A rationalized approach in tailoring EMI standards for Electronic Power Conditioners

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Abstract— *Electronic Power Conditioners (EPCs) are one of the very critical subsystems required for energizing various active subsystems of a spacecraft. For being state of the art technology for space applications EPC shall be realized in a light and compact package. However the compliance requirement of a very stringent EMI performance; as per MIL-STD-461E; often poses various challenges to EPC designers. This paper elaborates the conducted susceptibility CS101 requirements, challenges and constraints in meeting that, and tailoring of the standard for typical space applications.*

I. INTRODUCTION

Electronic Power Conditioners are switching mode power supplies used for space applications. EPC consists of dc-dc converters, filter circuits, tele-command/telemetry interface circuits to fit into a satellite platform. A typical communication satellite uses as many as hundred EPCs for powering various subsystems and systems. EPC Design engineers face several continuous challenges to satisfy the demand of conditioned DC power of today's satellite payload subsystems. The multitude of required voltages, varying current loads and increased tendency among system designers for packing more and more subsystems in a payload, poses high efficiency requirements on EPCs. This make yesterday's proven design approaches increasingly less practical while, the modern designs are more complex and difficult to implement.

In recent years, there has been rapid progress in terms of quantity, complexity and diversity in the Communication, Navigation and other spacecraft payloads of ISRO. With the limitation in the availability of orbital slots and frequency spectrum together with the advances in device technologies, the communication payloads are increasingly become more complex, increasingly using higher frequencies, employing more transmitting power and larger number of transponders. As the requirement of Microwave, Optical, Electro-mechanical subsystems in a satellite, in terms of quantity, complexity and variety become large, it poses serious challenge to the EPC design teams, which have to keep pace with the developments, meet large quantity requirements (as every subsystem needs at least one EPC) and also meet the power needs of special subsystems with extreme demands.

Space grade EPCs requires judicious combination of design, analysis and testing to realize as a flight worthy hardware. They operate in an environment considerably different from that in which they are built and after launch they are inaccessible to routine maintenance and repair. So, EPCs for space applications require design solutions that provide a reliable product with the highest of confidence.

II. ELECTRO MAGNETIC INTERFERENCE (EMI)

Most electrical and electronic devices can generate and/or be affected by EMI. The high-speed switching process is intrinsic to EPC and provides its improved efficiency and reduced size when compared to linear power supplies. However, as a side effect, this switching generates unwanted EMI. It is the function of the EMI filter to keep any internally generated noise contained within the device and to prevent any external noise from entering the device. Often its design meeting the MIL-STD-461E standard is challenging. The input filter on a switching power supply has two primary functions. To prevent electromagnetic interference generated by the switching power supply from reaching the input power line (as it affect other equipment) and to prevent high frequency noise on the power line from entering into switching power supply. MIL-STD 461 is the controlling document for emissions and susceptibility requirements for electronic equipment used by space community for several years. Every space agency oversees this specification for assessing constraints in realization. Especially space systems are made compact size and mass due to exorbitant launch cost. So compliance to stringent standards is often proving costly and so expedites to tailor the specifications. This will be done with no trade off in performance or reliability aspects of the system and also for an optimized and miniaturized design.

III. DESCRIPTION OF THE WORK

This paper attempts to bring out the reasons, which limit the injection levels to the EPCs during CS101 tests to 1Vrms levels. A need to rationalize the standards of EMI that are currently being followed at SAC with the standards being followed worldwide by other Spacecraft manufacturers, equipment manufacturers and other ISRO centres. Conducted Susceptibility: MIL-STD-461 E Purpose of the low-frequency conducted susceptibility tests CS101 (30 Hz to 150 kHz). To ensure that electrical/electronic equipment connected to a common power bus is not susceptible to spurious frequencies generated and propagated (conducted emission) due to other subsystems operations and dynamics. The tests are applicable to both the input power leads. Purpose of the high frequency conducted susceptibility test CS114 (10 KHz to 400MHz). To simulate the currents that will be developed on equipment leads as a result of EMI/RFI generated by antenna transmissions. The tests are applicable to all interconnecting leads, including power leads of the EUT. The CS101 low frequency test methodology Injects the disturbance voltage onto power leads through a coupling transformer with its secondary connected in series (as shown in Fig.1). A line impedance stabilization network (LISN) is placed between the power source and the coupling transformer

