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LIGHTNING PROTECTION OF FULL AUTHORITY DIGITAL ELECTRONIC SYSTEMS

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ABSTRACT

Modern electronic systems are vulnerable to transient and they now provide safety critical functions such as full authority digital control units for fly by wire aircraft. There has been some confusion as to the precise specifications for these transients, however, within Europe there has been a preference for pin injection of the transient, line by line at the full threat. Given this the use of Transient Suppression Devices is essential, but with the magnitude of the threats these consume considerable volume and weight budgets.

Of the traditional suppression technologies available diodes have gained the widest acceptance, however, they lack the current handling capacity to meet existing threat levels. The development of high speed fold back devices where, at a specified voltage, the off state resistance switches to a very low on state one has provided the equivalent to a semi-conductor spark gap. The size of the technology enables it to be integrated into connectors or interconnection cables .

To illustrate the performance the technology has been developed to meet the Lightning Protection requirements for FADEC units within aeroengines. This calls for Level 5 transients to be handled on a pin by pin basis and at temperatures between -65°C and 125°C. For this application the technology was packed at 0.050" spacing within connectors inside the equipment. Results are given of the performance of the technology to the waveforms at Level 4 and 5.

Work was also carried out to study switching behaviour with the new waveform 5, the 500us, 10kAmp pulse applied to cable assemblies. This test enabled all the switches in a connector to be fired simultaneously.

INTRODUCTION

Modern electronic systems based on semi-conductor technology are very vulnerable to transient voltages or currents. As these devices are fabricated with smaller and smaller features with higher and higher densities then their vulnerability to external transients increases. Today with micron size features and millions of circuits per device, burn out levels can be lower than one milli joule of energy. Dielectric punch through

can occur with voltages of only a few hundred volts for nanosecond time periods.

These electronic systems now fulfil key rolls in modern aircraft, they often provide safety critical functions such as full authority digital control units in fly by wire aircraft. The number of these systems in each application is also increasing rapidly resulting in high packing densities which in turn leads to increased system to system interaction. Finally these systems are now being located in exposed regions of the aircraft outside of any Faraday cage where they are both more vulnerable to a strike and the resultant transient more severe.

The new draft Advisory Circular (SAE AE4L-87-3 Rev B 1989), Airbus Industries Specification ABD0007 and the RTCA/DO-160C Document on lightning protection of flight critical/essential electrical and avionic systems demonstrate the growing industry concern for aircraft safety as the airframe structures and electronic systems evolve. The airframe designer or system integrator must use whatever techniques of cable routing, shielding and grounding necessary to ensure that the actual transients induced in the aircraft wiring do not exceed transient control levels. The equipment designer has to ensure that the electronics can tolerate the assigned transient level.

Various suppression technologies have been used in the past and diodes have gained strong support because of their high speed, consistent performance and reliability. However, they lack the current handling capacity unless they are very large. The development of high speed fold back technology has lead to the equivalent of a semi-conductor spark gap. They still operate with the same very high speed of diodes but have a very low on-state resistance. The result of the combination of high speed and low on state resistance is that any overshoot is limited and that the current handling capability is very high. This occurs since the energy of the pulse is not dissipated within the device but into the ground. This enables very small devices to be fabricated which can be directly integrated into the interface connectors.

The application of this type of technology has lead to the development of connectors capable of protection electronics from the most severe transients directly applied to each interface line .

TRANSIENT THREAT LEVELS

There is still considerable confusion as to how these assigned transients should be applied to the equipment wiring interface. There are three basic techniques , ground injection, bulk cable injection and pin injection and these were reviewed by Wiles [1]. If one is developing a protection technology one cannot be anything but specific about the capability of the device. One has to assume the worst possible case unless each application is studied separately. This means

that the technology should be capable of withstanding the most severe transient applied to the smallest possible cable i.e. one wire. It is not possible to make assumptions as to likely current sharing and coupling and hence assuming full threat by each waveform on each line is extremely conservative but essential given the large numbers of unknowns within a design.

This has been the stance taken by Airbus Industries in their specification where pin injection of both the long and short waveform as well as the oscillatory waveform are specified at the assigned threat level. A final aspect of the testing is that none of the specifications call for the testing to be carried out at anything other than room temperature. Given the extreme temperature sensitivity of most semi-conductor technology this is a major oversight.

