Secondary EMP Coupling Analysis Approach To Unit Design

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INTRODUCTION

Traditional design approaches for hardening enclosures (boxes) to the effects of electromagnetic pulse (EMP) usually involve placing transient protection devices (TPDs) at the enclosure input/output (I/O) connectors. This typically has several immediate influences on the mechanical and electrical design. From a mechanical standpoint, this can and often does affect the physical space the I/O connector requires inside the enclosure (e.g., a longer overall connector). The basic concerns of the EMC engineer with respect to hardening the typical I/O circuit against EMP have to do with the location and type of device used to circumvent the defined EMP threat. Usually the I/O engineer is faced with the prospect of placing devices at the unit I/O connector to prevent the coupling of the EMP signal into the device. This generally necessitates that a custom connector be made to incorporate the TPDs. Also, additional thought should be given to the design of the custom connector due to reliability concerns with the internal filter elements when the connector is used in its actual operational environment, and to the inherent cost of the custom connector. While a proven approach, this is not the only solution to the I/O hardening problem.

Nonconnector embedded TPDs can be used for some EMP applications.

This article provides an alternative wherein the protection devices are located within the enclosure on the backplane (motherboard). This approach has to be viewed carefully in light of operational needs, but can be used in some cases to reduce the cost and improve the reliability of final designs. Additionally, there is the added benefit that the discrete parts can be individually replaced for unit repair, whereas a custom connector usually has to be replaced in its entirety, and that discrete components can be chosen which have greater reliability.

The following analysis methodologies were taken from multiple sources and are presented here as a vehicle to help the design engineer.

BACKGROUND

An important and devastating result of a nuclear explosion is its EMP radiation, sometimes called NEMP (nuclear EMP). EMP radiation from nuclear bursts can seriously damage or impair the function of electronic systems, devices, circuits, and components thousands of miles away. In nature, this pulse is very roughly comparable to the electromagnetic fields radiated from a nearby lightning stroke (LEMP). MIL-STD-461C contains several test methods which are intended to address EMP (RS05, CS10, CS11, CS12, and CS13). RS05 (a free-field radiated susceptibility test) provides the anticipated high altitude EMP field (Figure 1),[1] and the following short analysis indicates the potential coupling of this field into a typical aircraft cable (approximately 0.5 meters in length, 0.05 meters off the aircraft ground).

$A = 1$	A = area, given number is arbitrary.
$B = 1$	B = magnetic field, given number is arbitrary.
$t = 5 \cdot 10^{-9}$	Rise time of RS05 EMP pulse
$E = 4.5 \cdot 10^{4}$	Value of RS05 EMP pulse at end of rise time or 90% of peak amplitude
$Z_0 = 120 \cdot \pi\ 377$	Impedance of free space
$H = \dfrac{E}{Z_0}$	Relationship between magnetic and electric fields, H = ampere-turns/meter
$\mu_0 = 4 \cdot \pi \cdot 10^{-7}$	Permeability of free space
$B = \mu_0 \cdot H = 1$	Magnetic field from magnetic intensity given in Webers per square meter
$\phi = A \cdot B$	Magnetic flux, given in Teslas ($1\ \text{Weber/m}^2 = 1\ \text{Tesla} = 10^4$ Gauss)
$\dfrac{d\Phi}{dt} = A \cdot \dfrac{dB}{dt}$	Voltage, given area and time varying magnetic field
$V_{coupled} = \dfrac{d\Phi}{dt}$	Coupled voltage into cable
$\dfrac{dE}{dt} = Z_0 \cdot \dfrac{dH}{dt}$	
$\dfrac{d\Phi}{dt} = A \cdot \dfrac{\mu_0}{Z_0} \cdot \dfrac{dE}{dt}$	Substitution of variables into equation

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Therefore,

$$V_{coupled} = \frac{\mu_0}{Z_0} \cdot A \cdot \frac{dE}{dt}$$
$$= \frac{4 \cdot \pi \cdot 10^{-7}}{377} \cdot (0.025) \cdot \left(\frac{4.5 \cdot 10^4}{5 \cdot 10^{-9}}\right)$$
$$= 749.98$$

However, one must remember that there is an image plane correction (worst case) of x 2, so the actual answer is 2 x 749.98 = 1499.96 volts.