IV. EMI SPECIFICATIONS FOR ON-BOARD SYSTEMS

Switching power supplies for industrial applications, the EMI compliance requirements are subject to FCC and CISPR regulations. Similar line, for military and space system applications EMI regulations are done thru MIL-STD-461E, a general guideline document made by MIL system US Dept. of Defense. Noises can be generated in a system or systems can be affected by external noises. There are two paths for noise to travel; conducted and radiated. The four possible electromagnetic compliance requirements viz. conducted emission (CE), conducted susceptibility (CS), radiated emission (RE) and radiated susceptibility (RS).

TABLE V. Requirement matrix.

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS109	CS114	CS115	CS116	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships		A	L	A	S	S	S		A	L	A	A	A	L	A	A	L
Submarines	A	A	L	A	S	S	S	L	A	L	A	A	A	L	A	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S		A	A	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S		A	A	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S		A	A	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S		A	A	A		A	L		A	
Ground, Army		A	L	A	S	S	S		A	A	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S		A	A	A		A	L	A	A	L
Ground, Air Force		A	L	A	S	S	S		A	A	A		A	L		A	

Legend:
A: Applicable
L: Limited as specified in the individual sections of this standard
S: Procuring activity must specify in procurement documentation

This work only deals with conducted susceptibility; CS101 test criticalities and the tailoring requirement of this standard for space applications. The CS101 requirements and test set ups as per MIL-STD-461E is enclosed below.

Standard Product MIL-STD-461 Conducted Susceptibility Test Criteria: Conducted susceptibility is the response of the converter to unwanted signals applied to the power leads. Requirement CS101 tests the converter's ability to perform properly with audio frequency signals superimposed on the DC input. This is also called "audio frequency rejection." CS102 extends this into the RF range. Requirement CS06 applies positive and negative spikes to the converter's inputs. The objective of the CS (Audio Susceptibility Test) is to assure that the DC/DC Converter produces a usable output when subjected to a simulated worst case AC modulation of the DC power supply input. In the CS01 test, an audio signal ranging from 30 Hz to 150 kHz is connected between the DC/DC Converter and the power source. Both the positive and negative legs are tested if the input is isolated from the case. For a 42 VDC nominal unit, a 15.8 volt peak to peak is applied. In addition, the power of the susceptibility source is limited to 80 watts. For higher voltage units, the voltage is usually scaled proportionally. For meeting the CS101 requirements neither an internal or external filter can help to attenuate as filter component become bulky at such low frequencies. Therefore, the design of the converter itself must be capable of audio frequency rejection. This requires high loop gain at the high audio frequency range. CS101 rejection is typically achieved by using current mode or dual loop feedback. However the filter component stresses put constraints even there also as discussed in the following sections. A typical CS101 test set up is shown below with associated injection voltage and power envelopes.