To qualify transient protection devices it is necessary to test them with each of the waveforms at the maximum specified level, line by line and across the full specified temperature operating range. Further the number of operations that the device can withstand has to be substantially above the equipment specification. This is because given the number of lines in one FADEC (>450) and the required reliability one would have to specify at least one order of magnitude above the equipment specification. A further requirement would be to specify that any let through transient would have to have an energy content below the damage threshold of the equipment and the let through voltage spike was below any dielectric punch through level

A general specification for a FADEC unit in a critical zone for example in a engine could be summarized as follows:-

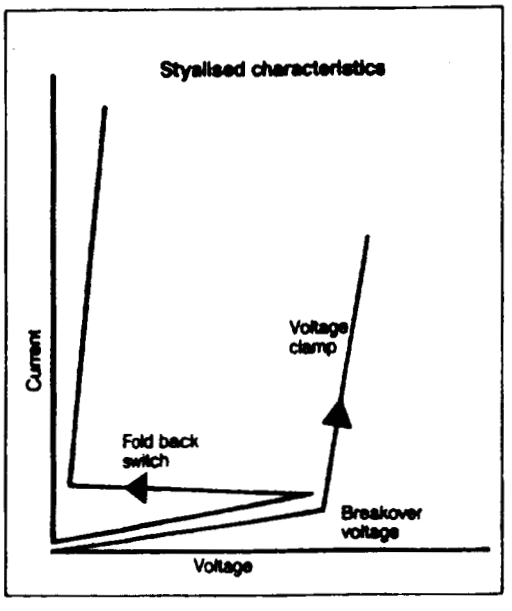
LIGHTNING TRANSIENT PROTECTION REQUIREMENTS			
TRANSIENT	Wfm 2	Wfm 3	Wfm 4
WAVESHAPE	6 us	1-50 MHz	70 us
PEAK CURRENT	320	128	320
PEAK VOLTAGE	1600	3200	1600
TEMPERATURE RANGE	-65 TO 125° C		
NUMBER OF OPERATIONS	100 BOTH POLARITIES		
LET THROUGH ENERGY	< 1 milli JOULE		
VOLTAGE SPIKE	< 500 VOLTS		

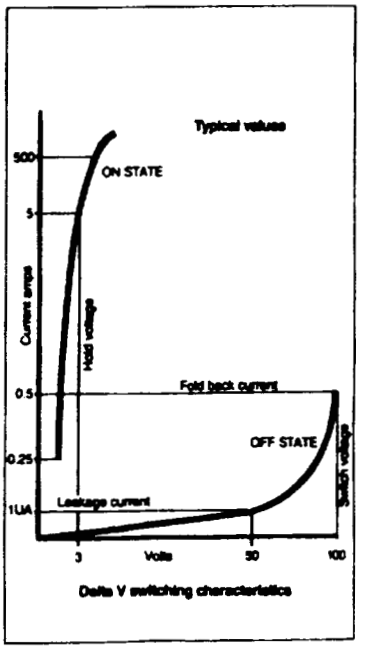
A further factor that should always be considered is the other parts of the EMC specification that the equipment would have to meet. For example a military aircraft would also have to meet EMP requirements and civilian aircraft the latest HIRF requirements of RTCA/DO 160C Chpt. 20. It is certainly the trend for the airframe manufacturers to assume the aircraft wiring gives no protection against all these EMC threats and to place the total requirements on the equipment supplier. In which case the protection devices are almost certainly working in conjunction with filters.

PROTECTION TECHNOLOGIES

There are various basic technologies used in transient protection and they are characterized into two distinct families, voltage clamps and voltage foldback. The two types are shown, however, there are variations on these basic curves and the author discussed these in previous papers [2,3] Typical voltage clamps have been Zener diodes and Metal Oxide Varistors whilst fold back technologies have included Gas Discharge Tubes and Fold Back Diodes.

