

LIGHTNING TESTING AT THE SUBSYSTEM LEVEL

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ABSTRACT

Testing at the subsystem or black box level for lightning hardness is required if system hardness is to be assured at the system level. The often applied philosophy of lightning testing only at the system level leads to extensive end of the line design changes which result in excessive costs and time delays. In order to perform testing at the subsystem level two important factors must be defined to make the testing simulation meaningful. The first factor is the definition of the test stimulus appropriate to the subsystem level. Application of system level stimulations to the subsystem level usually leads to significant overdesign of the subsystem which is not necessary and may impair normal subsystem performance.

The second factor is the availability of test equipment needed to provide the subsystem level lightning stimulation. Equipment for testing at this level should be portable or at least movable to enable efficient testing in a design laboratory environment. Large fixed test installations for system level tests are not readily available for use by the design engineers at the subsystem level and usually require special operating skills.

The two factors, stimulation level and test equipment availability, must be evaluated together in order to produce a practical, workable test standard. The neglect or subordination of either factor will guarantee failure in generating the standard. It is not unusual to hear that test standards or specifications are waived because a specified stimulation level cannot be accomplished by in-house or independent test facilities. Determination of subsystem lightning simulation level requires a knowledge and evaluation of field coupling modes, peak and median levels of voltages and currents, bandwidths and repetition rates.

Practical limitations on test systems may require tradeoffs in lightning stimulation parameters in order

to build practical test equipment. Peak power levels that can be generated at specified bandwidths with standard electrical components must be considered in the design and costing of the test system. Stimulation test equipment and test methods are closely related and must be considered a test system for lightning simulation.

A non-perfect specification that can be reliably and repeatedly applied at the subsystem test level is more desirable than a perfect specification that cannot be applied at all.

SUBSYSTEM LEVEL TESTING BENEFITS

Why test at subsystem or black box level? Why not let the system test qualify all the subsystem boxes? Subsystem testing provides two important benefits.

First - In most cases subsystem testing saves money by ensuring that the system tests will be successful. When failure of subsystems occur during system testing, the cost of redesign and rework is escalated by a factor to ten (10) times the cost of correcting a problem identified during subsystem test (Figure 1). In fact an even more ideal situation exists when testing can be performed at the bread-board level where costs to redesign are typically one tenth (1/10) the cost of redesign at the subsystem level.

The designer who depends on system tests alone to qualify a subsystem is facing costs one hundred (100) times greater for redesign at this level over redesigns at the board level. Testing only at system level is a gamble with the odds stacked against the subsystem designer.

Second - Subsystem performance can be characterized and defined more completely for various stimulus levels. The subsystem should be tested to full threat level or even over threat levels. The

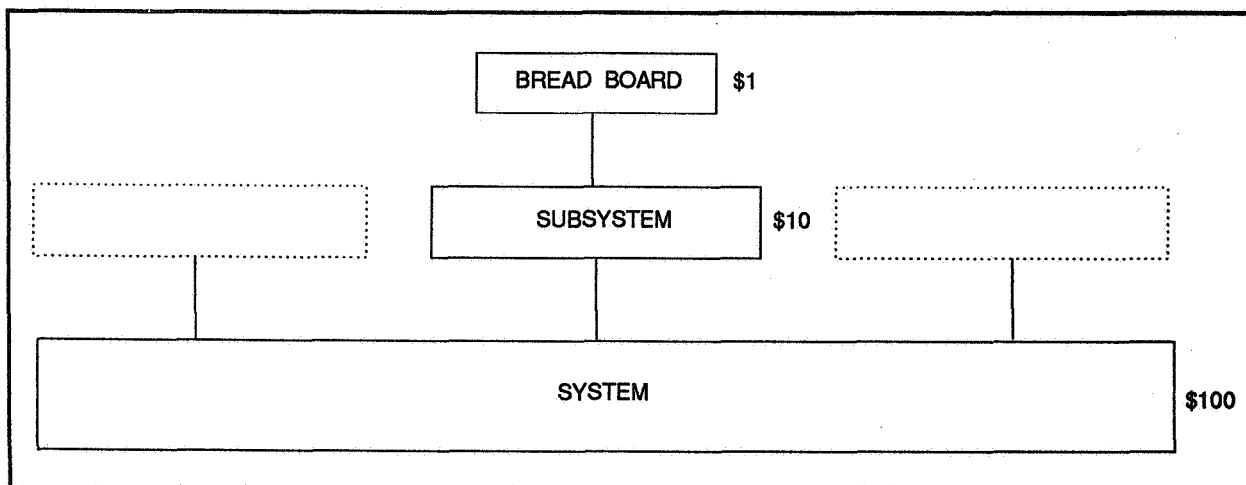


Figure 1. Test Levels.