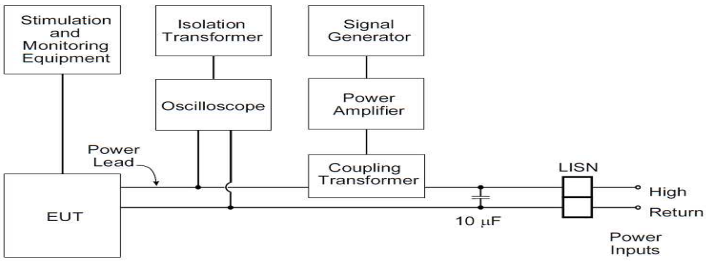


Fig.1 CS101 Test set up

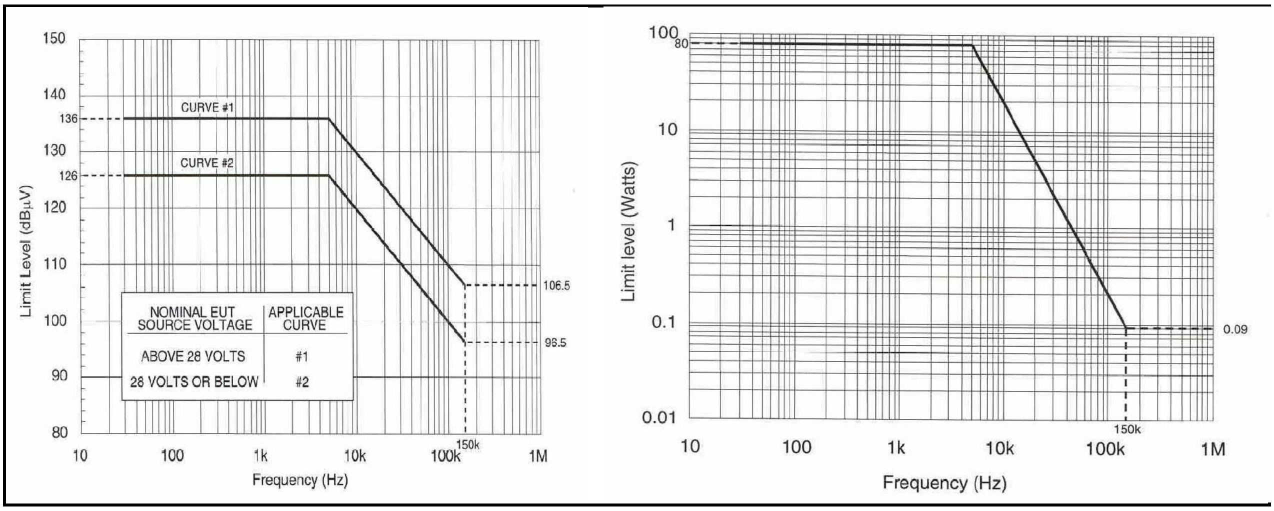


Fig 2 MIL-STD-461E CS Voltage Injection Level & Power Injection Level

V. CONSTRAINTS IN MEETING CONDUCTED SUSCEPTIBILITY STANDARD CS101, MIL-STD-461E

Filter-Converter Interaction & Middle-Brook criteria

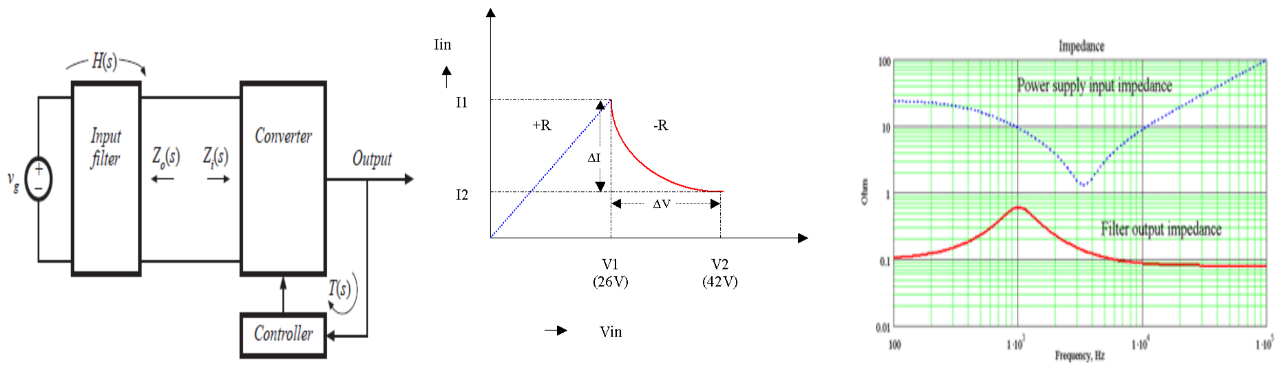
Before going into the details of constraints the CS101 standards put on EPC design, a glance on stability issues associated with input filter design of an EPC is sensible. DC-DC switching converters are a constant power load (decrease in the input current with increase in input voltage): Negative impedance characteristic, which could cause instability.

