture and DO-160 Applicability

4.6 Applying Margin

The 15VDC power is an ideal example because it supplies both the ILU and CTU. In this example, the 0.30V may not be sufficient if the CTU ripple requirement is the same. A worst-case scenario would be an in phase addition of noise injected on the 15VDC line (reduced to 0.30V) being added to noise from the CTU. Therefore the voltage ripple requirement should be 0.30V or greater to ensure compatibility.

Doubling the 0.30V level provides 6dB margin. This allows any two-noise sources to constructively add and remain within specification. Doubling the limit to provide 6dB of margin is also included in the untailored limit to keep the method consistent with the approach used in MIL-STD-461. Table 3 lists the original limit; Table 4 lists the new derived limit.

Table 3 DO-160 Section 18 Subsystem limit

Freq. Range	**Limit (Volts)**	**Power Limit (Watts)**	**Max Current (Amps)**
200Hz to 1 kHz	1.4	100	36
1 kHz to 15 kHz	4	100	36

This approach provides a potential of 6dB of margin to the ILU and CTU. If the two potential noise do not constructively add then the margin is realized, later if the output ripple is increased, only the margin is lost.

Table 4 DO-160 Section 18 Subsystem Derived limit

Frequency Range	**Limit (Volts)**	**Power Limit (Watts)**	**Max Current (Amps)**
200Hz to 1 kHz	0.6	6	10
1 kHz to 15 kHz	0.6	6	10

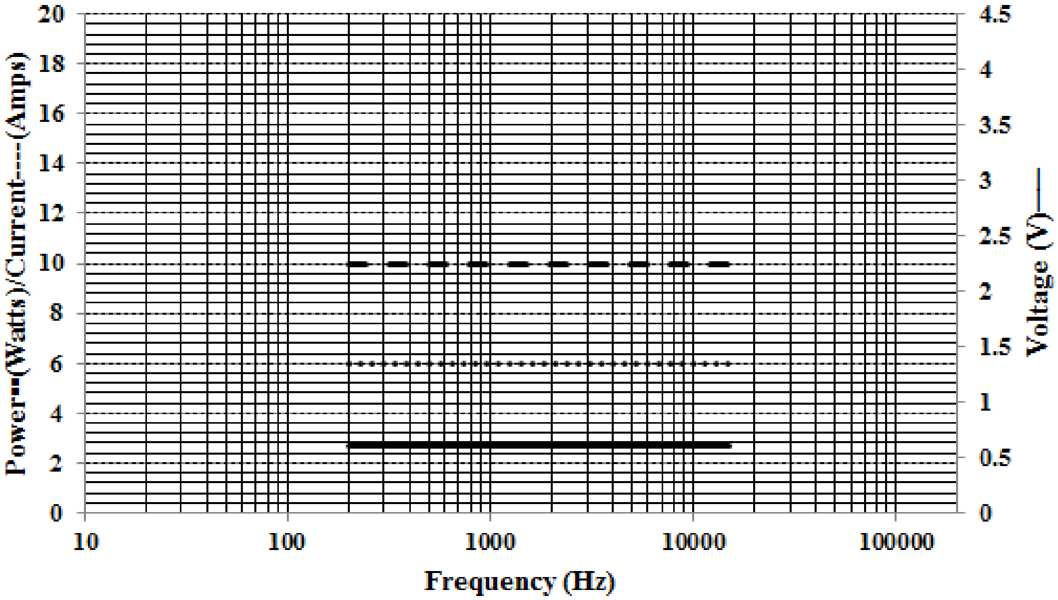


Figure 10 DO-160 Section 18 Subsystem Derived Limit

CHAPTER 5 CONDUCTED SUSCEPTIBILITY TRANSIENTS

Transients are a "Change in the steady state condition of voltage, current, or both" [18]. For the purposes of this dissertation, a more E3 relative description is helpful for edification. For verification, a transient must be determined quantitatively. Transients are often linked to their root cause or source, e.g. lightning induced transients or turn on transients. DO-160 section 22 defines lightning induced transients due to indirect effects; MIL-STD-461 CS106 is a power line transient due to load switching; MIL-STD-461 CS115 is a power and signal line transient due to inductive switching. Due to broad applications of transients, this dissertation expands the definition of a transient to include any "Disturbance with duration of less than a few cycles" [11] that occurs synchronously with an action or event.

Transients are caused by different environments, with differing types of induced transient waveforms (i.e. Spikes, surges, sags), and many types of transient test standards [9] [10] [11]. Conducted transients are a form of conducted susceptibility. They differ from conducted susceptibility due to radio frequencies in that transients are of a shorter duration and generally occur with a distinct event or action. Transients are often more severe in amplitude than radio frequency susceptibility and with relative short duration.

5.1 Commercial and Military

Recalling the strong correlation from EME to E3, it is natural that military requirements would be more severe, especially this is true of conducted susceptibility transient requirements. Military systems operate under severe circumstances while exposed to environmental extremes (i.e. out at sea, in space or the air) under critical operation with hostile and intentional threats, i.e. high power microwave transmitters, explosions. Given these considerations, it is reasonable to expect military requirements to be more severe than their commercial counterparts are. Commercial transients often relate to the product's intended use as opposed to consequences of environmental extremes; Table 5 gives a summary example of both. Figure 11and Figure 12 show examples of power quality characteristics [11]. Platform power characteristics, because they are common across multiple systems have common specifications. For example, satellite makers standardize power quality specifications. Large aircraft and automobile makers even have proprietary power standards. Military ship builders also have power quality standards [12].

Table 5 Ex. Commercial and Military Conducted Transients Requirements

Description	**Max Amplitude**	**Applicability**
Military:		
MIL-STD-461 CS106	400V	AC/DC Power Lines
MIL-STD-461 CS115	5A	All Cabling
MIL-STD-461 CS116	10A	All Cabling
Commercial:		
IEC-61000-3-2 Power Line Harmonics	3.5A	AC power lines
IEC-61000-3-3 AC Power Line Flicker	% of Amplitude	AC power lines
IEC-61000-4-4 Electrically Fast Transients	1kV	AC/DC Power
IEC-61000-4-5 Surge Immunity	4kV	AC power lines
DO-160G Section 16 Power Input	180V	For 115V line
DO-160G Section 17 Voltage Spike	600V	AC/DC Power

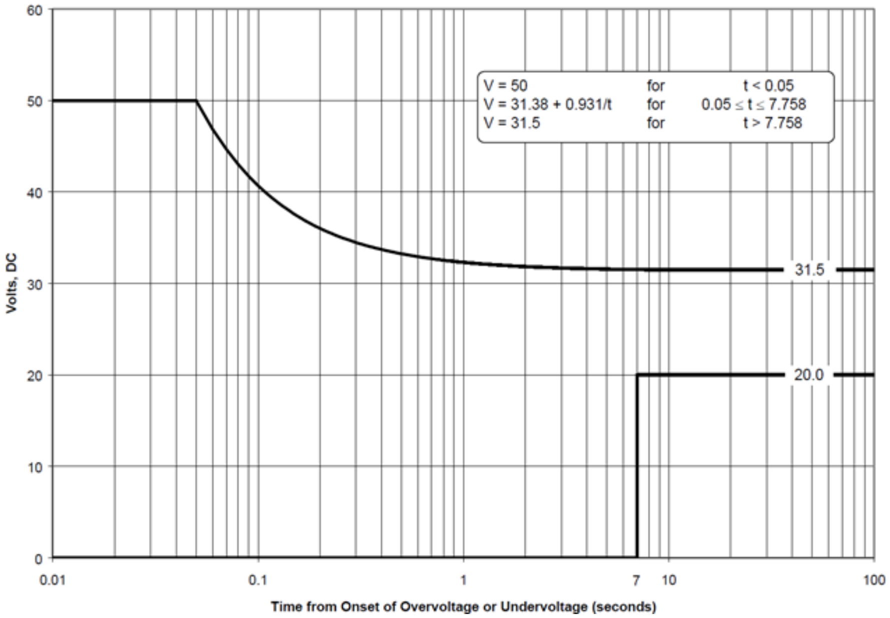


Figure 11 Example Power Spike Transient Waveform

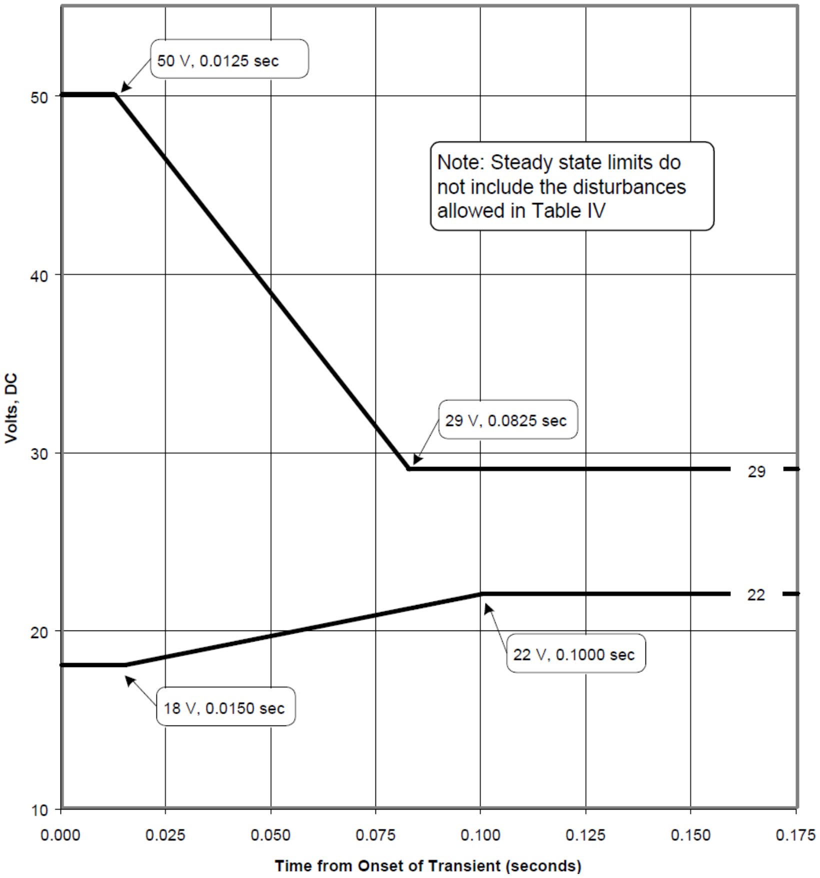


Figure 12 Example of Power Transient Definition

5.2 Tailoring and Derivation of CS Transient Injection Limits

From section 4.2 on tailoring and deriving CS radio frequency requirements, transients also must be "Tailored" to the most applicable level. Tailoring allows for test and verification at a lower equipment level, derivation goes one-step further by allowing test and verification at the module/component level. Transients differ from CS radio frequencies as stated previously. A vital consideration when tailoring and deriving the two is how they are experienced at system level.

For example, during a system level qualification the transient would occur during operation of the system. One particular port may cause or experience a specific transient. CS radio frequency environments occur over comparatively longer durations. For example, CS radio frequencies are often the conducted manifestation of radiated radio frequency sources, like intentional transmitters. In the derivation process, it is important to understand how the subsystem or component is operating during system level operation. For example, determine if the lower level subsystem is functioning, energized but not functioning, or is it performing a critical operation. Operational states determine how to test the subsystem or component, what are the states of operation and susceptibility criteria.

When deriving and tailoring from system to lower levels the number of subsystem or component configurations typically decrease. For example, a system may be flowed a requirement based on its operational environment, that in turn determines a distinct mode of operation for lower level subsystems and component. A common example from airplanes is an on board entertainment subsystem that during landing operations is turned off. This is also an example of how validation serves to eliminate unnecessary modes of operation or configurations from the verification test scenarios. Transients are by definition tied to specific events of the system itself and are often more sensitive to these scenarios than would be CS radio frequency susceptibility. CS radio frequency exposure is often intermittent where CS transients correlate to recurring system operations. For example, a heavy inductive load from an electric braking motor suddenly switched in through a mechanical relay.

5.3 Specific Architecture Example for CS Transients

This example borrows the architecture detailed in section 4.3 to edify an approach to allocating MIL-STD-461 CS115 requirements from system level to subsystems to module/component level including derivation. For purposes of discussion, assume the same example restrictions as given in section 4.3 for suppliers or another secondary designer. Figure 13 shows the example architecture and MIL-STD-461 applicability; since the PCU provides conditioning it would be incorrect to prescribe full MIL-STD-461 requirements to its outputs. MIL-STD-464 and MIL-STD-461 both exclude secondary output lines. To achieve compatibility it is necessary to allocate derived versions of MIL-STD-461 to each component separately. Figure 6 shows the full MIL-STD-461 limits allocated to PCU and ELU inputs. The CTU/ILU inputs and the PCU/ELU outputs limits are derived and allocated.