It is worth mentioning that the calculated coupled voltage in the above example is the same magnitude as CS12 (conducted susceptibility test #12) given in 461C Notice 2, Part 2, which is a bulk cable injection test.[2]

APPROACH

One approach to EMP protection is to install terminal protection devices (TPDs) on the motherboard (backplane). Figure 2 shows the general layout for a TPD. The longest wire, the internal I/O cable, is approximately 5 inches in length. This cable is typically 0.5 inches (average) away from the side of the chassis, and the backplane is elevated 0.5 inches off the unit chassis. Therefore, an approximation of the loop area for the transmit loop (source) is:

Circumference (c) = $5 \cdot 2 + 2 \cdot 0.5$	Inches
Circumference = 11	Inches
$Loop_c = 2 \cdot \pi \cdot r$	Inches
$r = \frac{Circumference}{2 \cdot \pi}$	Inches, approximation of circular loop radius
r = 1.751	Inches
$Loop_{area} = \pi \cdot r^2$	Square inches
$Loop_{area} = 9.629$	Square inches, area of transmit loop used in analysis

An advantage of this approach is that motherboard-mounted TPDs are significantly less expensive than other alternatives, such as custom connectors. A disadvantage is that the EMP current is allowed to enter the enclosure chassis before being shunted to ground. Allowing the EMP current to enter the chassis introduces the risk that the energy could couple around the TPDs and cause damage to the internal electronics. This requires careful and judicious placement of components and isolation of internal cables and traces. The following analysis assesses the risk of damage. This analysis does not take into account upset, although it is worth mentioning that the onset of susceptibility is typically on the order of 20 dB down from the minimum damage threshold.

For this analysis, generic X3T9.2 (representing a small computer system interface) SCSI Type II circuits will be utilized. The circuit design to be analyzed is shown in Figure 3.[3]

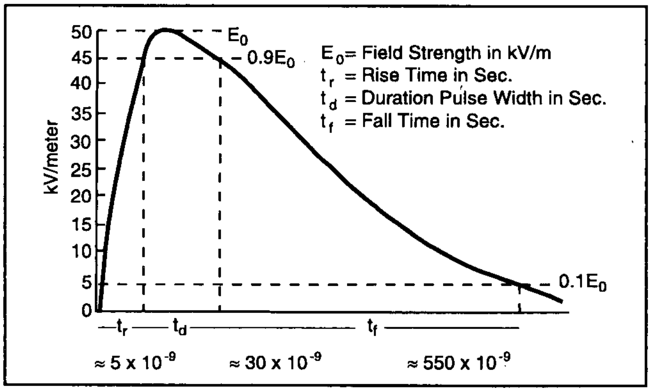

***Figure 1**. Limit for RS05.*

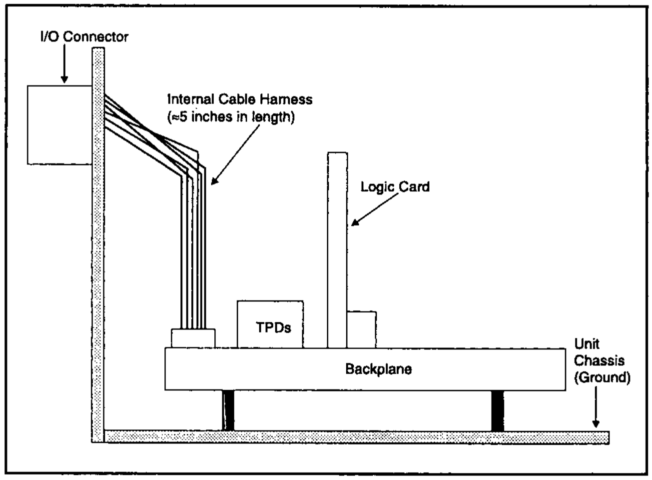

***Figure 2**. General Internal Layout for TPDs.*

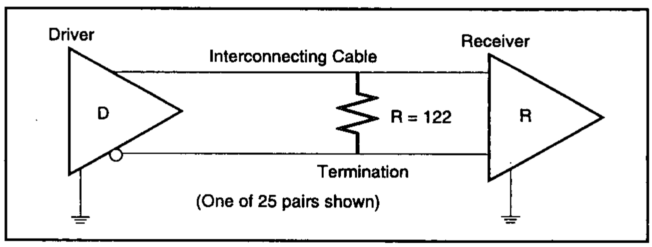

***Figure 3**. Design of SCSI Type II Circuit.*

RS05

The major issues associated with the protection of circuits to the requirements of RS05 are the calculation of the coupled currents and voltages. One method of calculating the coupled currents was developed by the Naval Surface Warfare Center (NSWC).[4] The approach was one in which the peak induced current could be obtained from the solution of the following integral based on the incident electric field and the cable geometry:

$$I_{short\ circuit}\,(peak) = h\left(\frac{c\tau}{a}\right) \cdot \int_0^{t_2} E(t) \cdot dt$$

Where

$I_{short\ circuit}$ (peak)	= Peak short circuit current
E(t)	= Incident electric field parallel to the cable
c	= Speed of light (3 x 10^8 meters/sec)

a = Cable radius

$t_2 = \frac{\ell}{2 \cdot c}$ where ℓ is the cable length (typically)

$\tau = \frac{t_2 - t_1}{2}$ t_1 is the rise time of the field

$h = \left(\frac{c\tau}{a}\right)$ = function representing the impulse response of the cable current on an infinite cable length.