Dynamic resistance

$$\Delta Z = \frac{\Delta V}{\Delta I} = \frac{V_2 - V_2}{I_2 - I_1} = -negative \quad \text{due to I1>I2}$$

Input current of switching regulator is always discontinuous

- Input filter prevents EMI: Generally low pass LC filters.
- Inductor high impedance (towards HF) minimizes converter switching current flow into the source (spacecraft bus) and capacitor low impedance minimizes spacecraft bus voltage ripple flow into converter. Middle Brook Criteria, to avoid Filter-converter Interaction says that the input impedance of the converter shall be greater than the output impedance of the filter and also shall be staggered in frequency in the entire frequency range to avoid interactions between filter and converter to make a stable EPC.



Negative Impedance characteristic of Converter.

The equivalent Impedance seen at interface of filter and converter is

$$Z_{eq} = \frac{Z_o . Z_i}{Z_o + - Z_i} \quad \text{Negative for } Z_o > Z_i \quad \text{Positive for } Z_o < Z_i$$

As you know, negative Impedance is regenerative and causes Instability. Middle Brook's Criteria says that system will be stable if $Z_o(s) << Z_i(s)$ throughout the frequency. Stable power systems must ensure that the output impedance of the filter is always less than the converter's input impedance. This objective must be achieved at minimum input voltage and maximum load (i.e., the lowest input impedance). Constraints of Designing Input filter to meet CS101. The design of input Low Pass LC filter becomes most critical and limiting factor for any switch mode power supply, when it is desired to meet the MIL-STD-461 EMI requirements. The input filter has to satisfy two requirements:

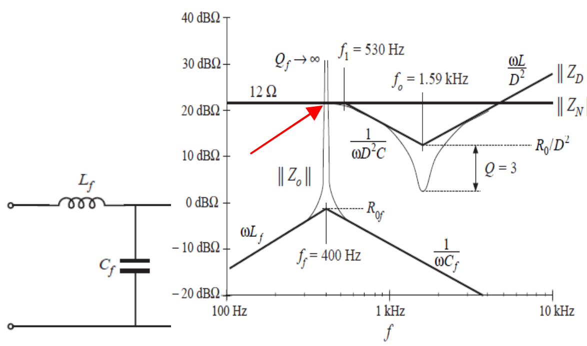
- Attenuate AC ripple current emanating from SMPS towards input bus; Conducted Emission requirements.
- Reduce undesirable voltage ripples coming from input bus towards SMPS; Conducted susceptibility requirements.

Design parameters

- Input-output transfer function
- Output Impedance
- Input Impedance

The Input-Output transfer function is determined based on attenuation requirement of to meet the CE102 and CS101. The maximum value of Zo is determined by the Middle Brook stability criteria. The stress level ratings of the input filter components determine lower limit for Zi.

Un-Damped Input Filter characteristics



Damped Input Filter characteristics

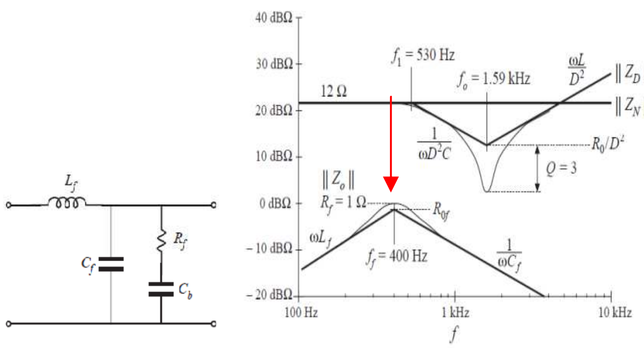


Fig.7 Un-damped input filter Zo (output impedance, bottom) and Zi (Conv. Input impedance, top)