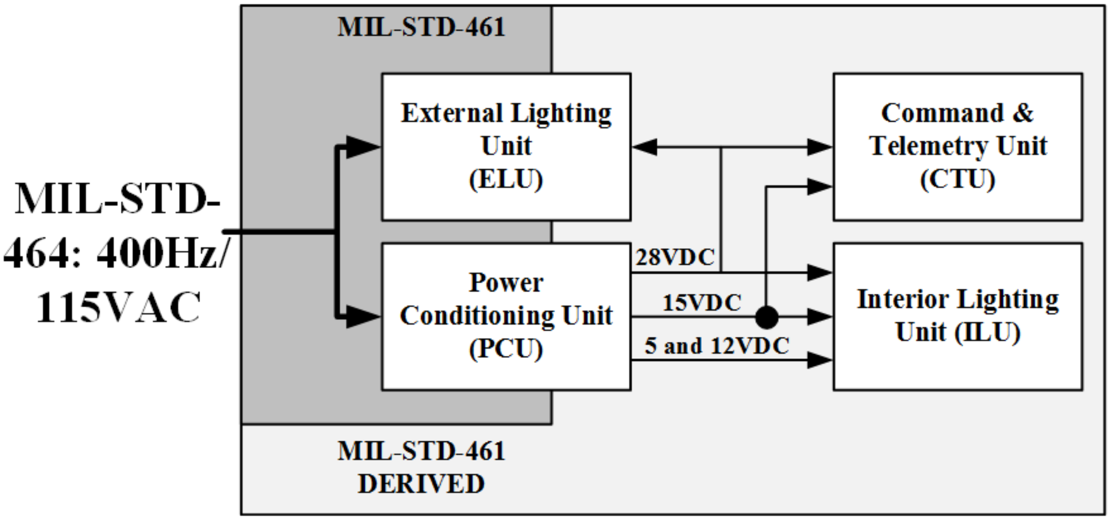


Figure 13 MIL-STD-461 Applicability

5.4 Detailed Example using CS115

The following example uses a 28VDC power waveform but methodology approach is the same and can be adapted to accommodate any power waveform VAC or VDC. The PCU output provides 28VDC power to the ELU, ILU, and CTU; it does not connect directly to platform power. For this reason, outputs of the PCU 28VDC are allocated derived limits. In this example, the 28VDC is lower than the system level 115VAC, assume this is because the PCU supplies power to multiple lower units, and provides conditioning to the 28VDC waveform, so the derivation is a reduction.

5.4.1 Procedure for Requirement Derivation

The following method details how to perform derivation of the MIL-STD-461 CS115 limit for applicability at the module/component level so the requirement maintains rationale and traceability to the system level compliance assessment. Other requirement limits may use the same method.

Step one) determine a starting limit from which to derive the module/component level limit. From MIL-STD-461, determine the untailored subsystem level requirement for the specific waveform, in this case 28VDC given in Figure 14 and Table 6. This is important because it must be directly traceable and will establish the maximum limit threshold.

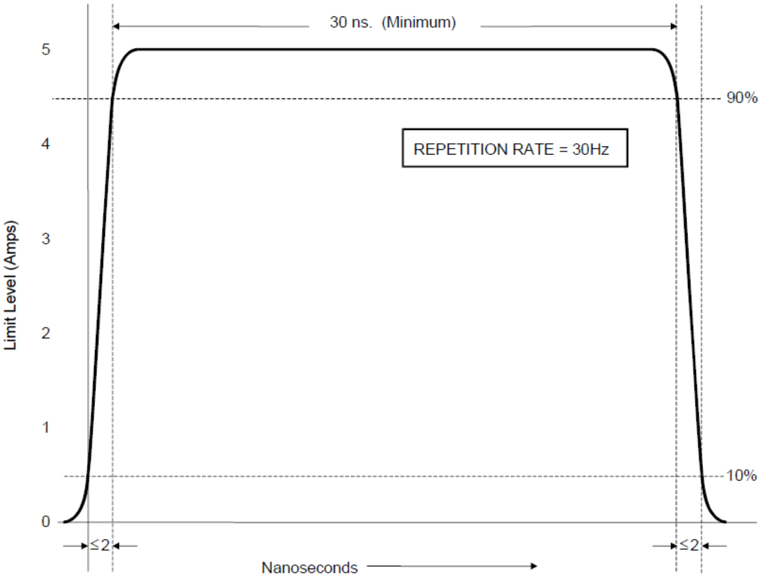


Figure 14 CS115 Transient Waveform

Table 6 Subsystem Level IAW MIL-STD-461

Frequency Range	Limit (Amps)	Rise Time	Pulse Width	Repetition Rate
Not Applicable, Transient	10	≤ 2nS	≥ 30nS	30 Hz

Step 2) Determine the correct subsystem, component, or module design parameters for limit comparison. Transient voltage as defined in [11] is most applicable to the CS115 limit. Depending on the derived requirement, different parameters may be used. For this example current associated with power input transient voltage spikes, turn on transients, or load switching are most applicable. Parameters correlate most readily to the injected current transient limit; both are transients, both defined in terms of current, and both tied to distinct events. This shows that often the location where the procurement process allocates requirements will determine the best approach.

Since the ELU is an existing product, it will have existing normal operation characteristics for its own power input. These are functional requirements required so the unit may integrate and work properly once integrated into the system or subsystem. If both units are new designs then it is necessary for the PCU output requirement to mirror the ELU's normal operation characteristics. Assume for this example the PCU is an existing product that has a maximum voltage transient requirement of no greater than 50V on the 28VDC output line. Voltage input is defined[11] in terms of a nominal level with a minimum and maximum; for this example the steady state voltage is between 22.0-29.0VDC. Therefore, the actual maximum induced voltage allowed by the transient is 28V when operating at 22VDC and 21V when operating at 29VDC. Worst case is 28V, because it is higher amplitude it requires more conditioning. This is the correct subsystem design parameter for limit comparison and compliance criteria.

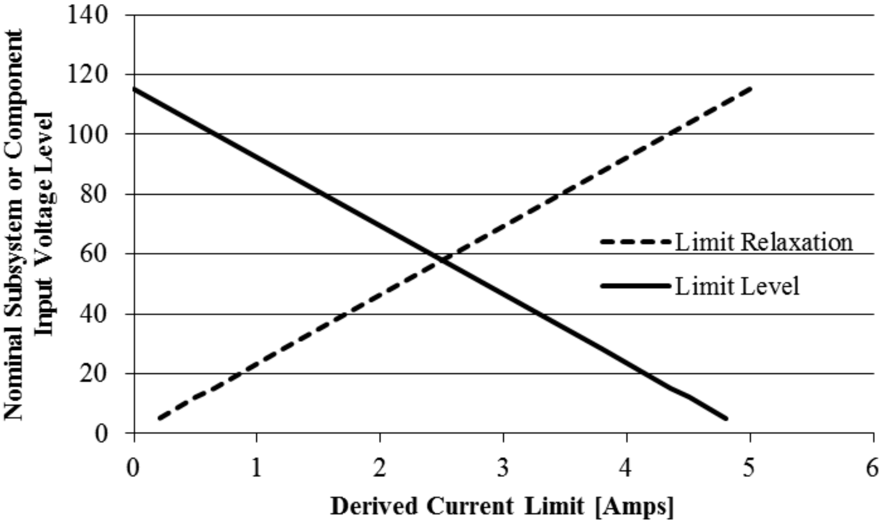
Derive the component level transient amplitude. For this example, CS115 has maximum tailored amplitude of 5 amps. If the PCU has input to output filtration then the derivation is a straightforward reduction by the amount of filter attenuation, say 20 dB. Therefore, the transient amplitude would be reduced to 0.5amp from 5 amps. Correspondingly, the calibration power reduces from 2500 watts to 25 watts. If the filter attenuation is unknown, it could also be flowed as a design requirement. For this example assume the filter attenuation is not known and has not been prescribed as a design requirement.

Given these constraints, the feasible approach is to scale the transient current and power amplitude by the ratio of the system level voltage input to the component level voltage input. This also accounts for the multiple loading scenarios because it is not dependent on one single load value or assumption. Table 7 and Figure 15 summarize these results for an 115VAC system input voltage level.

Table 7 CS115 limit Derivation

System Input Voltage (Volts)	Component Nominal Input Voltage (Volts)	Derivation Ratio	Derived Current Limit (Amps)	Derived Relaxation Amount (Amps)	Derived Transient Power (Watts)	Derived Limit Reduction (dB)
115	115	1	0	0	0	1
115	28	0.24	1.2	3.8	144	11.6
115	15	0.13	0.65	4.35	42.25	12.8
115	12	0.10	0.5	4.5	25	13.0
115	5	0.04	0.2	4.8	4	13.6

Figure 15 CS115 Limit Derivation and Relaxation



Step 3) Verify subsystem, component, or module level requirements are consistent and provide compatibility across the interface. In this example the PCU maximum induced voltage requirement must be less than or equal to the maximum allowed input voltage for the ILU, ELU and CTU units. Assume for this example none of these units have existing designs so their maximum induced voltage input requirement should be the same as the PCU output requirement to be compatible.

Figure 15 shows two expected trends when deriving lower level requirements. The first is as the nominal subsystem or module input voltage decreases the required attenuation or reduction in the transient amplitude increases. The derived requirement should not be greater than the system level. Secondly, limit relaxation stops at the nominal system input voltage. These trends show that the derivation is consistent and compatible across the interface. For example, the derivation did not arrive at an unattainable scenario.

5.4.2 Alternative Considerations

Another approach to this derivation is to reduce the waveform duration or rise time. This is not feasible from a system level flowdown perspective unless detailed information is readily available. For example, to choose the rise time to mimic EME or operational environments early in the design. Reducing waveform duration is also impractical unless design parameters are detailed. For example, to derive waveform parameters to coincide or mimic EME or operational environments requires knowing the waveform duration. This may not be the case early in design. Test equipment is often distinct and modularized this makes changing any parameters other than amplitude difficult. An example of this is the lightning waveform test equipment use distinct modules, created to produce one waveform, they do not allow for any adjustment.

The PCU maximum induced voltage output requirement is to be no greater than 28V, thus the PCU must reduce the CS injected transient on its input to no greater than 21V on its output to the ELU, ILU, and CTU units. Choosing 21V bounds worst-case, adaptable, and is traceable for all units. For protection the transient in terms of current needs reducing to no more than that which is required to raise the input voltage of the ELU, ILU, and CTU combined, a maximum of 21V. Since each component is a new design the impedance is assumed unknown. In the case of more than one unit, the unit with lowest impedance will receive the largest portion of transient current.

Reducing the EUT's input transient current proportionally accounts for uncertainty. For a 28VDC at 1 amp example, the impedance is the supply voltage divided by the supply current or 28 ohms. Therefore, it is necessary for the transient current to remain below the maximum input current necessary to keep the 29V input below 50Volts. At system level, the requirement is for the PCU to provide enough attenuation to reduce the transient to 36% from its full level.

Table 8 summarizes the derivation values for a subsystem input current of 1A. This example shows that at system level a 14dB reduction from the full limit level is necessary and a significant reduction in energy level. Note for test execution purposes the transient power limit needs a corresponding reduction; test methodology is not within the purview of this dissertation.

Table 8 Derivation for 28VDC at 1Amp Example

System Nominal Input Voltage (Volts)	Component Nominal Input Voltage (Volts)	Component Nominal Input Current (Amps)	Derivation Ratio	Derived Current Limit (Amps)	Derived Reduction Amount (Amps)	Derived Current Power (Watts)	Derived Energy level (uJ)	Energy Reduction (uJ)
115	28	1	0.24	1.2	3.8	144	4.32	71uJ

5.5 Example using DO-160 section 17

MIL-STD-461 CS115 and DO-160 section 17 are similar requirements; both are low frequency transient requirements, section 17 [9] is a voltage spike applicable to power inputs. DO-160 section 17 equates to 36 amps calibrated into a 50-ohm load.

