SPECIFYING CONTROL OF IMMUNITY TO POWER LINE SWITCHING TRANSIENTS

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Abstract –Theoretical and experimental investigation reveals discrepancies between common spike immunity requirements and real switching transients. In particular, excessively low source impedance forces unnecessary over-design of EMI filters. A test method using a LISN and switched high current load is investigated as an alternate transient generator, and the effect on filter design is noted. This test method has dual advantages: a) it simulates real world transients in both amplitude, duration and source impedance, and b) it uses commonly available EMI test equipment and requires no expensive single application acquisitions.

Introduction: Conducted Transient Sources and Characteristics

Power bus transients may arise from load switching, lightning, electrical faults, or electromagnetic pulse (EMP). The original MIL-STD-461 CS06 was built around load switching, in that the spike magnitude was related to the nominal power voltage (although, as we shall see, the relationship is between current and spike magnitude, not nominal voltage). MIL-STD-461B/C were more interested in lightning and external fields coupling to the bus.[1] MIL-STD-461D and MIL-STD-462D replace CS06 with a purely bulk current injection requirement; thereby completing the move from switching transient to a field-to-wire coupling concern. Some types of programs, either military or commercial, may wish to retain a requirement based on immunity to switching transients. One example is the civilian space industry, which is only concerned with switching transients. Specification of switching transient emissions (requirement variously designated CE07, or TT01) are fairly accurate representations. EMC engineers routinely invoke CS06 to demonstrate immunity from switching transients. Space EMC engineers want to compare load induced switching transients (CE07, TT01) to the CS06 spike amplitude/duration. Figure 1 demonstrates that this is hardly an apples-to-apples comparison. The CS06 spike amplitude, duration and source impedance are wrong for modeling switching transients. The effects of spike voltage and duration are quite different on victims, and immunity to one type of spike is no guarantee of immunity to spikes of a different shape factor.

This paper examines the real nature of switching transients, and demonstrates shortcomings in the traditional EMC approach as regards switching transients. A highly controlled test set-up built of test equipment commonly available at any EMI test facility is developed. The new spike immunity requirement and test compares directly to load induced switching transients.

Investigation of Switching Transients

In Figure 1, transients are shown on a 28 Vdc bus, since it is easier to see the transient activity on a dc than an ac bus. However, the principles do not change. Inspection of Figure 1 reveals that CS06 positive and negative spike shape factors are symmetrical. Because the pulse generator is the same, the source impedance of the spike will also be the same for each spike polarity. The "real" transients show different characterisitics dependent on whether the spike is positive or negative in polarity. A theoretical and experimental investigation of real switching transients explains how and why they differ – in both amplitude, shape, and source impedance. They could hardly differ more!

How does a switching transient occur?

Figure 2 portrays the elements of a power distribution system. There is a power source, distribution wiring, and a load. The power source may be simplified to an ideal voltage source in series with a resistive and/or inductive impedance. The distribution wiring contributes both resistance and inductance. The load, at turn-on or turn-off, provides a rapid change of current through the power source and wiring impedance. This simple model ignores any capacitive effects, other than the load. Source parallel capacitance (especially in a dc supply) contributes to source stiffness, which may be easily modeled in the transient case by using a smaller series source impedance. Line-to-line or line-to-ground wiring capacitance is easily accounted for by modeling the distribution wiring as an inductance bypassed by a resistor. That is to say, a lumped element model of a transmission line, otherwise known as a line impedance stabilization network, (LISN). Figure 3 shows a model for both calculating and measuring

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switching transients. In Figure 3, the LISN models the distribution wiring impedance.