The input filter output impedance must not contain any high Quality factor (Q) resonant "peaks" that could violate MB criterion by boosting Zo beyond Zi as shown in fig 8. The input impedance of the input filter also must not have resonant "valley" (dip), which could pull large current from the input power source or injecting power source, resulting in overstressing components. The high Q resonant peaks and dips are the worst cases to consider and must be limited by adding adequate damping resistors. With significant damping resistor or high ESR capacitors, the value of Q roughly falls between 1 and 5. The optimum-damping (Q is nearly 1) requirement for a parallel damped filter is derived from Damping resistor value, R= √ (L/C)

VI. CRITICALITY ON EPC POWER LEVEL TO MEET MIDDLEBROOK CRITERIA

Case I: High power EPC

For high power EPC, input impedance will be less and nears the input filter output impedance

$$\text{Input impedance } Z_i = \frac{V_{in}}{I_{in}} = \frac{V_{in}}{P_{in}/I_{in}} = \frac{V_{in}^{2}}{P_{in}}$$

$$\text{Therefore } Z_i = \frac{V_{in}^{2}}{P_{out}}.\eta$$

Zi will be worst case (minimum) for low bus voltage in our case 26V

$$Z_{i-\min} = \frac{V_{in-\min}^{2}}{P_{out}}.\eta = \frac{26.26.0.85}{100} = 6\Omega \text{ , for a 100W EPC}$$

In fact this is negative under dynamic condition, i.e. -6Ω

Thus, there is a need to limit the output impedance of filter less than 6Ω, including the peaking.

This is achieved by using optimum damping resistor value, which limits the impedance peaking.

$$\text{Damping factor } \zeta = \sqrt{\frac{L}{C}}$$

For high power EPCs, due to constraints of efficiency and CE performance, requirement of low value inductor and high value capacitor are unavoidable. The damping resistor value comes near 1Ω (See Eqn 1). If 17.8Vpp signal is injected for meeting CS101 test criteria, the power coming across damping resistor at resonance is:

$$P_w = \frac{V^2}{R} = \frac{(17.8/2.8)^2}{1} = 40W \text{ Approx. where (Vrms= Vpp/2.8)}$$

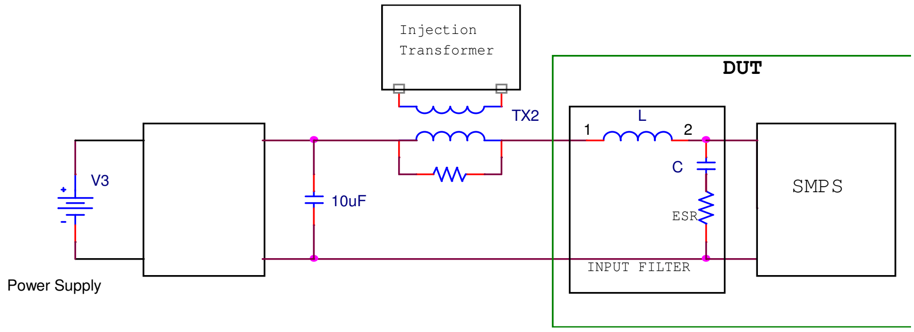
It is impractical to put a damping resistor with this much power de-rating to withstand stress conditions imposed by CS101 test. This limitation of damping resistor generally starts mattering for EPCs of above 20 Watts.