threshold of failure can be accurately measured when the test generator can produce reduced levels as well as the full threat level. It is desirable to test at full threat level rather than at a reduced level with linear scaling to full threat level since subsystems seldom react in a linear manner except over narrow ranges at low stimulus levels.

There is typically interaction between subsystems because they share a common power supply, have a common database and have interconnections. When a massive failure occurs at system level test it is important to know which subsystem started the failure chain. The subsystem which is the source of failure and which is the victim is often difficult to identify. If threshold levels are known for each subsystem, the failure mode and propagation paths can be easily identified and corrected.

An additional benefit arises from the testing of multi-purpose or generic subsystems. Once the response of the subsystem to specific waveforms and levels is known, the response to other waveforms can be accurately predicted, thereby reducing or eliminating the testing required when the subsystem is utilized in other systems having different system test parameters.

DEFINING SUBSYSTEM LIGHTNING STIMULUS

The task of translating system level lightning stimulus into subsystem stimulus is not a simple task. Although certain models of lightning waveforms for

direct and near strikes have been defined, it has been observed that each year the lightning model becomes faster and more intense (Figure 2). Which-ever model is used, the system response which is the subsystem stimulus must be defined on the basis of frequency, duration, levels, and coupling modes acquired from full scale models in full threat lightning simulators.

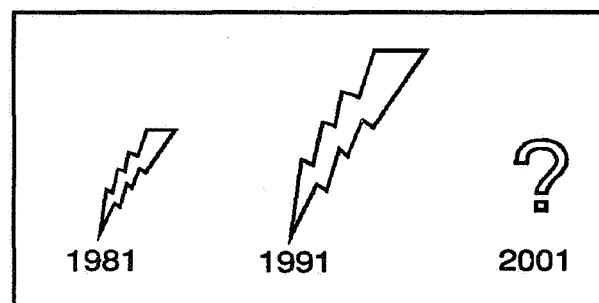


Figure 2. Lightning Stimulus.

Therefore, the criteria for defining the subsystem stimulus is the waveform stimulus that is coupled from the system to the subsystem. An example of coupled waveform stimulus can be found in MIL-STD-461C. The EMP test requirement is defined by tests specified as RS05, CS10 and CS11 for Naval equipment and CS12 and CS13 for Air Force equipment. The RS05 requirement duplicates the EMP field which is a double exponential of 50 kV per meter (Figure 3). This stimulus is used at the system level. The effect of the system stimulus is to couple damped sinusoid currents with a bandwidth of approximately 10 kHz to 100 MHz into the subsystem. The stimulus for subsystem tests CS10, CS11, CS12 and CS13 is

therefore a group of six damped sinusoid pulses at frequencies from 10 kHz to 100 MHz (Figure 4).

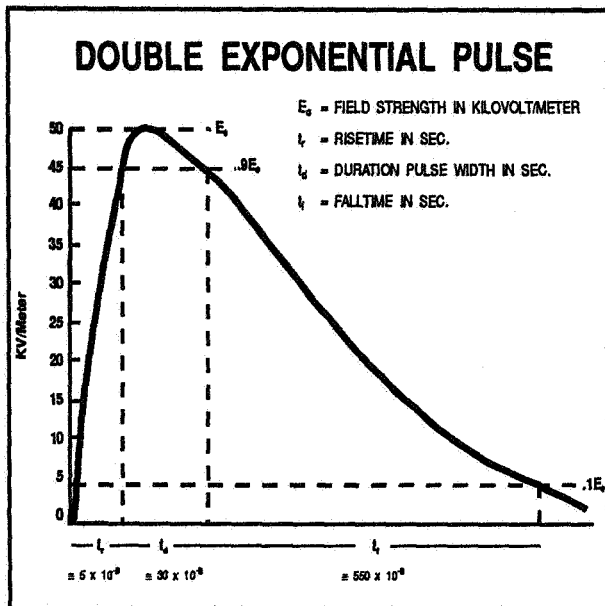


Figure 3. EMP System Waveform MIL-STD-461C RS05.