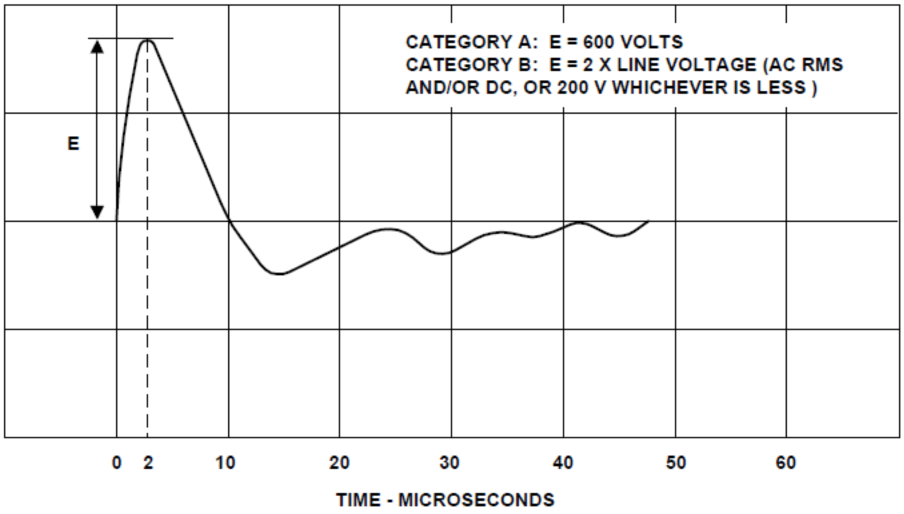


Figure 16 DO-160 section 17 Voltage Spike Waveform

Assume the system architecture is as given in Figure 17. This example derives CS requirements on the 15VDC power input for the Interior Lighting Unit (ILU) and assumes the ILU and CTU inputs have a nominal maximum operational voltage range of 12-18VDC with a transient specification of no greater than 30V. From the architecture in Figure 17 the PCU derives its 15VDC output from the 28VDC aircraft power. Thus at the maximum level of 18VDC, the maximum induced transient voltage allowed is 12Volts. The PCU must reduce a 56Vpk spike (twice the line voltage) [9] on its input to a 30Vpk spike on the ILU input line, which cannot induce greater than 12Vpk to remain within the ILU nominal operating voltage range. Because the ILU input operating voltage is no greater than 18VDC. The derived subsystem limit is 30Vk to match the specification requirement. This example highlights that derivation is simplest when comparable units are identical. Using the same approach outlined in section 5.4 while assuming an input current of 1 amp gives the results summarized in Table 9. This example shows a significant reduction in the limit due to the low current high impedance levels.

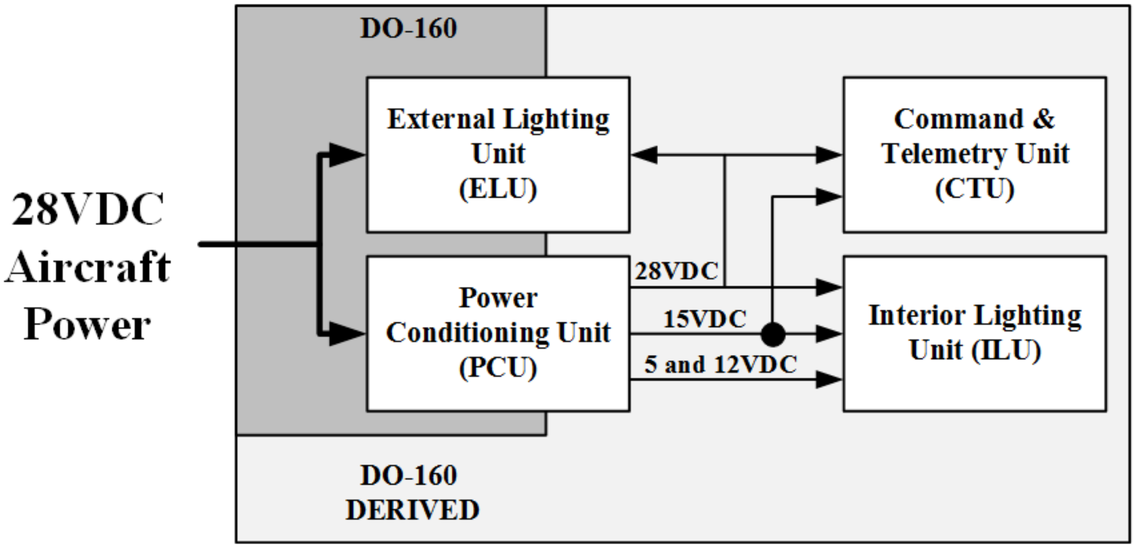


Figure 17 Example Architecture and DO-160 Applicability

Table 9 DO-160 Section 17 Limit Derivation

System Nominal Input Voltage (Volts)	Component Nominal Input Voltage (Volts)	Component Nominal Input Current (Amps)	Derivation Ratio	Derived Voltage Limit (Volts)	Derived Reduction Amount (Amps)	Derived Power (Watts)	Derived Energy level (uJ)	Energy Reduction (uJ)
28VDC	15VDC	1	0.54	16	14	2.56	25.6	90

5.6 Design Margin

The 15VDC power is an ideal example because it supplies both the ILU and CTU. In this example, the 12V limit may not be sufficient if there is a large delta between the ILU and CTU input impedance, as one would act to sink current over the other. A few scenarios occur for multiple impedance values; by deriving limit levels to the lowest impedance (when multiple units are present) for a current limit, the level prescribed may be higher than necessary to show compliance. This is because not all units maybe present at once. For a voltage limit, choosing the highest impedance value requires less current than may be necessary to show compliance. By choosing the output supply impedance, a reasonable tradeoff for derivation calculations is achieve, this accommodates both scenarios. Connecting more units, as long as they are not largely different, other impedances will share more of the transient energy. In general, this is a reasonable assumption because power supply design looks to maximize power transfer and balance outputs, which is precisely the scenario the requirements are testing.

CHAPTER 6 RADIATED SUSCEPTIBILITY RADIO FREQUENCIES

6.1 Commercial and Military

Commercial and military RS requirements like conducted requirements have two common forms, transient and continuous wave. Examples of transient radiated electromagnetic field requirements are MIL-STD-461:RS105, IEC 61000-4-25, and DO-160 section 22[6] [19] [9]. Examples of CW requirements are RS103, IEC 61000-4-3, and DO-160 section 20 [6] [20] [8]. These are singular examples not an exhaustive list. DO-160 section 22 circumvents radiated coupling mechanisms and prescribes conducted transients directly. This effectively makes DO-160 section 22 a conducted transient requirement that is addressed in section 5.2 . Other radiated requirements include radiated coupling mechanisms within their test method. Figure 18 shows how the RS103 setup includes the field coupling mechanism with field generating antennas. DO-160 section 20 uses a similar setup while RS105 uses a TEM cell to achieve the rapid rise time and amplitude required for radiated transient testing. All three requirements specify field strength limits in terms of volts per meter. Transient requirements also specify waveform parameters, for example rise time, fall time, repetition rate, and decay time. Radiated transients are redundant, tailoring and derivation wise with radiated susceptibility radio frequencies and conducted susceptibility transients already covered in section 5.4 .

These field strength limits are an absolute at no time during test should they be exceeded; otherwise damage or over testing may occur. Shielding is the principle mechanism for designing against the effects of radiated susceptibility. These factors are critical to tailoring and deriving radiated susceptibility requirements at the subsystem/module/component level and gauging performance of the EUT.

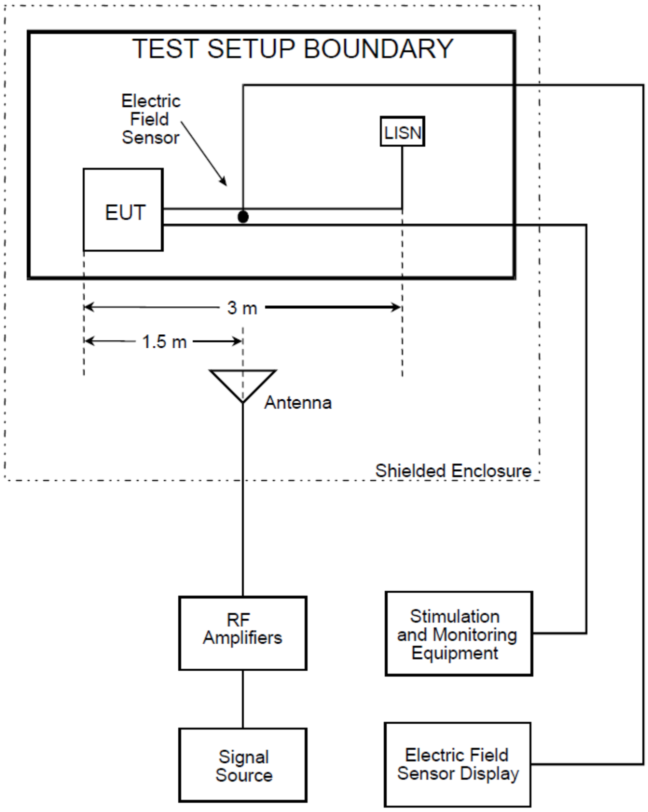


Figure 18 Example Radiated Susceptibility Setup

6.2 Tailoring and Derivation of RS Limits

From section 4.2 on tailoring and deriving CS radio frequency requirements the same is true for RS radio frequency requirements. Radiated requirements are a field phenomenon that consists of a source, path, and victim [23]. The requirement defines the source characteristics, like field strength amplitude, frequency content, illumination, while the victim is commonly a circuit. Two scenarios for dealing with RS requirements are to deal with the radiation only when it manifests itself as a conducted susceptibility the other is to break the coupling path with shielding. This dissertation has already addressed scenario of manifested CS; this section will focus on breaking the coupling path.

In the derivation process, it is important to understand how the subsystem or component is operating during system level operation. RS requirements are unique in that they often occur in some fashion all along the life of the EUT. For example, lower levels occur during assembly and handling, usually due to presence of personnel, while higher exposure limits occur in the fielded application. This will determine how to test the subsystem or component, what is the state of operation and susceptibility criteria.

6.3 Specific Architecture Example

This example borrows the architecture detailed in section 4.3 and details an approach to allocating RS requirements from system level to subsystems to module/component level including derivation. For purposes of discussion, assume the same example restrictions as given in section 4.3 for suppliers or another secondary designer. Figure 19 shows the example architecture and MIL-STD-461 applicability. The figure shows how shield layers attenuate RS; tailor these boundaries according to applicability. For example, Mil-Std-464 at system level, Mil-Std-461 at subsystem level, and derived Mil-Std-461 levels to modules and components.