Case II: Low power EPC

For low power EPCs also, CS101 MIL requirements are impractical to meet. Component stress ratings are a limiting factor. Input filter uses a Wet tantalum capacitor due to its superior surge current capability, but it has high ESR value in the range of 1Ω. The wet tantalum capacitor damps the filter (by compulsion) by its ESR. The capacitor is rated for specified ripple current capability, which is a function of ESR. The ripple current capacity of capacitor is measured with 1Vrms injection across the capacitor. This is indicative of the power limit $Iac\text{-}rms^2$ X ESR of the capacitor. During CS injection, the stress levels of capacitors can get exceeded if the injection voltage or current envelopes are not controlled accordingly. These conditions are severe near the resonant frequency of filter when the input impedance dips try to load the injecting source and draw more ripple current which superimposes on the exiting capacitor current and thereby stress the capacitor and even damage it. The inductor core also can go to saturation and degrade the output ripple of the SMPS during this condition.

VII. EFFECT OF CS INJECTION ON INPUT FILTER CAPACITOR

CS Injection set up with presence of filter in EPC



Condition for limiting the stress to acceptable level

$$Z_{i-\min} \geq \frac{V_{injection-rms}}{I_{ac-rms}}$$

Total Impedance across LC filter,

$$Z = \sqrt{(ESR)^2 + (XL - XC)^2}$$

At resonant frequency $XL = XC, XL - XC = 0, Z = ESR$

Therefore, $ESR \geq \frac{V_{injection-rms}}{I_{ac-rms}}$ i.e. $1 \geq \frac{V_{injection-rms}}{1.5A}$

(Typical ripple current rating of CLR79 type capacitor is 1.5A and typical ESR value is 1Ω)

Thus, the voltage injection limit is 1.5Vrms for a typical CLR capacitor. With margin, this should be limited to 1.0 V rms.

Typical capacitors values/types used in in-house EPC designs and CS injection limits

Sl No	Capacitor Value & Type	ESR @120Hz	Ripple Current @ 40KHz	Injection limits (Using Eqn-3)
1	22uF-100V CLR79	4.52Ω	965mA	4.36Vrms injection limit
2	68uF-100V CLR81	2.21Ω	1600mA	3.52Vrms injection limit
3	86uF-100V CLR79	1.54Ω	1800mA	2.7Vrms injection limit
4	120uF-100V CLR81	2.76Ω	2000mA	5.5 Vrms injection limit

The above table analyses the ESR @ 120Hz. ESR is highly dependent on the frequency. It typically reduces 2-4 times from 120Hz to 1 KHz (EPC input filter resonant frequency is around 1KHz) but ripple current capability does not increase in the same proportion. The ripple current rating for CLR capacitors is specified at high frequency of 40KHz while at resonant frequency it will be even less than the mentioned values. So the injection voltage limit in our case will be less than values given in the table. The safe level of CS injection as far as the stress level of capacitor is concerned should be 1Vrms. International standards also emphasize on this, which is discussed later this presentation

VIII. EFFECT OF CS INJECTED RIPPLE ON INPUT FILTER INDUCTOR

Inductor core selection is based on the Inductance needed for attenuating the switching current. Energy storage rating (LI^2) of cores is also one critical parameter which is determined by converter input current, where L is the inductance value and I is the true rms value of current through inductor (IDC and IAC together). This is a measure of DC magnetization withstanding capability of the core. Usually a margin of 20-30% is kept in the design to avoid saturation of the core. Injected voltages during CS101 (30Hz-150 KHz) produce ripple current, which superimposes on the steady state current in the inductor. The ripple current corresponds to the injected voltage and the input impedance of the filter at the injection frequency. Thus, the ripple current from the injection must be limited so that the LI^2 margins are not exceeded. Otherwise, the core saturates and degrades EMI performance.

$$\text{i.e. } I_{rms-margin} \geq \frac{V_{injection-rms}}{Z_i}$$

This calls for lower dips in input impedance of the filter (optimum damping) or usage of bigger cores with more LI^2 margin. Otherwise the saturation of core during injection makes the inductor ineffective and which in turn increases the ripple current through the filter capacitor and could overstress the capacitor, as explained in the previous section.