For MIL-STD-462 testing, the typical cable length is given as 2 meters for the typical test setup. Therefore,

$$t_2 = \frac{\ell}{2 \cdot c} = \frac{2}{2 \cdot 3 \cdot 10^8}$$
$$= 3.33 \cdot 10^{-9} \text{ seconds}$$

A typical twisted shielded pair has an outside diameter of approximately 0.245 inches (0.0062 meters). The calculation of the bulk cable current based on this approach results in I_{peak} = 11.24 A; this is the peak current induced on the cable from the incident field.

CS11/CS12

The major issues associated with the protection of circuits to the requirements of CS11/CS12 are the calculations of the coupled currents and voltages. The determination of the coupled voltage/current levels from the free field (RS05) levels is not required, as CS11/CS12 provide the current versus frequency to be applied to the bulk cable. Therefore, the major issues associated with the protection of circuits to the requirements of CS11/CS12 are the same as for CS10/CS13, the determination/calculation of the pin/wire coupled currents and voltages.

One approach to calculating the pin/wire coupled energy from the bulk cable currents is to use the manufacturer's shielding effectiveness information, and common sense. Specifically, for a single wire, the coupled current to the wire is the bulk cable current specified in MIL-STD-461 if there is no shield.

If there is a shield, the current is decreased by the shielding effectiveness (manufacturer's data or measured data). If there is more than one wire in the cable, then the assumption can be made that the current is evenly distributed across all wires in the bundle. Hence a division by the total number of wires (N) is appropriate. Some utilize the square root of N as a more conservative estimate of the current per wire since the current usually is not a perfectly even distribution. If there is more than one shield, then the shielding effectiveness of the second shield has to be taken into account using either prior experience, manufacturer's data, or measured data. Table 1 presents the current on the outer shield or pin/wire as defined by MIL-STD-461C, Notice 2, Part 2.

Given that the example (SCSI Type II circuit) has no gross shield, and that the shield of the shielded twisted pair typically would provide approximately 10 to 20 dB (assumed here to be 15 dB), and that the number of shielded twisted pairs is 25, then the calculated I_{wire} for CS12 is as shown in Table 2. As can be seen from the calculated pin/wire currents, the requirements of CS10/CS13 are more severe than the bulk cable levels translated to pin/wire levels. Therefore, this analysis will utilize the EMP requirement given in MIL-STD-461C Notice 2, Part 2, CS13 (single/multiple wire injection test); and the EMP test signals will be calibrated using MIL-STD-462, Notice 6, CS13 calibration techniques.[5,6] Concepts for this approach were gleaned from private correspondence.[7] CS12 was not chosen for this activity as its calculated coupled levels were less than the CS13 requirements, and CS13 has defined calibration techniques. CS13 provides this information as part of the test method, thereby allowing concentration on the main subject at hand, namely an alternate approach for TPD placement. The analysis approach for this activity is depicted in Figures 2, 4, and 5 and outlined as follows:

- The source voltage of the EMP generator is determined using CS13 calibration techniques.
- The current injected onto the enclosure interface cables is determined using the source voltage and assuming the TPD (TransZorb®) is in breakdown mode.
- The radiation inside the enclosure chassis is determined by modeling the radiating circuit as a magnetic dipole (loop).
- The voltage induced into the victim circuit is determined using Faraday's Law.
- Induced energy is determined by integrating peak power over time. The induced energy is compared to the electronics damage thresholds to determine damage (design margin).

It should be noted that since the CS13 method involves direct injection to the individual wire/pin, the external cable shields are not considered in this analysis.

	I_{wire}		I_{wire}	
MHz	**CS11**	**CS12**	**CS10**	**CS13**
0.01	0.16	0.05	0.16	0.05
0.1	1.6	0.5		0.5
0.63	10.0		10.0	
1.0	10.0	5.0	10.0	5.0
10.0	10.0	5.0	10.0	5.0
50.0		5.0		5.0
100.0	1.0	2.0	1.0	2.0

***Table 1**. Current in A on Outer Shield as Defined by MIL-STD-461C, Notice 2, Part 2.*

$\frac{I_{wire}}{10^{-3}}$	
MHz	**CS11**
0.01	1.25
0.1	12.57
1.0	125.74
10.0	125.74
50.0	125.74
100.0	50.29

***Table 2**. Individual Wire Current in mA.*

SECONDARY EMP ANALYSIS

The following provides the analysis and the results for the given example using MathCad 4.0.