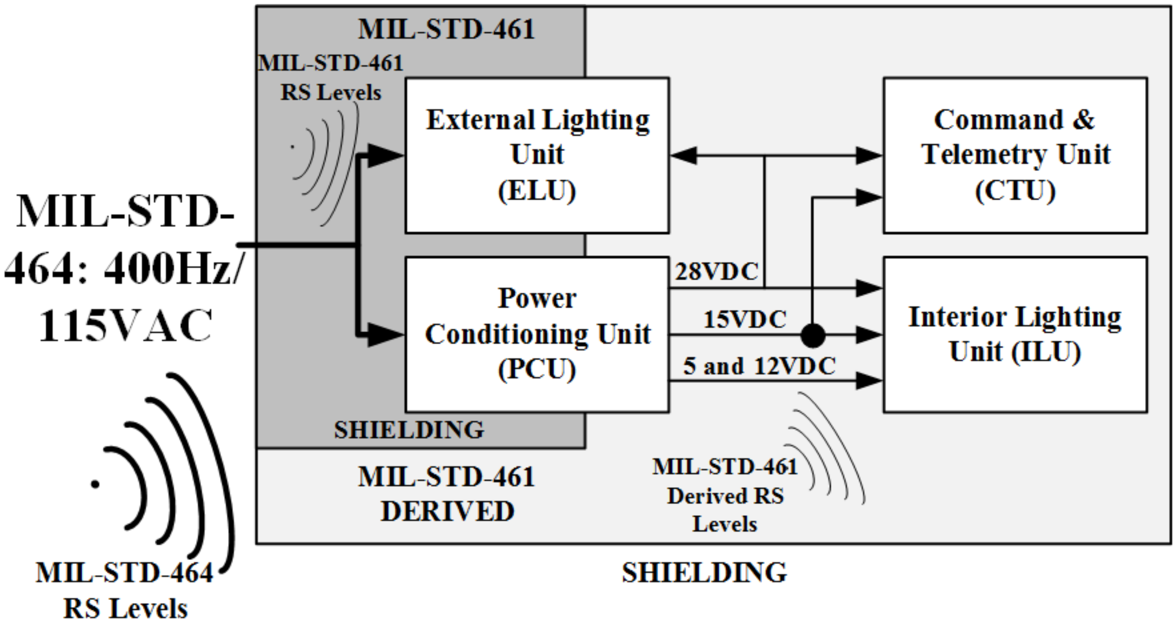


Figure 19 Example Structure showing Shielding and RS Exposure

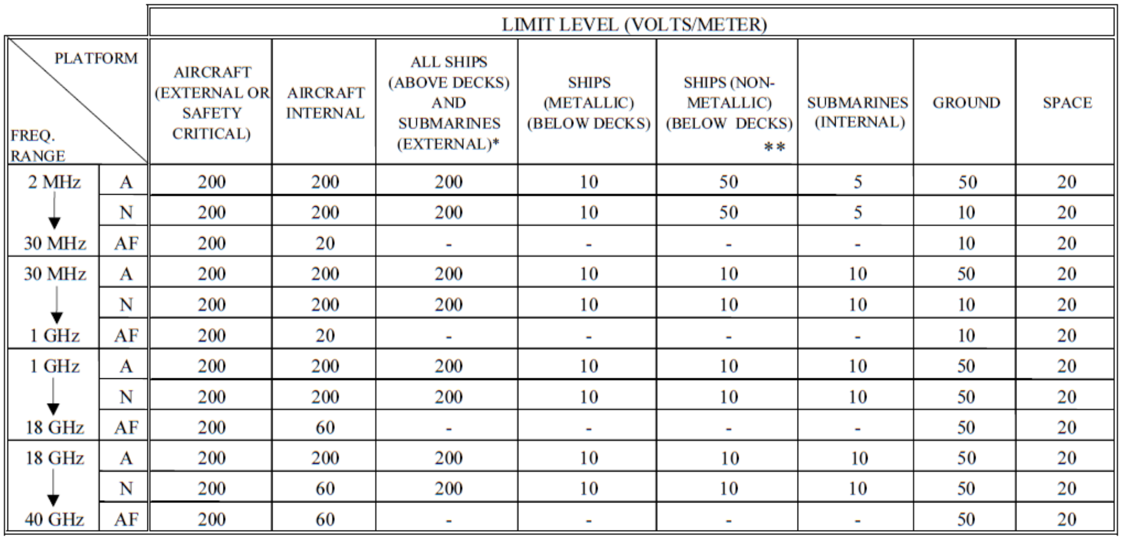
Requirements allocation begins at system level for each unit and continues through to modules and components. Figure 19 shows that since the PCU provides a shield boundary to the path of RS it would be incorrect to prescribe full MIL-STD-461 RS levels. To achieve compatibility it is necessary to allocate derived versions of MIL-STD-461 to each component separately. Figure 19 shows the full MIL-STD-461 limits allocated to PCU and ELU. CTU and ILU units and the PCU/ELU outputs allocated derived Mil-Std-461 limit levels.

6.4 Detailed Example using RS103

The following method details how to perform derivation of the MIL-STD-461 RS103 limit for applicability at the module/component level so the requirement maintains rationale and traceability to the system level compliance assessment. The same approach is valid for other RS requirement limits.

Step one) Determine a starting limit from which to derive the module/component level limit. From MIL-STD-461, determine the untailored subsystem level requirements. For this example, assume 200 volts/meter. Table 10 shows the diverse limit levels and applicability of RS requirement levels and variance over frequency [6]. This is important because it must be directly traceable and will establish the maximum limit threshold.

Table 10 Subsystem RS103 Levels IAW MIL-STD-461



FREQ. RANGE	PLATFORM	LIMIT LEVEL (VOLTS/METER)							
		AIRCRAFT (EXTERNAL OR SAFETY CRITICAL)	AIRCRAFT INTERNAL	ALL SHIPS (ABOVE DECKS) AND SUBMARINES (EXTERNAL)*	SHIPS (METALLIC) (BELOW DECKS)	SHIPS (NON-METALLIC) (BELOW DECKS) **	SUBMARINES (INTERNAL)	GROUND	SPACE
2 MHz ↓ 30 MHz	A	200	200	200	10	50	5	50	20
	N	200	200	200	10	50	5	10	20
	AF	200	20	-	-	-	-	10	20
30 MHz ↓ 1 GHz	A	200	200	200	10	10	10	50	20
	N	200	200	200	10	10	10	10	20
	AF	200	20	-	-	-	-	10	20
1 GHz ↓ 18 GHz	A	200	200	200	10	10	10	50	20
	N	200	200	200	10	10	10	50	20
	AF	200	60	-	-	-	-	50	20
18 GHz ↓ 40 GHz	A	200	200	200	10	10	10	50	20
	N	200	60	200	10	10	10	50	20
	AF	200	60	-	-	-	-	50	20

Step 2) Determine the correct subsystem, module or component design parameters for limit comparison. RS susceptibility is most often successful at creating a susceptibility scenario when it mimics the EUT operation. For example, a device operating at 40MHz clock frequency would be most susceptible in this region [23]. RS manifests itself as continuous wave radio frequency phenomena on conductors that are proportional in wavelength to the RS frequency. Depending on the derived requirement, different parameters may be used but ripple voltage is the most applicable. There can be disconnects here if ripple voltage does not cover the same frequency range as RS. For example, power waveform operational or functional ripple requirement specified only up to 150 kHz

while RS can go as high as 40GHz. Functional requirement need tailored in such a way as to allow the power supply designer to verify the ripple voltage requirement and meet the RS requirement.

Step 3) Derive the applicable RS limit level in accordance with design parameters. Assume shielding is present at the system and subsystem levels only. For this example, shielding effectiveness is the principle design parameter to defend against RS. From Figure 19 the system boundary shielding reduces the system level RS down to Mil-Std-461 subsystem levels. The subsystem boundary shielding further reduces the RS to a derived level. Shielding may not be present at the module or component level. No shielding allows the derived RS requirement to become a CS radio frequency requirement. This approach requires calculating the module or component level immunity according the methods outlined in section 4.2 for radio frequencies and 5.2 for transients.

Shielding effectiveness is difficult to characterize effectively. There has been considerable research performed on measurement methods [22][24][27], different formulations [25][26], enclosure variance , and design methodology to achieve maximum effectiveness. For example, a shield may attenuate the RS but not prevent the EUT being susceptible. From [23] and many more researchers it has been shown for a conductive metallic enclosure, thick enough to minimize diffusion effects to a negligible level, with minimal apertures that have been designed to reduce leakage [10] it has been shown SE demonstrates common trends. These design parameters are typical of system/subsystem/module level shielding design.

For example, SE is greatest at low frequencies where wavelengths are much greater than aperture dimensions and get progressively worse as the frequency wavelength diminishes. Aperture and cavity resonances occur for wavelengths that are proportional to dimensions, thus resonances tend to occur at higher frequencies when wavelengths approach the physical dimensions of the shield. For derivation purposes SE of a design may not ever be known. General practice is to assume a design objective for purposes of derivation. One example is to assume 20dB across the frequency range for each shield layer. However, SE is rarely a set value across the frequency spectrum. The proposed approach here is to follow the trending shown for typical SE.

Some common trends are SE reduces as frequency increases with a linear slope on a logarithmic scale; more negative the slope the lower the SE. Resonances will significantly reduce SE at specific resonant frequencies; resonances are seldom know early in the design process. Resonance can enhance field effects, relative to each other or amplify relative to external fields, but for system level shields, this is seldom the case due to loading effects of the whole system.

When resonance does occur, it occurs at distinct frequencies and tends to reduce the SE to its lowest level. Therefore, to accommodate these effects in the derivation process, for early design purposes it is reasonable to assume a set value of SE across the frequency band. Following the approach, SE maybe assumed as a set value across the lower frequency region until a point then it reduced. Because susceptibility occurs easiest close to operating frequencies this cutoff point should be chosen at the lowest operating frequency, or just prior to provide margin. A good tradeoff is half the fundamental because intentional transmission can have significant energy in the second harmonic. Reduce RS103 level by SE level; if SE level is unknown then a risk tradeoff is required.

For determining SE by measurement, two standards are prominent for performing SE testing [22][24]. Each of these methods details subtle differences related to reverberation and plane wave SE measurement techniques. The EME environment determines which method is more representative. For example, systems would often see plane wave radiation while modules would see what leaks into a subsystem level shield.

Step4) In terms of system, subsystem, component and module applicability level determine shielding effectiveness for each shield boundary. For example, Table 10 shows aircraft and ships have internal and external RS103 limit levels due to SE. Air Force system level RS103 the external aircraft limits are 200V/m while the internal aircraft limits are 20V/m, this assumes 20dB SE. For the higher frequency region 1GHz to 40GHz, SE assumed only as 10.45dB.

Step 5) Verify subsystem, component, or module level requirements are consistent and provide compatibility across the entire interface. In this example, from Figure 19, assume a shield between the outside electromagnetic environments. The PCU is part of the shield boundary for Mil-Std-461 subsystem electromagnetic environment levels. Expose modules and components to derived limits. Following the reasoning from the approach outlined above this alternative assumes SE design comparable to the system level for each level of shielding. Figure 20 summarizes the results.

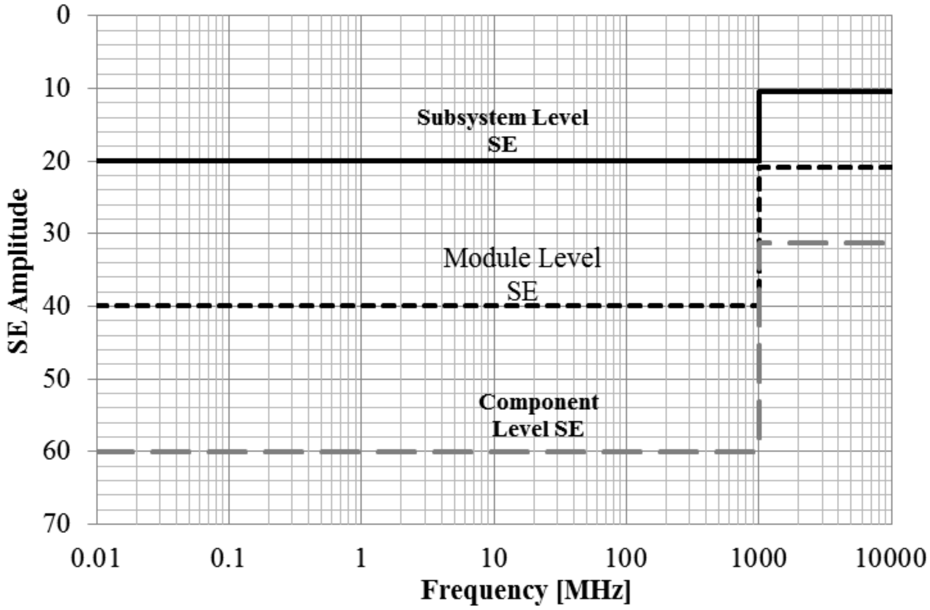


Figure 20 Summary of SE Level Derivation from RS Requirement

Step 6) Use the system level RS limits to derive the subsystem RS limit levels and similarly down to the module or component level. Each step requires knowledge of the SE for each shield boundary. For this example, the system level RS limits come from Mil-Std-464; tailor these levels to the subsystem level by Mil-Std-461. For deriving the module or component level, RS limit levels reduce Mil-Std-461 levels by the SE of the module or component. When there is no longer a shield layer the next step is to compare the circuit immunity to the RS levels, this is also an alternative if SE is completely unknown, this is accomplished by realizing the problem has changed from a radiated immunity to a conducted immunity scenario, as detailed in section 4.4 .

Table 11 RS103 Limit Derivation

Applicability Level	Frequency Range (Hz)	SE Level (dB)	Derived Limit (V/m)
System	200MHz to 1GHz	0	200
System	1GHz to 40GHz	0	60
Subsystem	200MHz to 1GHz	20	20
Subsystem	1GHz to 40GHz	10.45	18
Component	200MHz to 1GHz	40	2
Component	1GHz to 40GHz	20.9	5.4

This approach correlates each SE derived level to a system level requirement, assumes only the same design parameters for each, thereby providing traceability and closure. For example, low impedance bonds across faying surfaces, aperture treatment for electromagnetic leakage, metallic material, etc.