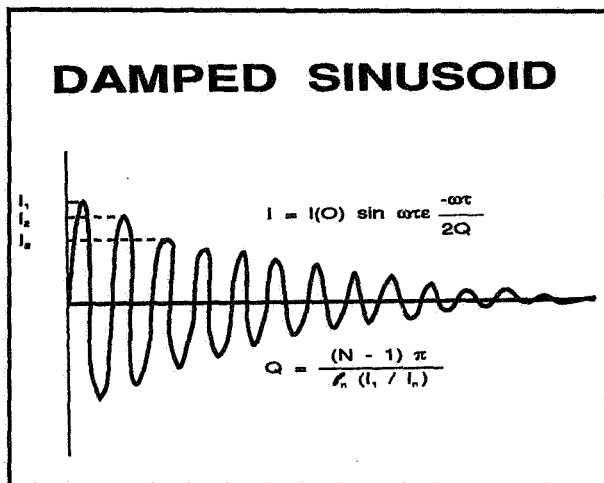


Figure 4. EMP Subsystem Waveform MIL-STD-461C CS10, 11, 12, 13.

Attempts have been made to define the lightning stimulus through various specification and advisories such as DO-160, Boeing Specs, SAE AE4L, FAA AC 20-136 and various modification of these documents. The range of waveforms include single pulse, multi-pulse and multiple bursts of double exponential and damped sinusoid waves (Figures 5, 6, 7). The levels for the various zones have been defined although with some confusion.

The purpose for the various waveshapes and levels is not adequately described in the specification and standards so it is not possible to substitute equivalent waveshapes when test equipment is not available to generate the specified waves. All too often the tests are waived when the exact waveform is not available. The use of equivalent test waveforms is an area that has not been rigorously pursued. Empirical data may suggest that a peak current or voltage and a total energy requirement is sufficient to simulate a particular threat. In this instance the test waveforms may be a rectangular pulse, a double exponential or damped sinusoid of equal energy waveforms having the same peak current. It is interesting to look at the relationship between different rise times for a fixed fall time pulse as shown in Figure 8. What appears to be a minor change in rise time relates to a significant change in total energy. It cannot be emphasized enough that equivalence of waveforms requires detailed analysis. Another factor that may have to be considered is the rise time of the waveform. Nonlinear devices such as spark gaps may not conduct if the rise time is fast and the pulse duration short. In this instance consideration of the subsystem circuit design must be made before selecting an alternate test waveform. The best person to define circuit response to alternate waveforms is the designer. When testing is performed on the designer's turf, involvement of the design team is assured. There are no guarantees that equivalent waveforms will identify circuit failure modes 100% of the time. It has been reported in some tests that rectangular pulses of a given energy and peak value will not cause circuit failure, yet an equivalent damped sine wave test produces failures approximately 10% of the time. Figure 9 shows how the energy level of a damped sinusoid may be changed by varying the Q . This characteristic provides a convenient method of controlling pulse energy level.

Although alternate means of qualification may be through analysis or expert opinion, I maintain that one good test is worth a hundred expert opinions.

SUBSYSTEM TEST EQUIPMENT REQUIREMENTS

Test equipment acceptable for breadboard and subsystem testing must possess properties that are quite different from the test equipment used for system level tests. The obvious difference is that the subsystem test stimulus is not a reduced level of the