Comparison of CE and CS limits used by ISRO, EUROSTAR and ALCATEL

There was a study performed by analysing the international tailored MIL-STD-461 CS specification which generally met by other space EPC manufacturers like ALCATEL, TESAT, and ASTRIUM etc. and found that most of them tailored the CS specification and comply only to 1Vrms injection and not 17.8Vpp or 6Vrms as per MIL-STD-461 due to the stress on devices and size-mass constraints.

The MIL-STD-461document is studied in detail and found some observations inferring to the constraints and how the tailoring of standards are proposed where ever essential. Those portions are appended here.

MIL-STD-461 E Document References

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4) The stated interface requirements are considered necessary to provide reasonable confidence that a particular subsystem or equipment complying with these requirements will function within their designated design tolerances when operating in their intended electromagnetic environment (EME). The procuring activity should consider tailoring the individual requirements to be more or less severe based on the design features of the intended platform and its mission in concert with personnel knowledgeable about electromagnetic compatibility issues affecting platform integration.

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1.2.2 Tailoring of requirements.

Application-specific environmental criteria may be derived from operational and engineering analyses on equipment or subsystems being procured for use in specific systems or platforms. When analyses reveal that the requirements in this standard are not appropriate for that procurement, the requirements may be tailored and incorporated into the request-for-proposal, specification, contract, order, and so forth. The test procedures contained in this document shall be adapted by the testing activity for each application. The adapted test procedures shall be documented in the Electromagnetic Interference Test Procedures (EMITP) (See 6.3). ‘’’’’’

IX. IMPACT ANALYSIS ON TAILORING CS101 SPECIFICATION

From the analysis and observations, the need for tailoring CS101 test is found inevitable. However the impact of this leverage in specification shall be studied before implementation. The impact analysis done on the spacecraft level as follows

Inferring CE 102, as per MIL-STD-461E

Acceptable CE levels

CE 102 limit at 10 KHz of the unit under this study is 94 dBuV.

Consider 24 similar units having same uncorrelated noise and propagating to another similar unit. Combined voltage becomes 94 + 13.8 = 107.8 dBuV (120dBuV=1V) = 0.25 V, Which is still having large (over 12 dB) margin from 1V rms. Thus, 1 V rms is adequate from conducted emission angle.

Acceptable RE levels

Assuming very bad RE of 90 dBuV, we arrive at the combined voltage of 103.8 dBuV which is 16dB away from 120dBuV. Assuming even 100% coupling, a subsystem could receive still less than CS level which it complies. Thus, RE non-compliance by even 66dB (w.r.to 24dBuV) is not an alarming situation, provided, there are no subsystem in the payload which have gains at the frequencies of RE non-compliance

Recommendations based up on the analysis and observations

CS 101 compliance level of 1 Vrms is felt adequate for ISRO spacecraft payloads. MIL-STD-461E specifies a 6.35Vrms (17.8Vp-p) voltage injection but recommends tailoring of specifications as per the requirement. The reputed space EPC manufactures from US, Germany & Japan comply with the requirement of CS101, with injection up to 1Vrms and with a Power limit of 1W, in the frequency of 30Hz-150 KHz. There are practical limitations of component stresses and penalty on size and mass of EPC, which is dictated by limit on CS injection. Otherwise based upon the filter characteristics the injection level need to be controlled below 17.8Vpp thru out the frequency range, to avert device stresses but it needs to be precisely done and seems a trivial job. Instead of that if we limit within 1Vrms and 1W which is the best. MLC capacitors can be explored at input filter of EPCs for withstanding injection more than 1Vrms, but with some trade-offs.

X. CONCLUSION

The EMI compliance requirements as per MIL-STD-461E for space systems are always challenging due to constraints of mass penalties. So it is essential to tailor certain specifications in such a way that it will not affect the overall performance the systems at spacecraft level. This work established a method to tailor the conducted susceptibility standard CS101 with adequate impact analysis on spacecraft level.

Acknowledgment

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