6.5 Example using DO-160 section 20

MIL-STD-461 RS103 and DO-160 section 20 are similar requirements with subtle differences for example differing limit levels and setups. Figure 22 shows the different categories and levels in DO-160 [9]. Following the process used for RS103, derive a SE level for each successive layer of shielding by using the differences between categories. This example uses the categories of Y and W; when performing actual derivation use the applicable categories for the specific design as defined in [9], but the approach is the same. Assume system architecture is as given in Figure 21. This example derives RS requirements at the system, subsystem, and component level. The ELU and PCU shield from the system level electromagnetic environment. The ELU and PCU see the DO-160 section 20 levels. The CTU and ILU are within an additional shielded area so they see a derived DO-160 section 20 limit level.

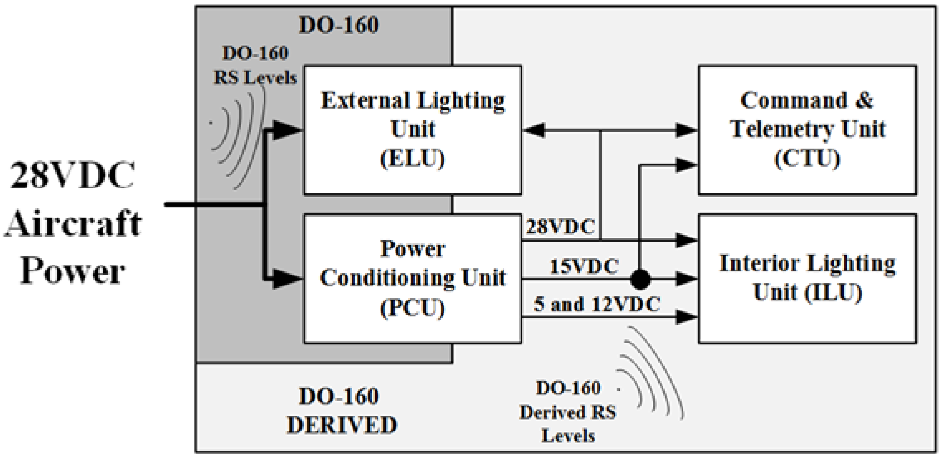


Figure 21 Example Architecture and DO-160 Applicability

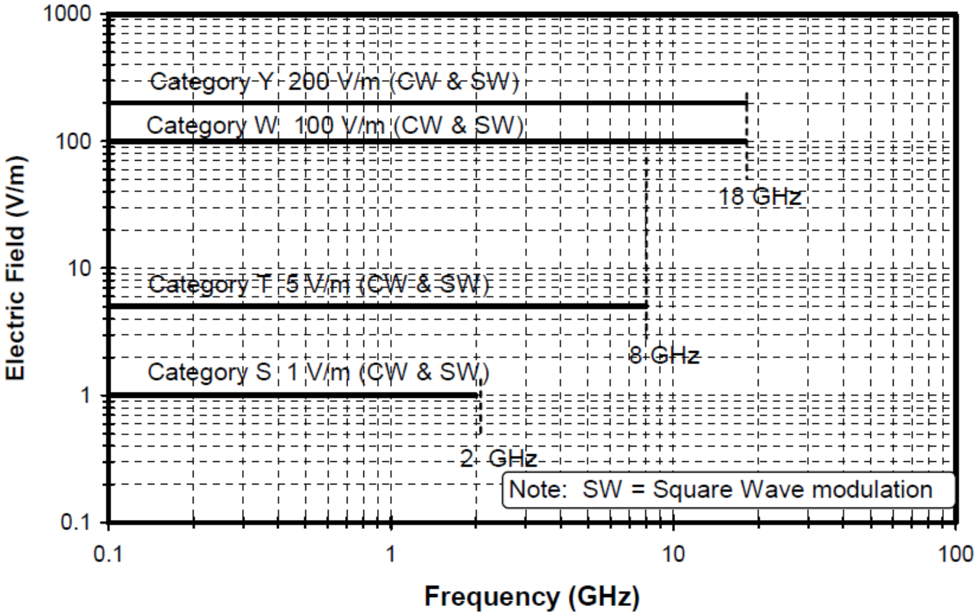


Figure 22 Example DO-160 Section 20 Limit Levels

Following the same approach, as before, derive the limit levels from the system level DO-160 section 20 levels to subsystem and component levels. Table 12summarizes the results.

Table 12 DO-160 Section 20 Limit Derivation

Applicability Level	Frequency Range (Hz)	SE Level (dB)	Derived Limit (V/m)
System	100MHz to 18GHz	0	200
Subsystem	100MHz to 18GHz	6	100
Component	100MHz to 18GHz	12	50

6.6 Applying Design Margin

Ideally, SE would be known well before RS levels were prescribed, unfortunately this is rarely the case. SE design relies mainly on a metallic mechanical structure. There has been much research on the effects of shield designs. For example, apertures, material, and bonding are shield parameters that heavily influence SE performance. In this example, assume SE. Applying margin is possible in several ways. One choice is to follow the observed trend of SE measurements. SE measurements often show a trend starting with very high SE on the low frequency region and decreasing linearly on a log scale at some slope. Often when SE fails to account for shielding correctly it is due to some parameter not accurately modeled or tested when SE was determined. Two examples are cavity and aperture resonances. Such effects are most prominent higher is frequency, due to wavelengths involved.

Numerous SE measurements have shown less SE trending as the frequency range increases. Unless there is some design outlier that drives SE, for example the need for an RF transparent window, an often used approach, for first level TBR type SE values is to adopt the lowest value for SE across the frequency spectrum. This occurs at the highest frequency. From reference [27], 20dB is readily achievable SE value. Afterwards assign that value across the entire frequency range; the approach is also capable of bounding resonances. Note this is not an absolute approach but it does allow two things. By assigning a reasonable level it can be refined later as need be. Then by assigning the level across the frequency spectrum, if a resonance or aperture leak does become apparent it still may be enveloped. Often repairing distinct and prominent leak in shielding is straightforward. This is because prominent leaks are typically the result of unintended design oversight. For example, two faying surfaces left painted when they should have been metal, another is screws not being properly torqued thus causing bonding resistance to increase.

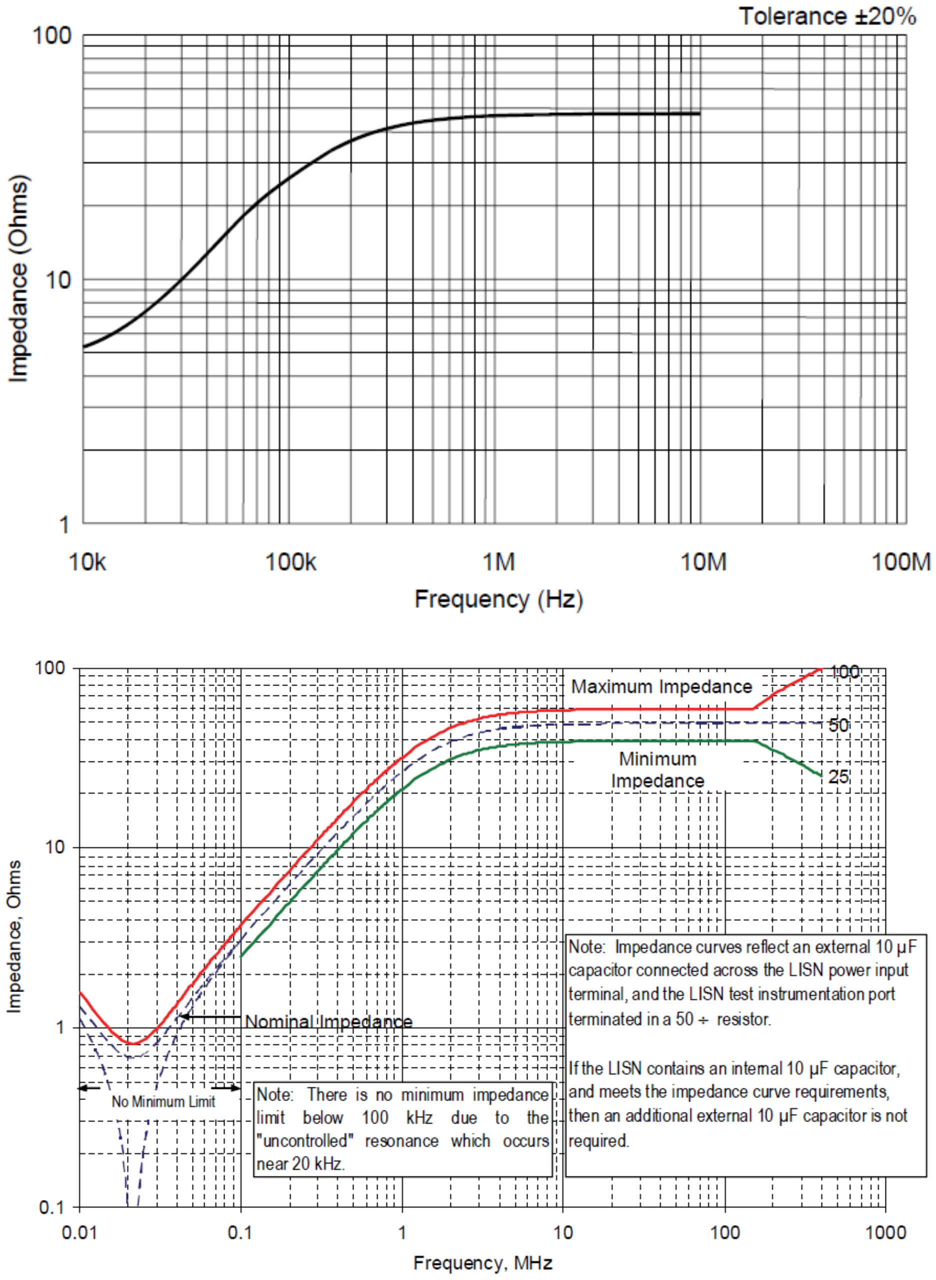
CHAPTER 7 CONDUCTED EMISSIONS

7.1 Commercial and Military

Commercial and military CE requirements have several forms according to applicability. These are conducted emissions on signals and more commonly power leads. These diverge further according to low or higher frequency measurements. Examples of CE requirements are MIL-STD-461:CE101, CE102, CE106, and DO-160 section 21.[6][22][9] These are singular examples not an exhaustive list. CE101is a low frequency emissions tests, they measure current. CE102 and DO-160 section 21 are higher frequency that measure voltage. CE and susceptibility requirements do not relate to each other; this is a common misconception. Each has a completely different origin.

Emissions are “the phenomenon by which electromagnetic energy emanates from a source”.[18] CE tests measure the amount of emissions from a source on known conductors. Common test limits are in units of amperes or volts; typically, lower frequencies measured in amperes and higher frequencies in voltage. Figure 24 shows the CE102 voltage, max current, and power limits from Mil-Std-461. Another important aspect about CE limits is how they are measured. Standards measure voltage limits across known impedance; typically called a Line Impedance Stabilization Network (LISN). Standardized measurement results provide simpler comparison. CE limits are in terms of current, because they are low enough in frequency to be unaffected by LISN impedance, shown in Figure 23.

Figure 23 MIL-STD-461 and DO-160 LISN Impedance



Note: There is no minimum impedance limit below 100 kHz due to the "uncontrolled" resonance which occurs near 20 kHz.

Note: Impedance curves reflect an external 10 µF capacitor connected across the LISN power input terminal, and the LISN test instrumentation port terminated in a 50 ÷ resistor.

If the LISN contains an internal 10 µF capacitor, and meets the impedance curve requirements, then an additional external 10 µF capacitor is not required.