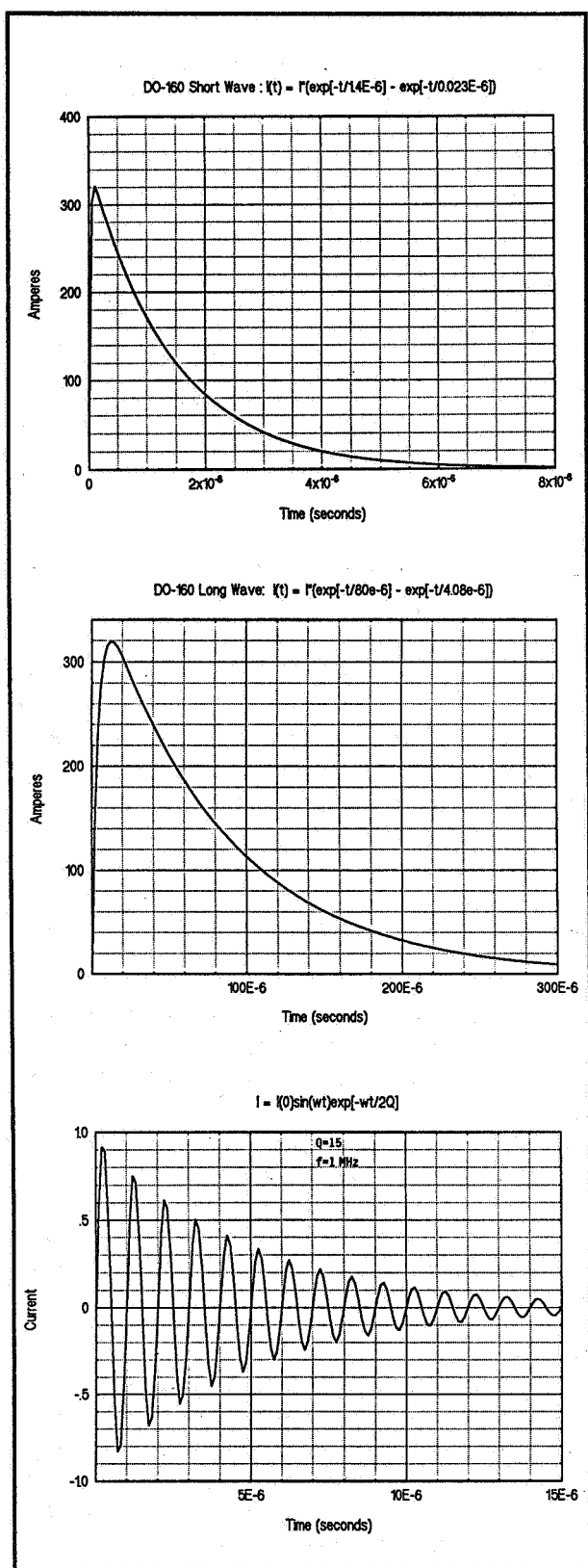


Figure 5. Single Pulse.

system test stimulus. It is critical that the system designer provide the subsystem designer with stimulus information early in the design cycle so that testing can begin as early as the breadboarding stage, but definitely not later than the subsystem test phase.

The subsystem test waveforms should be determined not only from equivalence considerations, but also from the availability of equipment and the waveforms and levels that can be produced by test generators suitable for use at the subsystem and breadboard levels.

Test equipment selection should be based upon the following characteristics:

- **Portability** - test equipment should come to the hardware to minimize set-up time and to be convenient for use by the design team.
- **Ease of Use** - design personnel should be able to operate the test equipment with minimal training. The test generators should be as familiar to the design group as an oscilloscope.
- **Controllability** - signal levels, polarities, source impedance, and frequencies and Q's for damped sinusoids should be variable.
- **Operationally Safe** - lethal voltages and energy levels are usually present in the test generators. Safety features such as interlocks, key switches, manual pulsing and standby modes should be incorporated.

Test equipment limitations should also be considered by the equipment selector. Test equipment weights are typically limited to 150 pounds for hand carry units by two people to about 1800 pounds for a console that can be wheeled through a standard doorway.