VARIABLE DEFINITION AND FREQUENCY COUNTER ESTABLISHMENT

$N = 1,2...6$ Counter

$j = -\sqrt{-1}$ Defining j as a negative j for ease of calculation

$\lambda_N = \frac{(3 \cdot 10^8)}{freq_N}$ Wavelength for each frequency indexed to N, the counter

$\beta_N = \frac{(2 \cdot \pi)}{\lambda_N}$ Phase shift constant (radians/meter)

$\omega_N = 2 \cdot \pi \cdot freq_N$ Angular frequency

$\mu = 4 \cdot \pi \cdot 10^{-7}$ Absolute permeability (air) (Henrys/meter)

$$Freq_{MHz_N} = \frac{freq_N}{(1 \cdot 10^6)}$$

In Table 3, $FREQ_{MHZ_N}$ depicts the analysis frequency in MHz. Note that all tables in this analysis are indexed to these frequencies.

$Freq_N$ (Hz)	$Freq_{MHz_N}$
10,000	0.01
100,000	0.1
1,000,000	1.0
10,000,000	10.0
50,000,000	50.0
100,000,000	100.0

***Table 3**. Frequency Equivalents.*

$Freq_N$ (Hz)	Z_{source_N}
10,000	100
100,000	106.25
1,000,000	112.5
10,000,000	118.75
50,000,000	123.119
100,000,000	125.0

***Table 4**. Source Voltage at Designated Frequencies.*

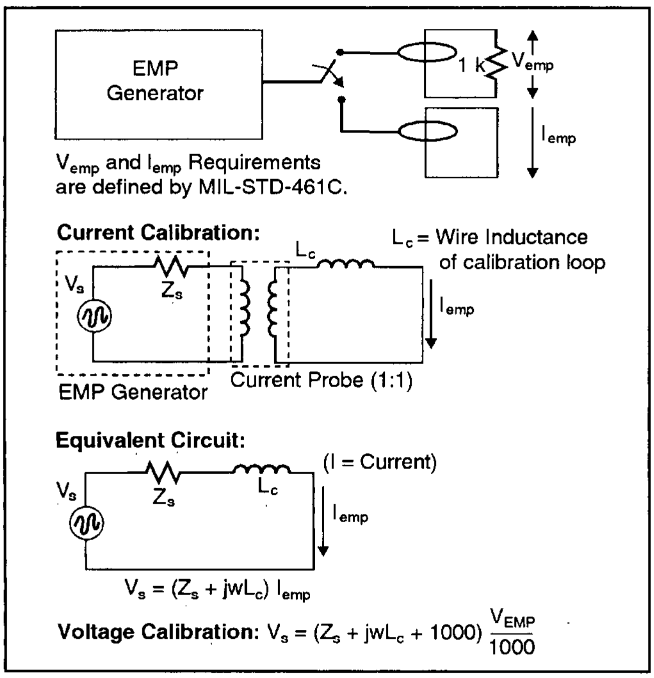

***Figure 4**. CS13 Calibration.*

SOURCE VOLTAGE OF EMP GENERATOR

$L_{calibration\ loop} = 4.1 \cdot 10^{-7}$ Inductance of the calibration loop (18 inches @ 0.023 µH/in)[8]

$Z_{source_N} = \frac{25 \cdot \log_{10}(freq_N)}{4} + 75$ Source impedance of the transient generator (Table 4)

Note that the source impedance of the transient generator may vary with frequency. The above equation is an arbitrary impedance relationship used only to demonstrate the concept. The actual impedance of the transient generator may be 100 ohms, required for CS10 and CS11, called out in MIL-STD-462, Notice 5, as the same generator would probably be used for all of the EMP tests. [9]

The CS13 requirement specifies current and voltage calibrations. The source voltage for each calibration (current and voltage) requirement will be evaluated (Tables 4 and 6).

Current Calibration

The current with respect to frequency, I_{EMP_N}, is defined by MIL-STD-461C, Notice 2, Part 2, CS13 (current calibration) (Table 5).

$$Vs_{current_N} = (Z_{source_N} + j \cdot \omega_N \cdot L_{calibration\ loop})\, I_{EMP_N}$$

$Vs_{current_N}$ is given in Table 6.