Each of these suppression technologies have been used in the past and diodes have been preferred because of their fast response time (< 1ns), consistent performance and high reliability. However, these acts as voltage clamps and they do not have the necessary current handling capability in an economically sized package. Fold back devices, because of their low on state resistance, have far higher current handling capabilities. The development of multi-layered thyristor technology provided the equivalent of a high speed semi conductor Gas Discharge Tube.





Protection Mechanism

The device under consideration is based on a four layer thyristor structure which gives a fold back crowbar type action which is voltage triggered. The switch has a high holding current which ensures reset after the transient has subsided. The initial action of the switch is the same as a Zener and hence one achieves a balance of their good points with those of a Gas Discharge Tube but without their disadvantages. The switch has the same rapid response as Zeners to fast voltage transients and at low currents acts as a similar voltage clamp. Higher currents initiates the fold back action and the voltage across the switch falls to a low level.

The switch acts as a shunt element which is voltage triggered and to ensure bidirectional operation, consists of two switching elements. The switch can sink very high levels of current in the low voltage "on" state. Because of this the active area is efficiently used enabling small devices to be made. A normal 100 volt Zener under 40 amps pulsed conditions might develop 4 kW whereas with a foldback switch the "on" voltage may only be 3 volts giving 120 W. This greatly reduces the heat that has to be dissipated and reduces the junction temperature. This also results in the power derating with temperature being much less than for Zeners.

Delta V 'off state' electrical properties

Parameter	Test conditions	Units	Minimum	Typical	Maximum
Leakage current I off	+/- 50V 25°C 125°C	micro amps	 0.001 0.5	 0.020 1.0	 1.0 10.0
DC withstand voltage	I off <1uA	Volts	50	50	50
Capacitance coef	1Khz	pF	100	140	200

Delta V switching characteristics

Parameter	Test conditions	Unit	Minimum	Typical	Maximum
Switch voltage Vt	0.1/10 us pulse 500 V	Volts	80	100	100
Switch speed Tsw	As Above	nano-secs	0.5	1.0	2.0
Fold back time Tfb	As Above	nano-secs	100	250	500
Charge transfer Qt	As Above	nano-C	200	500	1000
Fold back current Ifb	As Above	Amps	0.5	0.5	0.5
Hold current Ihold	As Above	Milli amps	150	250	400
Characteristics	Sine Wave	Bipolar			

Specification Levels

The testing and qualification of the electronic system was carried out in a series of steps. The system was a Full Authority Digital Electronic Control for an Aeroengine. As such the specified threat level was 5 except that for waveform 4 this was reduced to 4. Since this appears somewhat contradictory test were carried out at level 4 & 5 with waveform 4.

The basic procedure adopted was that of the Airbus Specification ABD007, i.e. pin injection. There is one serious drawback to this and that is only one line is tested at the same time whilst in the real world it would be assumed that the transients would appear on all the lines at approximately the same time period. Indeed the author reported in an earlier paper [4] that during whole aircraft testing that the waveform that appeared on each pin was a composite of all three waveshapes giving a combination of high frequency oscillatory components as well as a wide pulse. Because of this experiments were set up with more than one pulse generator to drive several lines simultaneously at the peak specified current.

A further test added was an evaluation with the new waveform 5 of the SAE advisory circular i.e. 500 us width at 10 kA. This was a ground injection test onto the screens of the cable and this test certainly excited all lines simultaneously.

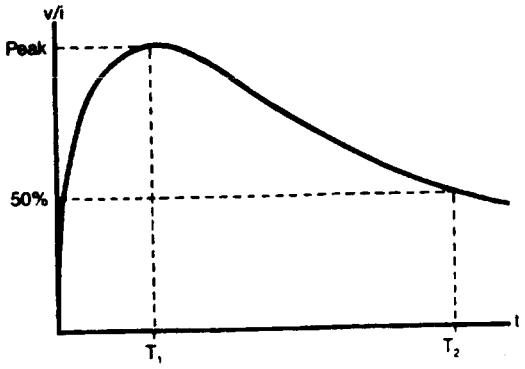
All waveforms and test levels specified are those described in the SAE AE4L 87-3 Rev B 1989 advisory circular.