Transient generators which are suitable for generating the waveform types previously described are of store and dump design rather than of amplifier design. Using a low level waveshape generator and a power amplifier to generate the desired signal is not practical due to the high peak power required from the amplifier. A waveform requirement of 10 amp peak current through a 100 ohm load calculates to a peak power of 10 kW which could be supplied by an amplifier of about 5 kW average power. An amplifier of this size is very expensive and could only meet the

lower level waveform requirements. In comparison the store and dump design is an order of magnitude lower in cost for most of the higher level waveforms. In the store and dump generator design, energy is usually stored in a capacitor bank and then switched (dumped) into a pulse forming network. The switching element is either a spark gap or a high voltage relay. From practical and safety considerations the charging voltages are usually kept below 30 kV. The largest contributor to the weight of the generator is the energy storage capacitor or capacitors. High energy capacitors can store 8J/in³ or 488KJ/m³ at a weight of 10 lbs/KJ.

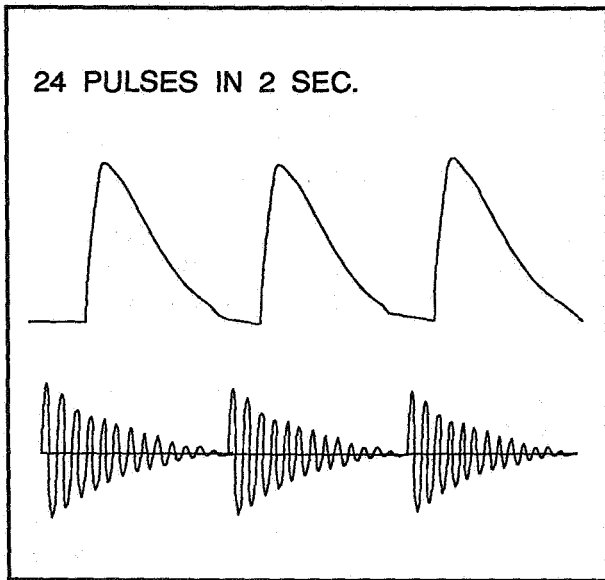


Figure 6. Multiple Pulses.

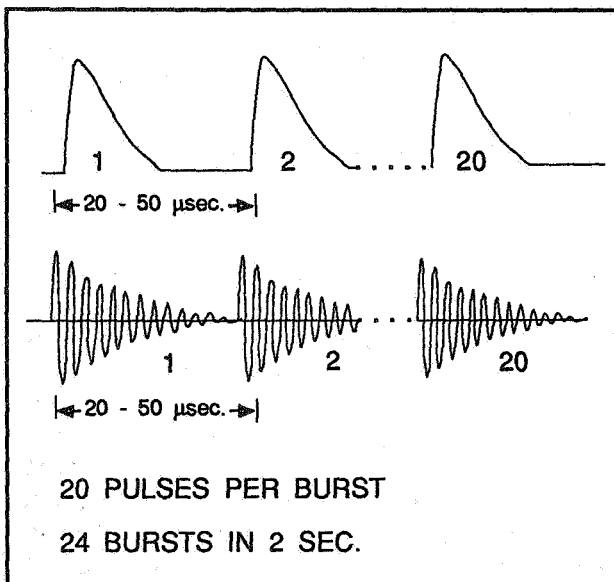


Figure 7. Multiple Bursts.

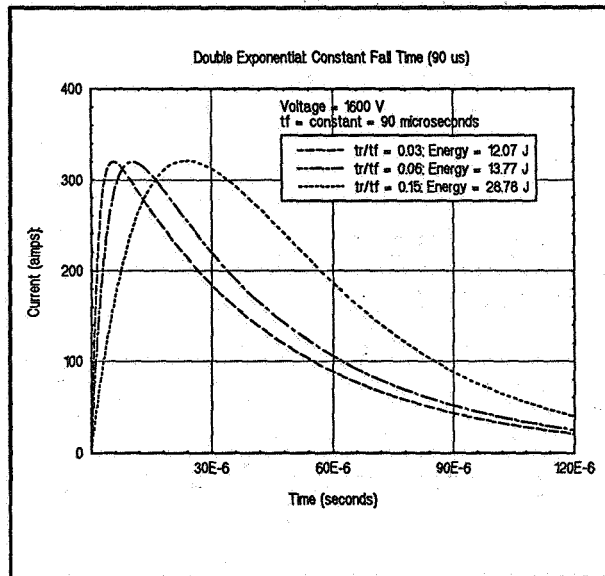


Figure 8. Time Constant-Energy Factors.