Voltage Calibration

The voltage with respect to frequency, V_{EMP_N}, is defined by MIL-STD-461C, Notice 2, Part 2, CS13 (voltage calibration) (Table 7).

$$VS_{voltage_N} = (Z_{source_N} + 1000 + j \cdot \omega_N \cdot L_{calibration\ loop}) \cdot \frac{V_{emp_N}}{1000}$$

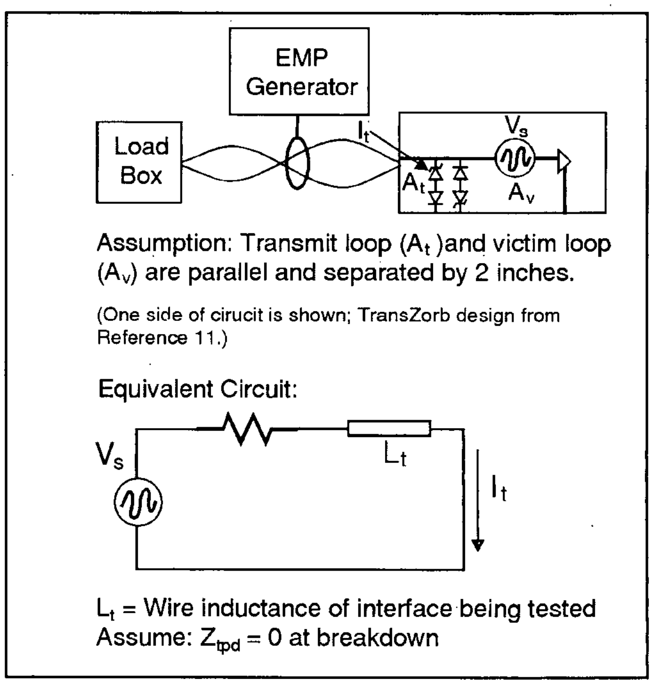

***Figure 5**. EMP Test Model.*

Source voltage of the transient generator during voltage calibration in accordance with Figure 3 is given in Table 8.

MIL-STD-461C requires that the higher of the current and voltage calibrations be applied as the test signal. Therefore, Vs_N is defined as the worst-case composite of the current and voltage calibrations (Table 9).

INJECTED CURRENT DETERMINATION

The worst case current occurs if the load is a short circuit. When a TransZorb is in an avalanche breakdown mode, its impedance is low and can be modeled as a short circuit.[10,11]

$L_{\text{test circuit}} = 1 \cdot 10^{-6}$
Inductance of circuit being tested, 3 feet of AWG-#22.[8]

$$I_{\text{injected}_N} = \frac{Vs_N}{(Z_{\text{source}_N} + j \cdot \omega_N \cdot L_{\text{test circuit}})}$$

Current injected into the interface circuit being tested in accordance with Figure 5 is given in Table 10.

INTRA-BOX RADIATION FROM SECONDARY EMP CURRENTS

The EMP current travels on the interface cable from the input connector to the motherboard (Figure 2), then to the TransZorb (TPD). After being shunted to ground by the TransZorb, the EMP current returns via the chassis. Since the radiating circuit has a low impedance (Z_{source} < 150 ohms) and the circuit geometry is small compared to the wavelength (100 MHz = 3 m), the antenna model used will be a magnetic loop. (The model assumes that the electric field coupling will be small relative to the magnetic field coupling.)[12]

$I/O_{\text{backplane}} = 5.0$
This is the length of internal cablefrom the I/O connector to the backplane plus reasonable length of the TPD placement to chassis ground, in inches.

$A_{\text{transmit loop}} = 9.63 \times 0.0254^2$
The area of the radiating (transmit) loop is 9.63 square inches (Figure 2).

$r = 2 \cdot 0.0254$
The victim circuit is assumed to be anaverage of 2 inches from the radiating circuit (worst case).

$m_N = -I_{\text{injected}_N} \cdot A_{\text{transmit loop}}$
Magnetic flux referenced to frequency

H_r = H-field
Component propagating away from the loop (max H_r at $\theta = 0$).

$$H_{r_N} = \frac{[j \cdot 2 \cdot \omega_N \cdot \mu \cdot m_N \cdot \beta_N{}^2]}{(4 \cdot \pi \cdot 377)} \cdot \left[\frac{1}{(\beta_N)^2 \cdot r^2} - \frac{j}{(\beta_N)^3 \cdot r^3}\right] \cdot e^{-(j \cdot \beta_N \cdot r)}$$

The following calculation of H_θ is presented as complete, but generally H_r is larger than H_θ (Table 11).

$$H_{\theta_N} = \frac{[j \cdot 2 \cdot \omega_N \cdot \mu \cdot m_N \cdot \beta_N{}^2]}{(4 \cdot \pi \cdot 377)} \cdot \left|\frac{j}{(\beta_N \cdot r)} + \frac{1}{(\beta_N)^2 \cdot r^2} - \frac{j}{(\beta_N)^3 \cdot r^3}\right| \cdot e^{-(j \cdot \beta_N \cdot r)}$$

$H_r > H_\theta$ with maximum radiation from the loop at $\theta = 0$ (on Z-axis). Therefore, the rest of the analysis will be performed using H_r.