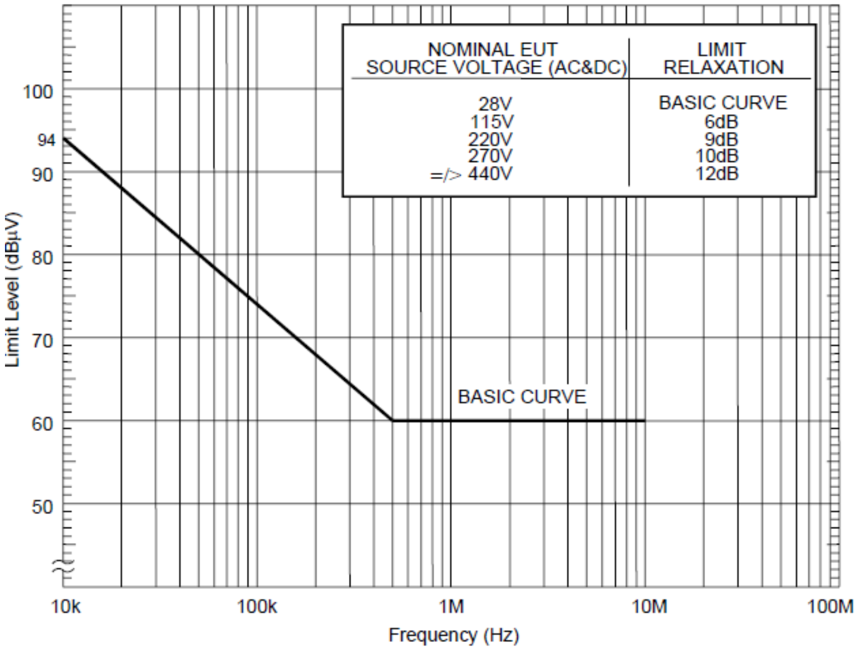


Figure 24 Example CE102, Max Current Limit and Applicability

7.2 Tailoring and Derivation of Conducted Emission (CE) Limits

From section 4.2 on tailoring and deriving CS radio frequency requirements much the same is true for tailoring CE requirements. Emissions limits must be "Tailored" to the most applicable level. Tailoring allows for test and verification at a lower equipment level, derivation goes one-step further by allowing test and verification at the module/component level. A key discriminator between the two is how they are experienced at system level. An important aspect of emissions is how much influenced by the operation of the system itself they are. Choose the EUT operational mode to be worst case from an emissions generating point of view. Traditional guidance has been to select the mode that uses the high current draw, for power systems. System level operational modes influence emissions; for example, current draw.

7.3 Specific Architecture Example

This example borrows the architecture detailed in section 4.3 and details an approach to allocating MIL-STD-461 CE102 requirements from system level to subsystems to module/component level including derivation. For purposes of discussion, assume the same example restrictions as given in section 4.3 for suppliers or another secondary designer. Figure 25 shows the example architecture and MIL-STD-461 applicability.

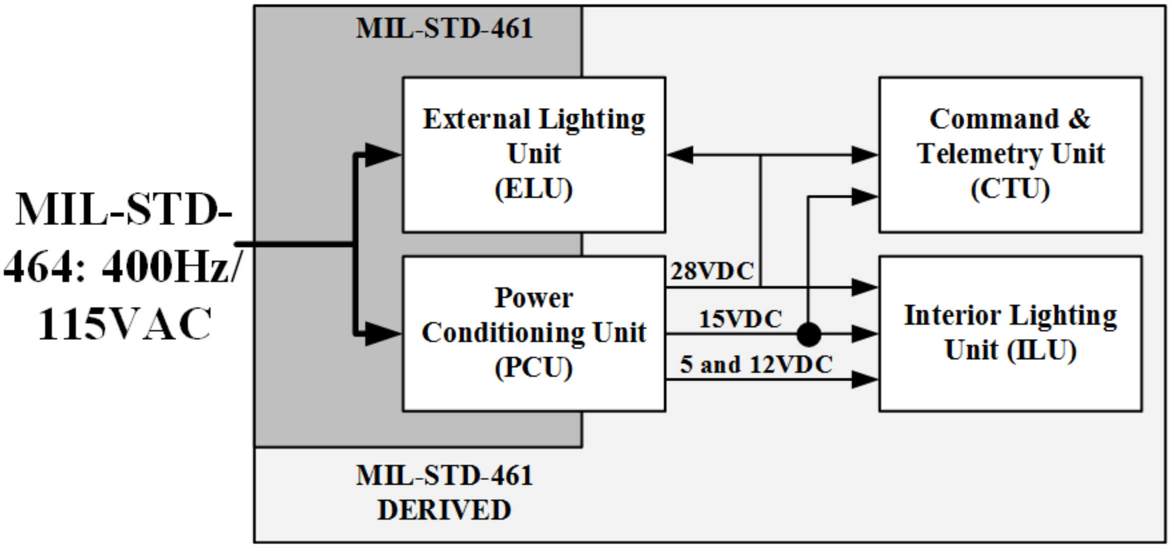


Figure 25 MIL-STD-461 Applicability

Requirements allocation begins at system level for each unit and continues through to modules and components. Figure 25 shows that since the PCU provides conditioning it would be incorrect to prescribe full MIL-STD-461 requirements to its outputs. MIL-STD-464 and 461 both exclude secondary output lines. To achieve compatibility it is necessary to allocate derived versions of MIL-STD-461 to each component separately. Figure 25 shows that full MIL-STD-461 limits get allocated to PCU and ELU inputs. The CTU/ILU inputs and the PCU/ELU outputs limits are derived and allocated.

7.4 Detailed Example using CE 102

The following example uses a 28VDC power waveform but methodology approach is the same and can be adapted to accommodate any power waveform VAC or VDC. The PCU output provides 28VDC power to the ELU, ILU, and CTU; it does not connect directly to platform power. For this reason, outputs of the PCU 28VDC are allocated derived limits.

7.4.1 Procedure for Requirement Derivation

The following method details how to perform derivation of the MIL-STD-461 CE102 limit for applicability at the module/component level so the requirement maintains rationale and traceability to the system level compliance assessment. Other requirement limits may use the same method.

Step 1) Determine a starting limit from which to derive the module/component level limit. From MIL-STD-461, determine the untailored subsystem level requirement for the specific waveform, in this case 28VDC given in [11]. This is important because it must be directly traceable and will establish the maximum limit threshold. The limit level called out as “Basic Curve” for a 28VDC power supply in Figure 24.

Step 2) Determine the correct subsystem, module, or component design parameters for limit comparison. Ripple voltage as defined in [10] is most applicable to the CE102 limit; similar specifications for and emission limit derivations may also be used. Depending on the derived requirement, different parameters may be used. For this example, nominal voltage associated with power input applies. Often the location where the procurement process allocates requirements will determine the best approach. Assuming since the ELU is an existing product; it will have existing maximum ripple specifications for power input. If both units are new designs then it is necessary for each PCU output requirement to mirror the ELU's input requirement.

Step 3) Verify subsystem, component, or module level requirements are consistent and provide compatibility across the entire interface. In this example the PCU output ripple requirement must be less than or equal to the maximum allowed input ripple for the ILU, ELU and CTU units. Assume for this example none of these units have existing designs and their input ripple voltage requirement should be the same as the PCU output requirement.

Step 4) Derive the max power limit using the derived ripple voltage level. For this example, figure CE102-1 of MIL-STD-461 shows the 28VDC system level is applicable at the PCU input. Thus, the PCU must not produce CE on its input greater than the CE limit. ELU, ILU, and CTU units may not produce emissions greater than the CE limit otherwise; the PCU will need to suppress them to below the CE limit on its own input lines.

Step 5) Verify subsystem, component, or module level requirements are consistent and provide compatibility across the entire interface. CE limits must account for all system level scenarios. One prominent system level scenario is the chance that emissions will compound by coupling from two different sources and exceed the system level requirement. For example, synchronous switching loads or synchronous switching mode power supplies can produce over lapping emissions profiles.

To account for this compound coupling scenario of two sources adding together the subsystem and component level CE limits should be 6dB below the next successive level. For example, if the system CE limits are 10volts then the subsystem level should be 5 volts or 6dB lower. This would allow two emission sources to constructively add and remain under the system level limit. For example, synchronous loads or switch mode power supplies that generate similar spectral content are capable of adding constructively. This would not be necessary if no synchronous threat existed; requirement wording should capture this exclusion.

7.5 Detailed Example using DO-160 section 21

MIL-STD-461 CE102 and DO-160 section 21 are similar requirements; both are low frequency power input requirements. However, DO-160 specifies CE limits in terms of current.

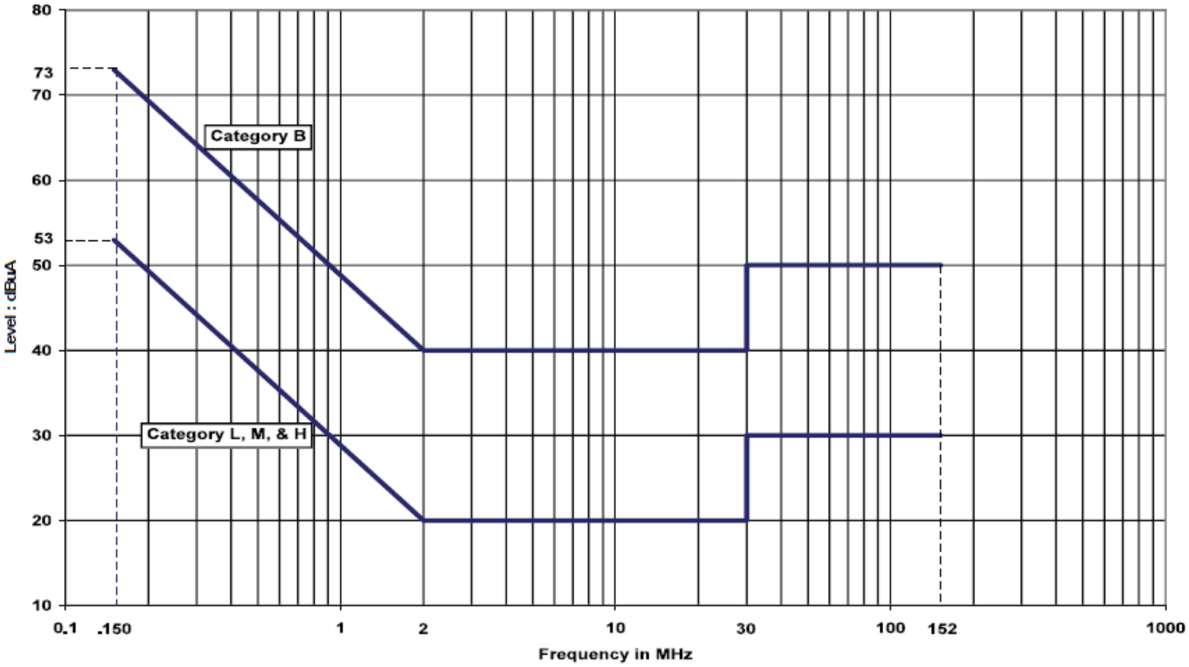


Figure 26 Example DO-160 Section 21 Max Current Limit

Assume the system architecture is as given in Figure 27. This example derives CE requirements on the 15VDC power input for the Interior Lighting Unit (ILU). From the architecture in Figure 27, the PCU derives its 15VDC output from the 28VDC. Following the approach detailed in section, 7.4.1 allocate the ILU a CE limit 6dB lower than the PCU CE limit on the 28VDC line, and 15VDC but not on the 5 and 12VDC lines. Due to multiple units being present on the 28and 15VDC lines, for this example the ELU and CTU, the 5 and 12VDC lines have only the ILU.

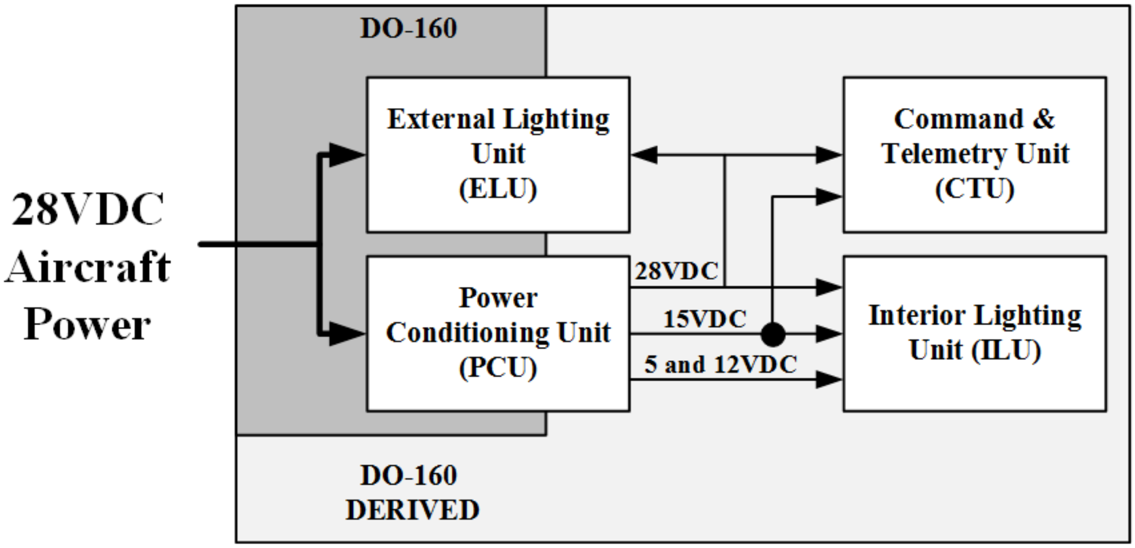


Figure 27 Example Architecture and DO-160 Applicability

7.6 Applying Design Margin

The 15VDC power is an ideal example because it supplies both the ILU and CTU. In this example, the 6dB would be sufficient but not if an additional unit, possible of constructively adding emissions shares the same power line. A worst-case scenario would be an in phase addition of each emission on the 15VDC line being added to noise from each other exceeding the PCU attenuation capability. This allows any two-noise sources to constructively add and remain within specification.