In order to provide a certain amount of flexibility in a test generator, a multiple of capacitors is preferred rather than a single large unit (Figure 10). Smaller capacitor units allow reconfiguration of the system to generate additional waveforms at low additional cost.

Multiple resistors also offer a certain amount of flexibility; however resistor changing is not usually a large expense.

Another consideration for test equipment is the type of waveform that is to be generated. The double exponential waveshapes usually require a charging voltage 15% than the generated voltage while the generation of a damped sinusoid requires a charging voltage 5% higher than the product of the peak waveform and "Q" (i.e., $1.05 \times V_p \times Q$). It is understandable why damped sinusoid generators cost more than exponential generators for equal peak voltage values.

The power requirement for the test generator is an important factor that usually is overlooked. To generate waveshapes by the charge and dump technique requires ten to twenty times the energy/power that is delivered to the subsystem under test. Although the peak power produced by the generator may be very high, the average line power requirements are within the range normally available in a design laboratory environment. A well designed transient test generator will produce waveforms that

will vary less than 10% in amplitude, rise and fall times and source impedance over the open circuit to short circuit range of the generator.

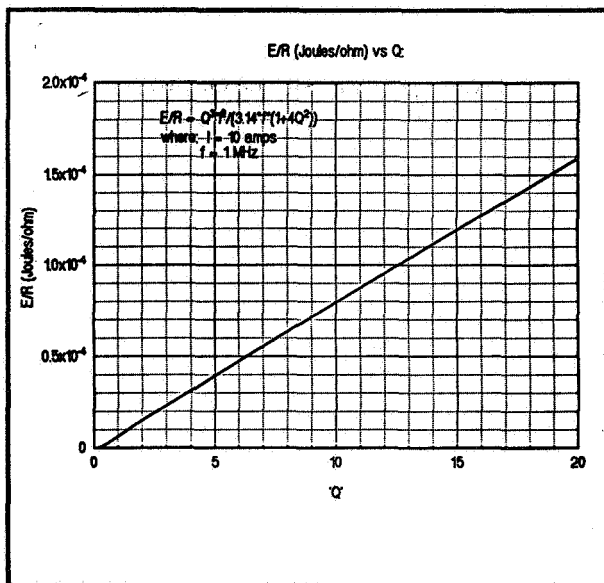


Figure 9. Q-Energy Factor.

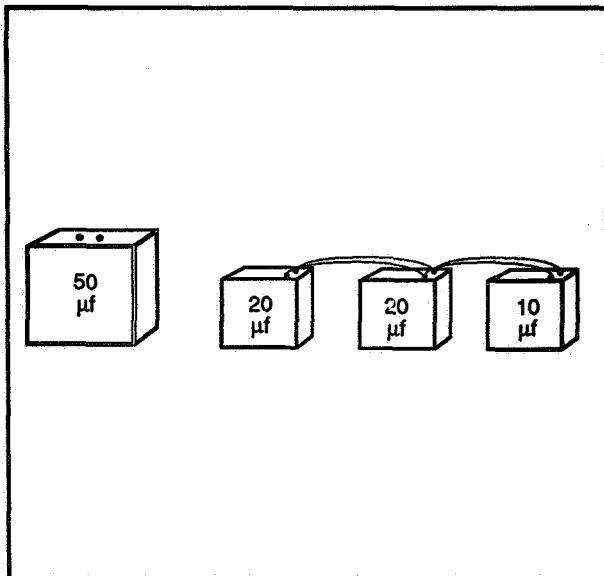


Figure 10. Modular Capacitor Design

CONCLUSIONS

The increasing application of sensitive electronics to subsystems that are susceptible to damage by lightning requires a new test philosophy. Testing at levels below system level is practical and offers potential cost savings that can approach several orders of magnitude.

Additional efforts are required to define the test stimulus that must be applied to subsystems so that test waveforms and equivalent test waveforms can be defined. Circuit designers must be included on the test team in order to ensure that the subsystems are properly stressed by equivalent waveforms.

Test equipment is available to produce damped sinusoids and double exponentials, the most commonly specified test waveforms. Selection of test equipment must be based on a knowledge of the signal generation technique and the variable features of the equipment. Test generators should be considered an essential instrument in the design lab.

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