INDUCED VOLTAGE INTO VICTIM CIRCUIT

For this analysis, A_{victim} is the area of the victim loop (4 sq. inches assumed). V_{noise} is the noise voltage developed in a loop by an incident B-field. Thus,

$$A_{\text{victim}} = 4 \cdot 0.0254^2$$
$$B_N = \mu \cdot H_{r_N}$$
$$V_{\text{noise}_N} = j \cdot \omega_N \cdot B_N \cdot A_{\text{victim}}$$

Induced voltage values are given in Table 12 and Figure 6.

ENERGY INDUCED BY SECONDARY EMP EFFECTS

The damping factor Q ± 5, is defined by MIL-STD-461C. Z_{SCSI} is the bus input impedance. P_{p_N} is the peak power induced into the SCSI receiver by secondary EMP effects (Table 13). Thus,

$$Pp_N = \frac{(V_{\text{noise}_N})^2}{Z_{\text{scsi}}}$$

$$W_N = P_{p_N} \int_0^{\infty} e^{\left[\frac{(-\pi \cdot \text{freq}_N \cdot t)}{Q}\right]} dt$$

$$W_N = \frac{(Q \cdot Pp_N)}{(\pi \cdot \text{freq}_N)}$$

where
$Q = 20$
$Z_{\text{scsi}} = 122$

CMOS DAMAGE THRESHOLDS

The CMOS damage threshold has to be determined for comparison to the coupled energy to determine survivability of the circuits to the coupled secondary power. To determine the CMOS damage threshold, the Wunch model will be utilized using the lower 95% values for MOS parts from the EMP assessment handbook.[13]

$A_{in} = 0.0063$
$A_{out} = 0.00042$
$A_{pwr} = 0.038$
$B_{in} = 0.483$
$B_{out} = 0.819$
$B_{pwr} = 0.543$

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$\tau_N = \dfrac{freq_N}{2.4}$ = Conversion of EMP frequency (sine wave) into equivalent square wave frequency

$T_N = \dfrac{1}{\tau_N}$ = Period associated with the equivalent square wave frequency (seconds)

INPUT PIN DAMAGE CALCULATION

To calculate input pin damage,

$A = A_{in} = 0.006$
$B = B_{in} = 0.483$
$P_{input_N} = A \cdot (T_N)^{-B}$

In Table 14, P_{input} is in watts for the input, and represents the required input power to cause failure (damage). Thus,

$$\frac{P_{input_N} \cdot T_N}{10^{-6}} =$$

the micro-joule equivalent for the input

OUTPUT PIN DAMAGE CALCULATION

To calculate output pin damage,

$A = A_{out} = 4.2 \cdot 10^{-4}$
$B = B_{out} = 0.819$
$P_{output\ N} = A \cdot (T_N)^{-B}$

Table 15 gives P_{out} in watts for the output, which represents the required power at the output to cause failure (damage) and the micro-joule equivalent for the output.

POWER PIN DAMAGE CALCULATION

To calculate power pin damage,

$A = A_{pwr}$
$B = B_{pwr}$
$P_{power_N} = A \cdot (T_N)^{-B}$

Table 16 gives values for power pin damage. P_{power} is in watts for the power input, and represents the required power at the power input to cause failure (damage). The micro-joule equivalent for the power input is also given.