Doubling the limit to provide 6dB of margin is also included in the untailored limit to keep the method consistent with the approach used in MIL-STD-461. The 6dB margin can be a challenging design driver, particularly at lower frequencies. Reserve assigning recommended margin for design scenarios where the addition of emission sources is synchronous or completely unknown. Cascading this margin requirement can quickly lead to infeasible design requirements on the emission or required filtering.

CHAPTER 8 RADIATED EMISSIONS

8.1 Commercial and Military

Commercial and military RE requirements measure transient and continuous wave emissions. Transients associated with intermittent singular events or intentional emitters are not applicable. For example, transient emissions associated with a onetime turn on of a system or the fundamental transmit frequency of transmitter. Examples of RE requirements are MIL-STD-461:RE102 and DO-160 section 21. Both give field strength limits in terms of voltage per meter and each has a max power limit. Figure 28 shows the RE102 voltage, max current, and power limits from Mil-Std-461.

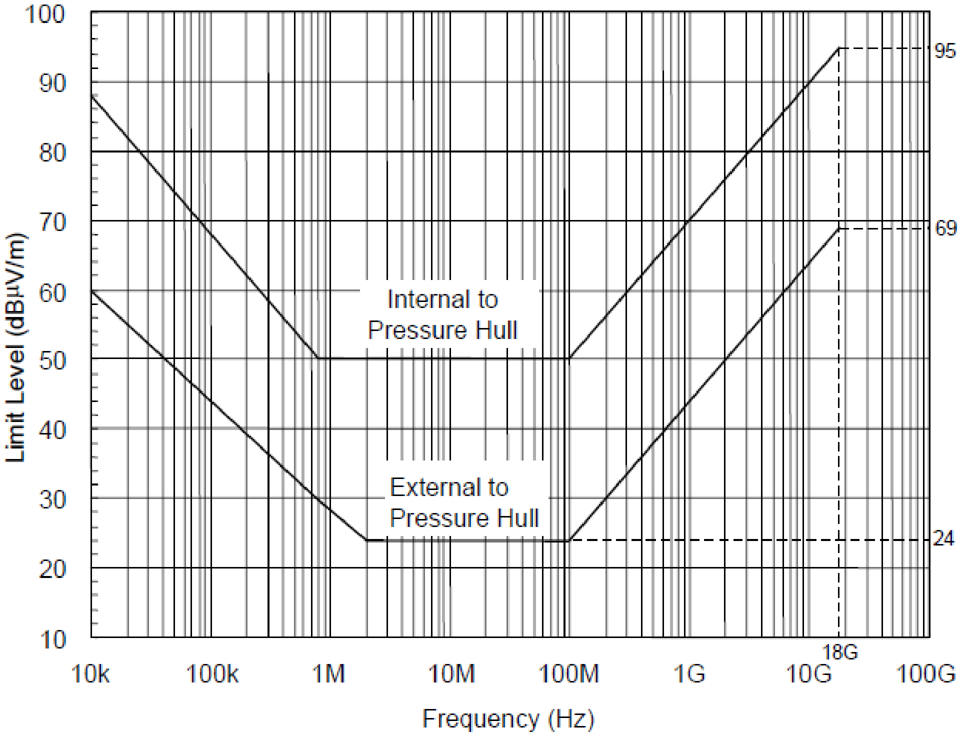


Figure 28 Example RE Voltage Limit

8.2 Tailoring and Derivation of RE Limits

From section 6.2 on tailoring and deriving RS radio frequency requirements much the same is true for tailoring RE requirements. Each must be “Tailored” to the most applicable level. For example, passive subsystems or modules, like cabling, would not be flowed requirements. Tailoring allows for test and verification at a lower equipment level, derivation goes one-step further by allowing test and verification at the module/component level.

8.3 Specific Architecture Example

This example borrows the architecture detailed in section 4.3 and details an approach to allocating MIL-STD-461 RE102 requirements from system level to subsystems to module/component level including derivation. For purposes of discussion, assume the same example restrictions as given in section 4.3 for suppliers or another secondary designer. Figure 29 shows the example architecture, coupling mechanism, and MIL-STD-461 applicability with shield boundaries.

Requirements allocation begins at system level for each unit and continues through to modules and components. Figure 29 shows prescribing the CTU and ILU each derived RE requirements because they are behind two layers of shielding. The PCU and ELU would get the full subsystem level RE requirement because they provide a boundary to the outer system level. To achieve compatibility it is necessary to allocate derived versions of MIL-STD-461 to each separately. This identifies the same failure scenario as CE, namely that RE from independent sources may constructively add. This is less likely than CE since the two would have to be synchronous spatially; this is unlikely but possible for certain scenarios. RE requirements are not tied to susceptibility requirements, this is a common misconception. Each has a completely different origin. An emission may become an RS source but typically, this is only the case for communication systems, because of the low level of most emissions.

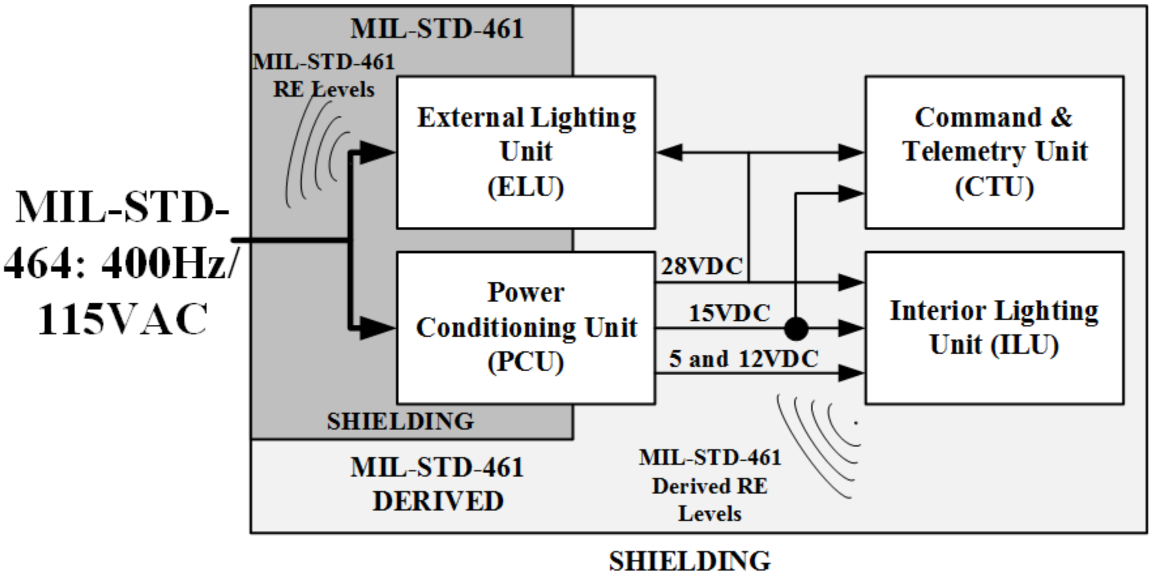


Figure 29 Mil-Std-461 Applicability

8.4 Detailed Example using RE102

The following example details the derivation for prescribing RE limit levels to the PCU, ELU, ILU, and CTU for achieving system level RE compatibility at system level.

8.4.1 Procedure for Requirement Derivation

The following method details how to perform derivation of the MIL-STD-461 RE102 limit for applicability at the module/component level so the requirement maintains rationale and traceability to the system level compliance assessment. Other RE requirement limits may use the same method.

Step 1) Determine a starting limit from which to derive the module/component level limit. From MIL-STD-461, determine the untailored subsystem level requirement for the specific waveform.

This is important because it must be directly traceable and will establish the maximum limit threshold. Figure 28shows the RE102 limit levels.

Step 2) Determine the correct subsystem, module or component design parameters for limit comparison. Radiated emissions have no direct design parameter unless the design is an intentional emitter. In general, radiate emissions are unintentional, with the exception of intentional transmitters; consequently, there is no design parameter to compare directly. Alternatively, a comparison could be made to some aspect of the design is an intended radiation source. Depending on the derived requirement, different parameters may be used; for example, cabling, conductors, apertures, assuming these aspects are unknown.

Step 3) Verify subsystem, component, or module level requirements are consistent and provide compatibility across the entire interface. In this example, prescribe the PCU and ELU the system level or full RE102 external RE limit level, while prescribing the ILU CTU the internal RE102 limit. Assume for this example none of these units have existing designs. The difference is approximately a 26dB delta due to external shielding; this delta is due to shielding design [6] [10].

Using the same design principles and guidelines on the component level shielding would amount to another 26dB relaxation. Note emissions limits get a “Relaxation” meaning the limits are increased or relaxed. A relaxation is due to the multiple shielding layers attenuating the emissions. This is not the case if the component (or module) level has no shielding, since the next successive shield layer will have to shield both subsystem and component (or module) level sources.

Step 4) Verify subsystem, module, or component level requirements are consistent and provide compatibility across the entire interface. Table 13 and

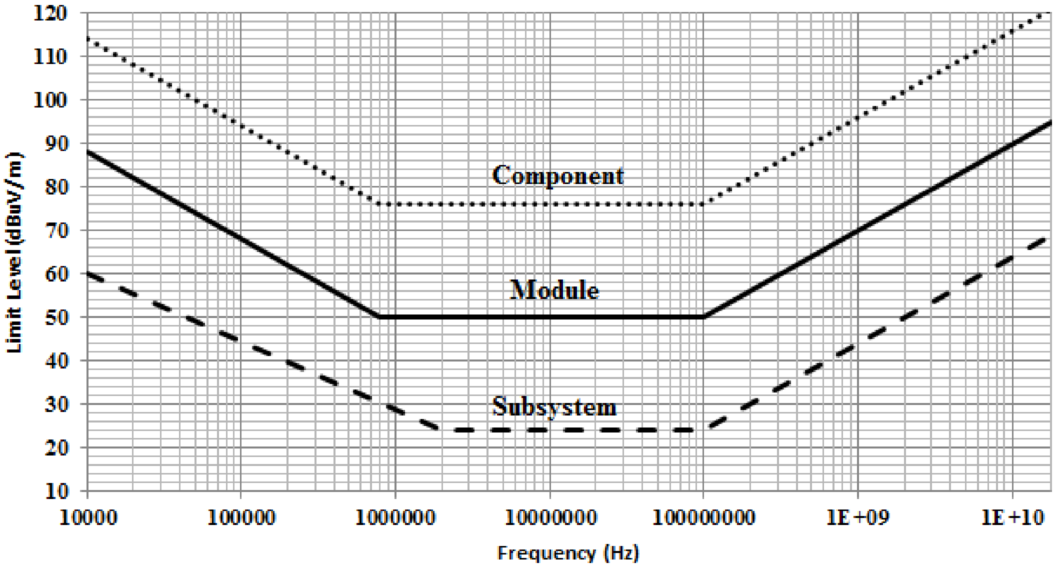


Figure 30 shows the derived RE102 limits for systems, subsystems, and module level; note, worst-case frequency range envelopes the worst-case scenario.