Test Methodology

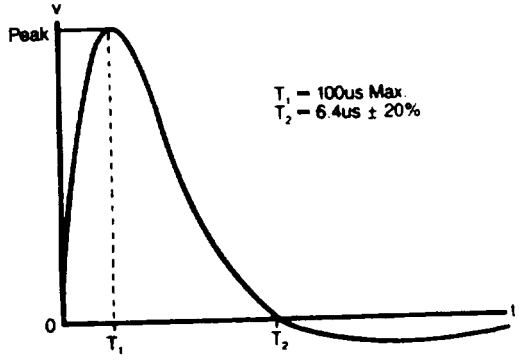
The equipment was complicated with several input connectors with the number of protected lines > 500. The technology was packaged into two product forms, the Raychem MTC (Trade Mark) flat modular connector system and a Splice unit designed to be fitted into the interconnection from connectors to the electronics. There were also filters on most lines which were in the connectors interfacing directly with the aircraft wiring. Because of this the testing was carried out in separate blocks.

Component Test. This was the simplest test and involved testing individual connectors, pin by pin at the full threat of each waveform. In each case the voltage transient remaining on the line was recorded as well as the energy it dissipated into a 50 ohm system. These tests could also be carried out at a range of temperatures between -65 and + 125^{o} C and also over a high number of operations.

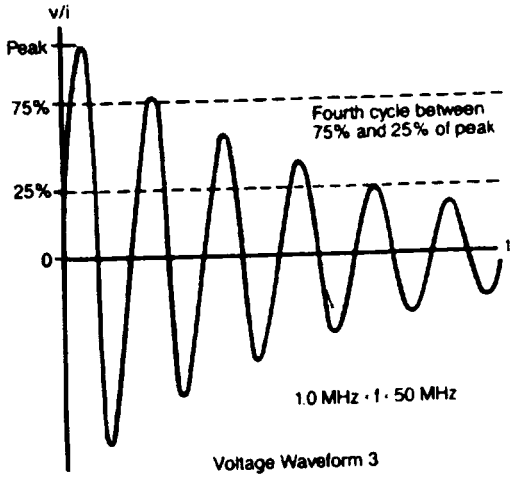
Box Interconnection Test. Here the filter connector was in place and the protection switch fitted to the interconnections within the box. Each input line was tested with each transient at the full threat level. The tests were carried out at room



Current Waveform 1	T1 = 6.4 us ± 20% T2 = 70 us ± 20%
Voltage Waveform 4	T1 = 6.4 us ± 20% T2 = 70 us ± 20%
Current Waveform 5A	T1 = 40 us ± 20% T2 = 120 us ± 20%
Current Waveform 5B	T1 = 50 us ± 20% T2 = 500 us ± 20%



Voltage Waveform 2



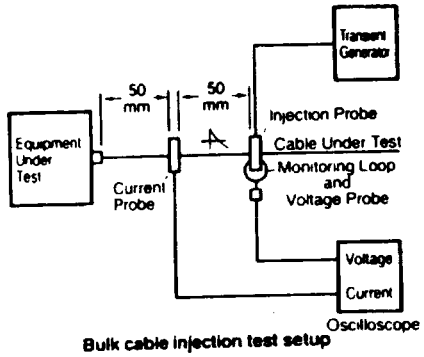
Voltage Waveform 3

Idealised induced voltage and current waveforms

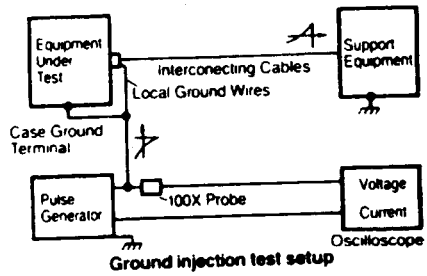
Level	Waveforms			
	2 Vp/Ip	3 Vp/Ip	4 Vp/Ip	5 Vp/Ip
1	50/10	100/4	50/10	N/A
2	125/25	250/10	125/25	N/A
3	300/60	600/24	300/60	300/100
4	750/150	1500/60	750/150	750/1000
5	1600/320	3200/128	1600/320	1600/3000 to 20.000

Vp = Peak Open Circuit Voltage Line-to-Ground
Ip = Peak Short Circuit Current On A Line