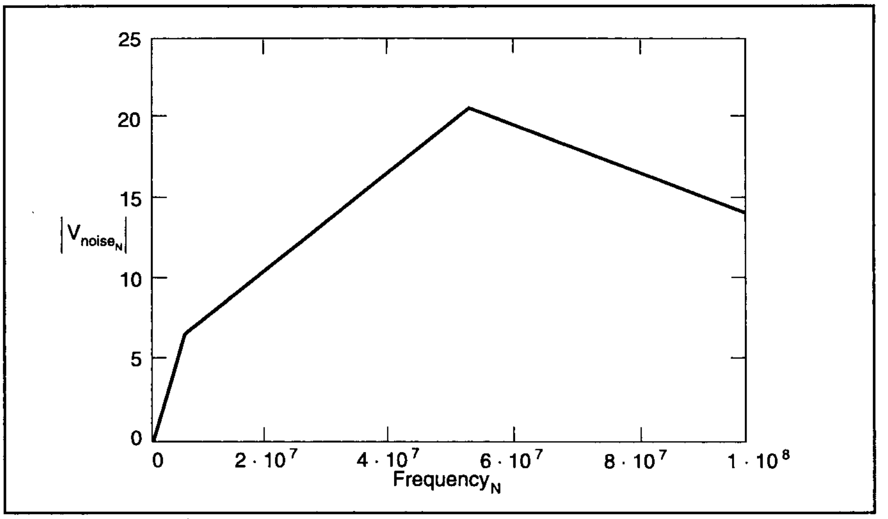

Figure 6. *Induced Voltages vs. Frequency.*

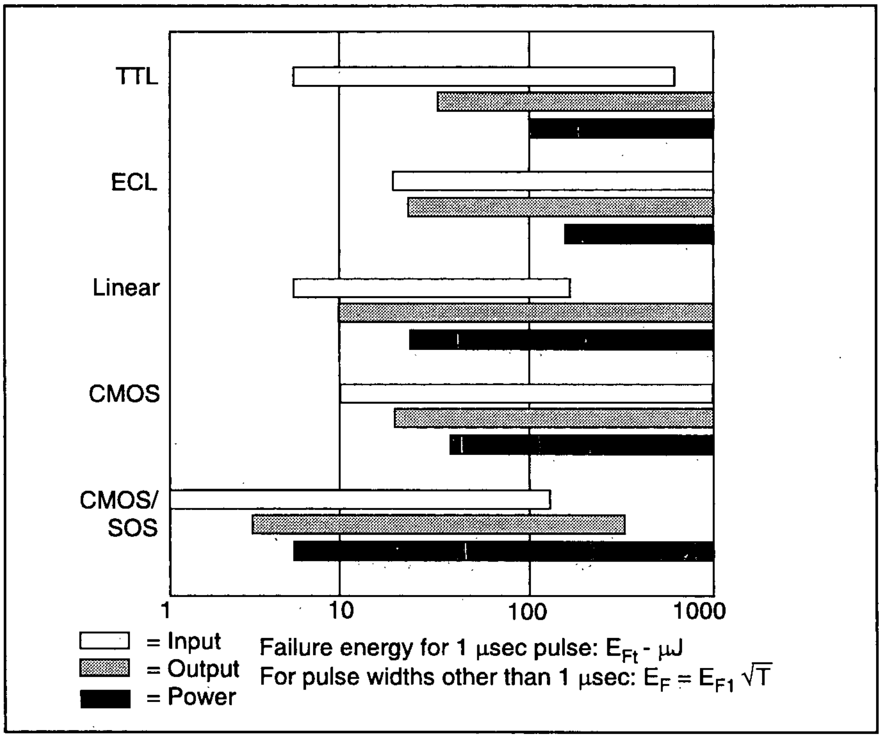

Figure 7. *Microcircuit Pulse Injection/EMP Burnout.*

CONCLUSIONS

The failure levels and coupled power are shown in Table 17. It would appear that the worst-case energy failure is at 0.724 µj, which is approximately 1 µj at 100 MHz. The worst-case coupled energy levels (50 MHz) for damage appear to be approximately 2.3 dB (1.68 times) smaller than the 100 MHz level, or approximately 0.43 µj coupled energy vs. 0.72 µj damage level. Table 18 and Figure 7 provide typical burnout data for different microcircuits and devices, for comparison purposes, to the levels calculated in this example.[14]

The results of this worst-case analysis indicate that the SCSI parts will not be damaged by the secondary EMP energy, and hence will survive. Although there is not a large design margin established via this example, it has been demonstrated that nonconnector embedded TPDs are potential alternatives to traditional approaches in some applications.

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$Freq_N$ (Hz)	I_{EMP_N}
10,000	0.05
100,000	0.5
1,000,000	5.0
10,000,000	5.0
50,000,000	5.0
100,000,000	2.0

***Table 5**. Current at Designated Frequencies.*

$Freq_N$ (Hz)	$Vs_{voltage_N}$	$Vs_{voltage_N}$
10,000	5.5	$5.5-1.288i \cdot 10^{-4}$
100,000	55.313	55.313-0.013i
1,000,000	556.251	556.25-1.288i
10,000,000	559.523	559.375-12.881i
50,000,000	565.24	561.559-64.403i
100,000,000	230.824	225-51.522i

***Table 6**. Absolute Values and Imaginary Values for Source Voltage of the Transient Generation at Designated Frequencies.*

$Freq_N$ (Hz)	V_{EMP_N}
10,000	5
100,000	50
1,000,000	500
10,000,000	500
50,000,000	500
100,000,000	200

***Table 7**. EMP Voltages at Designated Frequencies.*

$Freq_N$ (Hz)	$Vs_{voltage_N}$	$Vs_{voltage_N}$
10,000	5.5	$5.5-1.288i \cdot 10^{-4}$
100,000	55.313	55.313-0.013i
1,000,000	556.251	556.25-1.288i
10,000,000	559.523	559.375-12.881i
50,000,000	565.24	561.559-64.403i
100,000,000	230.824	225-51.522i