Table 13 RE limit Derivation

Applicability Level	Frequency Range	Derived Limit (dBuV/m)
Subsystem	10kHz to 2MHz	60/24
Subsystem	2MHz to 100MHz	24
Subsystem	100MHz to 18GHz	24/69
Module	10kHz to 800kHz	88/50
Module	800kHz to 100MHz	50
Module	100MHz to 18GHz	50/95
Component	10kHz to 800kHz	114/76
Component	800kHz to 100MHz	76
Component	100MHz to 18GHz	76/121

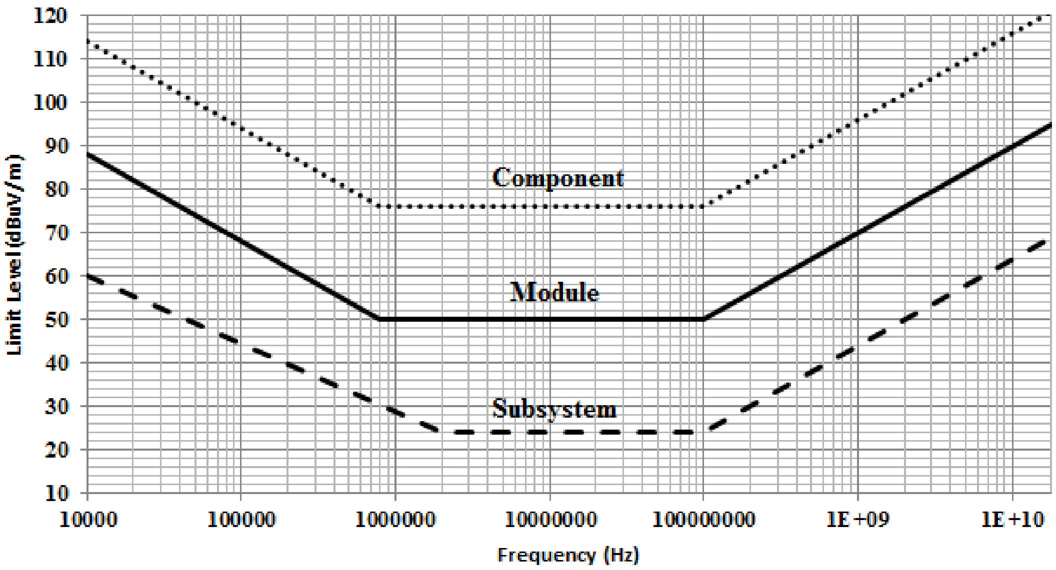


Figure 30 RE Limit Derivation

8.5 Detailed Example using DO-160 section 21

MIL-STD-461 RE102 and DO-160 section 21 are similar requirements; both are RE requirements. Each has different measurement techniques and limit levels. For this example were concerned with categories B and L. Category be is for controlled exposure and category L is for uncontrolled exposure electronics, thus requiring shielding. Assume the system architecture is as given in Figure 33. This example derives RE requirements for the PCU, ELU, CTU, and ILU. Following the approach detailed in section 8.4.1 the Table 14 summarizes RE limits for subsystem, module, and component levels.

Table 14 DO-160 Section 21 RE Limit Derivation

Applicability Level	Frequency Range	Derived Limit (dBuV/m)
Subsystem	100MHz to 6GHz	45/73
Module	100MHz to 6GHz	65/93
Component	100MHz to 6GHz	85/113

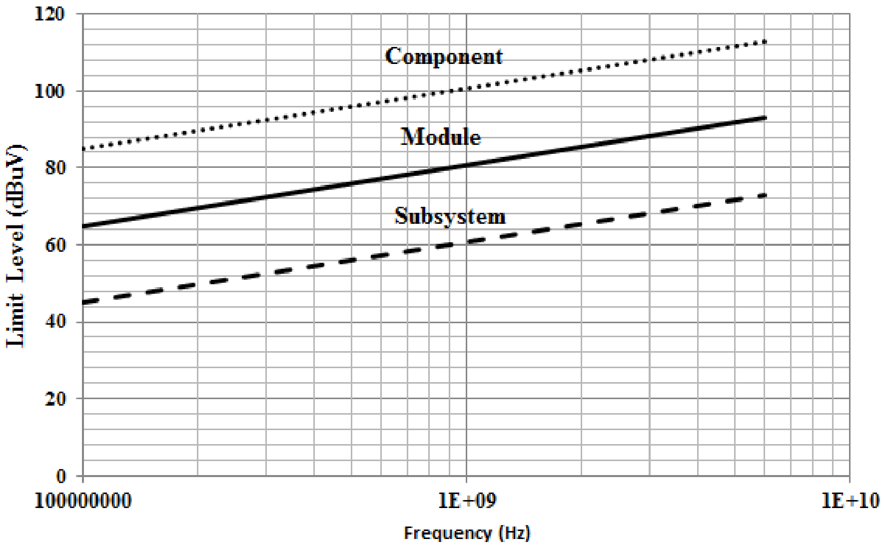


Figure 31 DO-160 Section 21 RE Limit Derivation

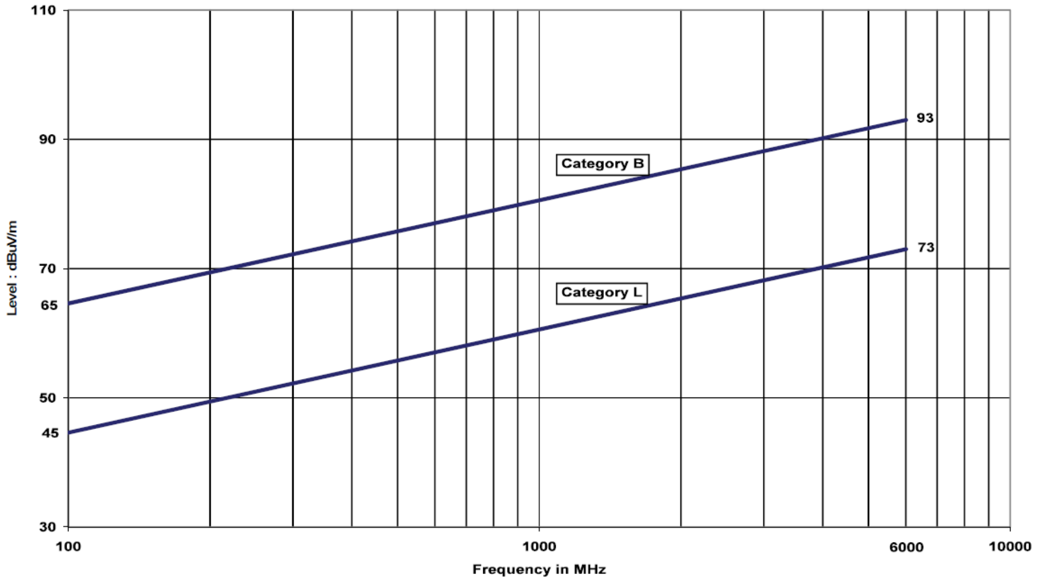


Figure 32 DO-160 RE Limit

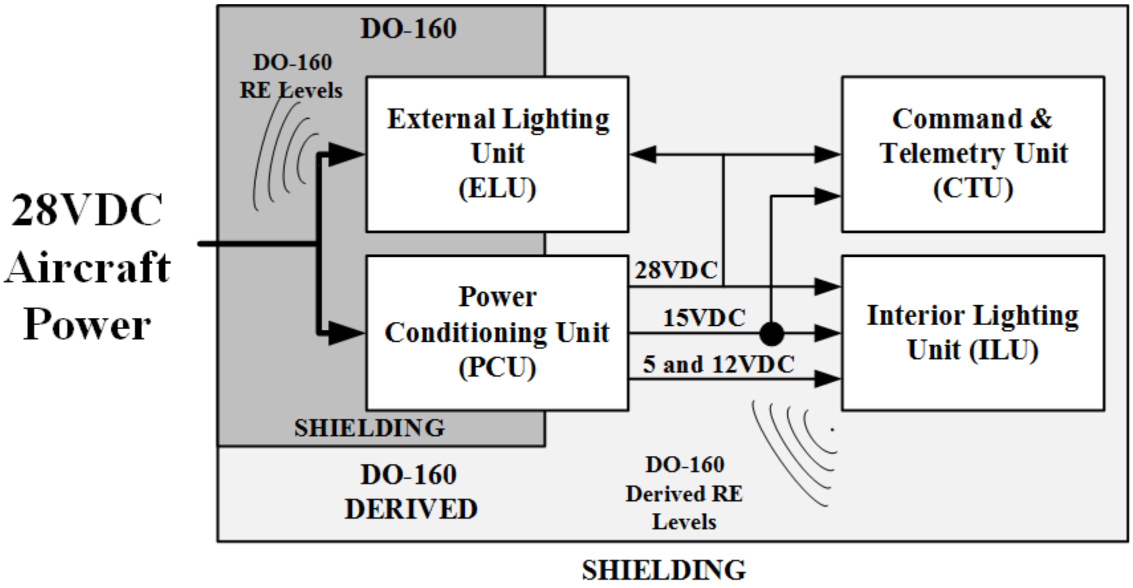


Figure 33 Example Architecture and DO-160 Applicability

8.6 Applying Design Margin

A worst-case scenario would be an in phase addition of radiated emission noise from multiple sources. While this is highly unlikely, and could be ruled out for non-synchronous emission sources a worst case scenario could account for such a happening however unlikely by adding 6dB to the subsystem and component level limits. This allows any two-noise sources to constructively add and remain within specification.

CHAPTER 9 FILTER DESIGN ASSESSMENT AND VERIFICATION

Input filters are a major design aspect to reduce the risk of conducted susceptibility. Unless filter performance correlates to quantifiable requirements, then filter performance is subjective and unverifiable; it provides no validation, verification, traceability, or closure. Insertion loss presented without direct relevance to requirements is not sufficient. Deriving specific requirements to the module/component level quantifies the required attenuation. Having quantifiable limits will allow verification at the module/component level as opposed to testing late at the system level to identify a deficiency.

Compliance testing at the module/component level can be difficult and challenging. For example, a LISN is required at system level testing but would not be applicable at module/component level. Another complexity is unless a filter tests against the actual emission levels as it would be subject to when implemented in the system it may not show deficiencies. An alternative is to replicate the correct module/component impedance. Ref. [11] and [12] present a discussion based on measurements and modeling of differential mode CS currents and the impact of impedance. When impedance is unknown, use a LISN for standardization. If use of a LISN is not feasible, then characterize the impedance during test for comparison to known impedances. Ref. [13] details a thorough approach to accommodate impedance variance. The RF attenuation measurement setup shown in figure 4 of [13] is ideal because it measures differential mode under variable loads. The range would need extended to cover the lower frequencies for CS.

CS requirements are of particular concern because these requirements apply potentially damaging levels more than other requirements. For example, an untailored MIL-STD-461 CS101 test method can inject up to 12.65A [5]. Numerous test efforts have resulted in damage due to the use of improperly derived injection levels, particularly the power limit. Besides traceability, closure, and system level compliance another advantage of this technique is reuse of system level setups, test equipment, and procedures. For example, the tailored and derived level tests use the same setup. This is possible because the derivation method uses existing standards.

9.1 Input Filter and Requirement Derivation

For completeness, a discussion on input filters and their potential effect to this process has been included. This is important because derivation naturally decomposes requirements allowing a direct assessment of filter performance. For example, if the output side of a filter feeds multiple inputs then a bi-directional filter must attenuate noise from output to input and input to output. Decomposing the CS requirements from a level that applies at the filter inputs to a level that applies to the filter output (or ancillary inputs) defines the required attenuation.

Too often, designers use insertion loss to gauge filter performance or improperly reference MIL-STD-220 characterization and measurement method. This method assumes constant 50-ohm termination impedance and is inappropriate for gauging RF performance in the filter’s intended application; ref [6] presents a thorough explanation of this insufficiency and presents an analysis setup that can be readily adapted for CS101. Input impedance is difficult to address because it can vary over frequency. An important aspect of this variance is to understand the necessary impedance to achieve the voltage limit and not the power limit. Ref. [7] gives detailed examples on how to measure varying source impedance; it discusses differential and common mode methods along with experimental results, and assumes no compliance level. This is important because failures often occur at the max power limit so it is important to know if the filter design will see voltage or the max power limit during testing.

CHAPTER 10 CONCLUSION

There has been limited research on derivation of system level EMC requirements through to the module/component level. While there has been considerable research and study devoted to design techniques and tools, comparatively little research has focused on establishing the correct requirements through tailoring and derivation to the module/component level. This dissertation establishes a detailed method to derive system level requirements for allocation and verification at the module/component level. Each method maintains traceability for the requirements decomposition and flowdown process. This latter step is necessary to maintain feasible test methods for use at system, subsystem, and module/component level. This is important because requirements at all levels must be verifiable to be useful.

Examples of commercial and military requirement standards were included to delineate each step of the method. Examples taken from four most common divisions of requirements provided edification. This dissertation uses requirements from both emissions and susceptibility examples because they are required from system derivation. CS requirements typically have the largest disparity between system and module/component level requirements. CS requirements also require careful consideration, because more so than other requirements they can cause damage.

Examples of radiated and conducted requirements established distinctions between the two. Commercial and military requirement standards show the overall versatility of the approach. An overall flowdown process, systems requirements flowdown, and formal approach are included for edification. Detailed example discussions were included relative to an overall allocation approach for ensuring system level EMC as well as how to overcome some common obstacles. Examples given show how to derive specific injection levels for direct comparison for evaluating filter performance. Implementation of this method can be challenging. A tacit goal of this work is to foster discussion and further research in this area.

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