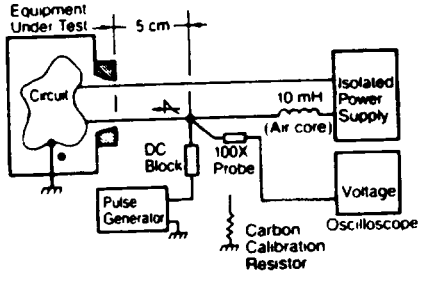
Suggested ETDL Voltage and Current Levels



Bulk cable injection test setup



Ground injection test setup



● External equipment grounds should be tied to case for these tests

Pin injection test setup

temperature and the resulting voltage across each filter pin was monitored as well as at the board level. The functionality of the board mounted components were evaluated at the end of the tests for damage or degradation of performance.

In this series covering 37 input lines, tests were carried out using waveform 2 at level 5 on a total of 3 lines using three separate generators. The lines were chosen that interfaced with the same board area.

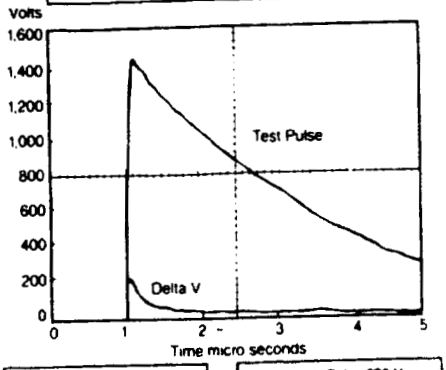
Waveform 5 Testing. This test did not represent part of the original specification. However, it was considered essential to demonstrate that the protected harness which consisted of individual screened twisted pairs should be tested. More details of the test and the method are given in a separate paper to be given by this author in this conference. Basically a current waveform of 500 us width and of 10 kA peak amplitude was ground injected into the protected cables and the resultant voltage transients on each pin monitored. A total of 10 twisted pairs were tested giving 20 lines which was one half of a hardened connector. The performance of each switch element was re-evaluated at the end of the test.

TEST RESULTS

Box Interconnection Test. The resulting waveshapes were distorted by the presence of the filters and the system LC parameters. During testing at component level there were high voltage transients (2 - 300 V) when the high frequency waveform 2 with its 100 ns rise time was used as well as with the 10MHz oscillatory waveform 3. With these tests the filter reduced these significantly and the most severe test was the waveform 4 the slow pulse. In all cases the voltage across the filter pins never exceeded 150 Volts. The transient let through energy was recorded and never exceeded 250 micro Joules. Since no damage occurred to any of the board mounted components it was concluded that these transients were below their susceptibility levels.

Waveform 5 Test. The result is shown with the other transients and it is interesting to note that the voltage induced without protection was 200 volts on each line which with a protected line caused the switch to fire at 100 volts and operate in the normal fashion. There was no other damage to the switches with this test.