***Table 8**. Absolute Voltage and Imaginary Voltage Values at Designated Frequencies.*

$Freq_N$ (Hz)	Vs_N	$Vs_{current_N}$	$Vs_{current_N}$	Vs_N
10,000	$Vs_{voltage_1}$	5.0	5.5	5.5
100,000	$Vs_{voltage_2}$	53.125	55.313	55.313
1,000,000	$Vs_{current_3}$	562.647	556.251	562.647
10,000,000	$Vs_{current_4}$	607.561	559.523	607.561
50,000,000	$Vs_{current_5}$	890.912	565.24	890.912
100,000,000	$Vs_{current_6}$	572.672	230.824	572.672

***Table 9**. Current and Voltage Calibrations.*

$Freq_N$ (Hz)	$I_{Injected_N}$
10,000	0.055
100,000	0.521
1,000,000	4.994
10,000,000	4.522
50,000,000	2.64
100,000,000	0.894

***Table 10**. Current Injected into Circuit.*

$Freq_N$ (Hz)	$\lvert H_{r_N} \rvert$	$\lvert H_{\theta_N} \rvert$
10,000	0.415	0.207
100,000	3.926	1.963
1,000,000	37.663	18.832
10,000,000	34.111	17.054
50,000,000	19.943	9.943
100,000,000	6.78	3.352

***Table 11**. H_I = H-field Component in the θ Direction. Max H_θ, at θ = 90 Degrees.*

$Freq_N$ (Hz)	$\lvert V_{noise_N} \rvert$
10,000	8.45310^{-5}
100,000	0.008
1,000,000	0.767
10,000,000	6.95
50,000,000	20.318
100,000,000	13.816

***Table 12**. Induced Voltages.*

$Freq_{MHz_N}$	$\lvert W_N \rvert$
0.01	$3.728 \cdot 10^{-14}$
0.1	$3.34 \cdot 10^{-11}$
1.0	$3.073 \cdot 10^{-8}$
10.0	$2.521 \cdot 10^{-7}$
50.0	$4.308 \cdot 10^{-7}$
100.0	$9.96 \cdot 10^{-8}$

***Table 13**. Calculated Energy Coupled Into The Circuit.*

$Freq_N$ (Hz)	P_{input_N}	$\frac{P_{input_N} \cdot T_N}{10^{-6}}$
10,000	0.353	84.705
100,000	1.073	25.758
1,000,000	3.264	7.833
10,000,000	9.924	2.382
50,000,000	21.592	1.036
100,000,000	30.179	0.724

***Table 14**. Input Pin Damage.*

$Freq_N$ (Hz)	P_{output_N}	$\frac{P_{output_N} \cdot T_N}{10^{-6}}$
10,000	0.387	92.911
100,000	2.552	61.245
1,000,000	16.821	40.371
10,000,000	110.881	26.611
50,000,000	414.298	19.886
100,000,000	730.897	17.542

***Table 15**. Output Pin Damage.*

$Freq_N$ (Hz)	P_{power_N}	$\frac{P_{power_N} \cdot T_N}{10^{-6}}$
10,000	3.51	842.442
100,000	12.255	294.131
1,000,000	42.789	102.693
10,000,000	149.393	35.854
50,000,000	357.989	17.183
100,000,000	521.59	12.518

***Table 16.** Power Pin Damage.*

$Freq_{MHz_N}$	$\frac{\lvert W_N \rvert}{10^{-6}}$	$\frac{P_{input_N} \cdot T_N}{10^{-6}}$	$\frac{P_{output_N} \cdot T_N}{10^{-6}}$	$\frac{P_{power_N} \cdot T_N}{10^{-6}}$
0.01	$3.728 \cdot 10^{-8}$	84.705	92.911	842.442
0.1	$3.34 \cdot 10^{-5}$	25.758	61.245	294.131
1.0	0.031	7.833	40.371	102.693
10.0	0.252	2.382	26.611	35.854
50.0	0.431	1.036	19.886	17.183
100.0	0.1	0.724	17.542	12.518

***Table 17.** Failure Levels and Coupled Power.*

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Type	Minimum Energy (Joules)
Audio Transistors	5×10^{-3}
Switching Transistors	5×10^{-5}
Digital Integrated Circuit	8×10^{-5}
Analog Integrated Circuit	8×10^{-6}
FETs	1×10^{-1}
SCRs	3×10^{-3}
Vacuum Tubes	1.0
Diodes	
Microwave	1×10^{-7}
High Speed Switching	2×10^{-5}
Rectifier	6×10^{-4}
Tunnel	5×10^{-4}
Relay	2×10^{-3}
Microammeter	3×10^{-3}

Table 18. *Minimum Observed Energy to Cause Burnout.*

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