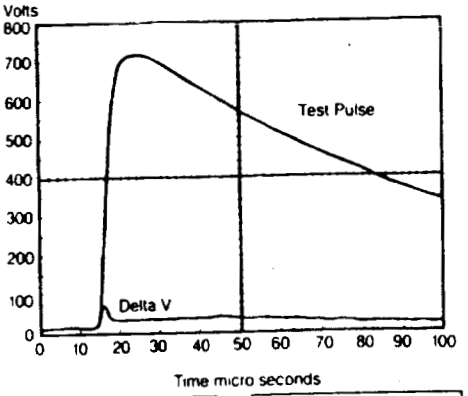
DELTA V PROTECTION LIGHTNING Wfm 2



Test Pulse 1500 V 300 A
2 us Width
50 ns Rise

Delta V Pulse 230 V
Let Through Energy
into 50 Ohms 1 mJ

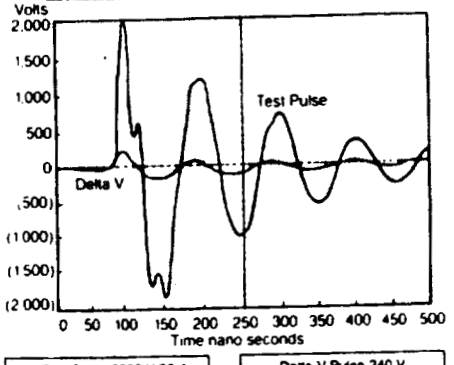
DELTA V PROTECTION LIGHTNING Wfm 4



Test Pulse 750 V / 150 A
70 us Width
5 us Rise

Delta V Pulse 85 V
Let Through Energy
into 50 Ohms 1 mJ

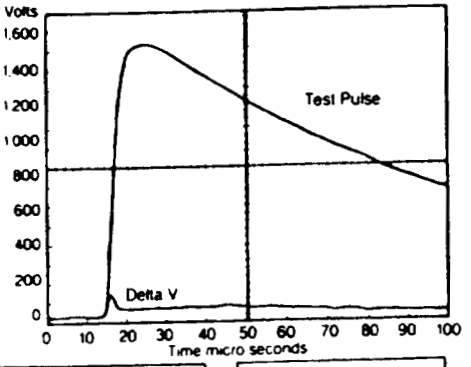
DELTA V PROTECTION LIGHTNING Wfm 3A



Test Pulse 2000 V 80 A
Damped Sinusoidal
10 MHz Frequency

Delta V Pulse 240 V
Let Through Energy
into 50 Ohms 0.3 mJ

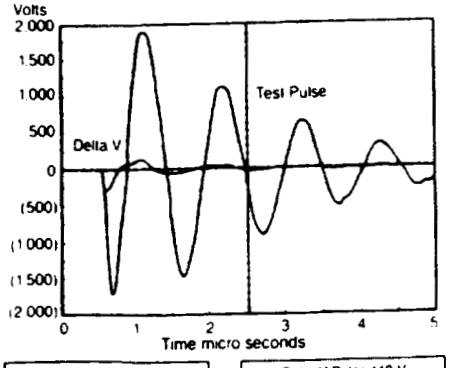
DELTA V PROTECTION LIGHTNING Wfm 4



Test Pulse 1500 V 300 A
70 us Width
5 us Rise

Delta V Pulse 140 V
Let Through Energy
into 50 Ohms 1 mJ

DELTA V PROTECTION LIGHTNING Wfm 3B

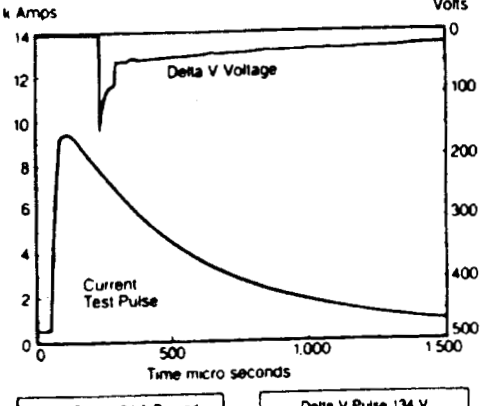


Test Pulse 2000 V 80 A
Damped Sinusoidal
1 MHz Frequency

Delta V Pulse 140 V
Let Through Energy
into 50 Ohms 0.1 mJ

DELTA V PROTECTION LIGHTNING Wfm 5B

Ground Injection into Cable Shield



Test Pulse 10 kA Ground
Injected 500 us Width
Current in Cable Braid

Delta V Pulse 134 V
All conductors of Cable
Commoned Short Drive End

Component Test. The results are graphically represented for each waveform at level 5 (waveform 4 is also given at level 4). The results represented are the 100th. shot on each line and at room temperature. To obtain clear performance data like this it is necessary to use very short test leads, when testing at elevated temperatures the longer test leads causes some difficulties in accurate measurements

In all cases the switches were able to perform to specification across the full temperature operating range.

CONCLUSIONS

This test programme demonstrated that it is possible to protect electronic equipment interfaces to the full threat currents of each waveform on a pin by pin basis.

It was demonstrated that current levels of 320 amps with a 70 us wide pulse could be handled even at 125° C for a number of operations an order of magnitude above the specified number of 10.

The performance of multiple firing of a number of switches was demonstrated including with the new proposed waveform 5.

It is recognized that this type of testing represents a very severe case and is applicable to component testing where the specific application is not known whilst for know systems bulk cable injection would be preferable to pin injection.

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