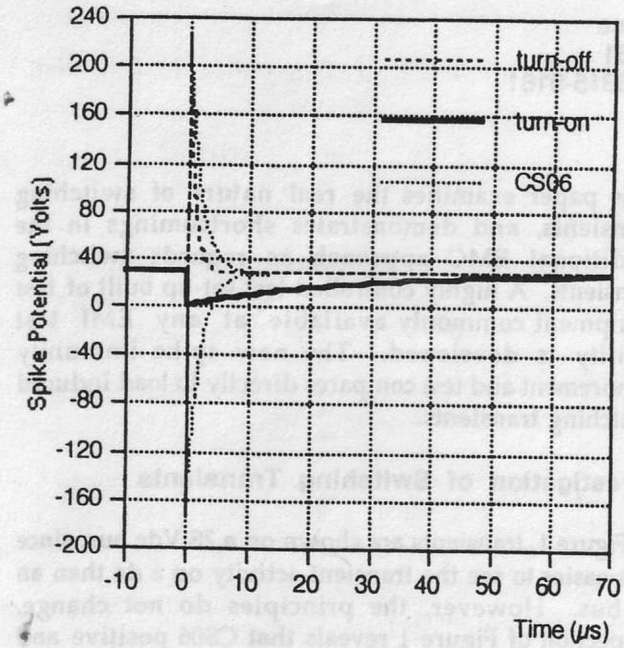

Figure 1: *Turn-on and turn-off transients envelopes: 28 Vdc bus, 50 µH, 50 Ω LISN, 7 Ω //100 µF load*

Because both the commercial and military EMC communities have settled on the 50 µH, 50 Ω LISN as a standard for measuring emission, this LISN has been arbitrarily selected to serve as a worst case model of wiring impedance. There is some intuitive rationale for the selection. Consider that the inductance of a wire above a ground plane is roughly one microhenry per meter (for typical geometries). Fifty microhenries would account for a wire length of 50 m, which is certainly a reasonable worst case for this type of power distribution (only feasible in metallic vehicles). A two-wire line will have an inductance about one-tenth of that of the wire-above-ground; therefore 50 µH represents about 500 m of wiring in a commercial setting. This is also a worst case model.

The transient generating mechanism is the switching on/off of the heavy load while the EUT is in steady-state operation. The LISN is the common impedance to the EUT and the switched load. Qualitative analysis of the on/off transients is now presented.

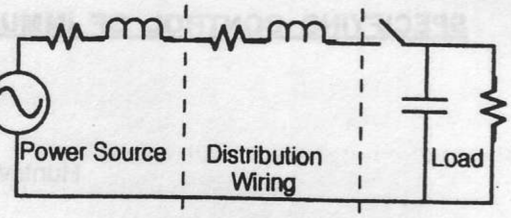

Figure 2: *Model of electrical power distribution system*

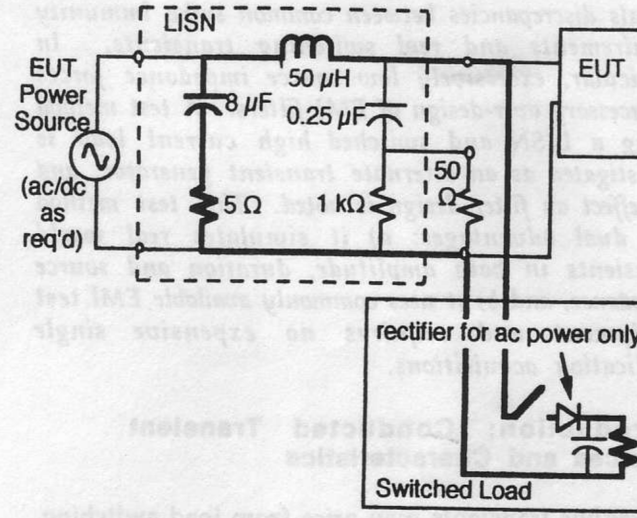

Figure 3: *Proposed spike generator: Heavy lines show flow of high current to spike generating load.*

The Turn-on, or Negative Going Transient

In Figure 3, the initial condition is that the load switch is open, no current is flowing in the switched load. The EUT is on and in steady-state operation. Upon switch closure current attempts to flow through the load. The LISN inductance opposes the change in the current by dropping the source voltage across itself. The LISN output voltage momentarily dips to near zero, and then gradually increases as the inductor relaxes. The transient time constant is a function of the LISN inductance and the RC time constant of the load, with oscillations due to inductor-capacitor energy transfer. The source impedance of the transient is the impedance of the switched load. In this investigation, the supply voltage is 28 Vdc, and the load bank is 7 Ω paralleled by 100 µF, drawing 4 Amps after the capacitor charges. (The rectifier diode and ac power source shown in Figure 3 are not applicable in this case.) The turn-on transient for these conditions is shown in Figure 1.

The Turn-off, or Positive Going Transient

In Figure 3, the initial condition is that the load has been on long enough to achieve steady-state 4 Amp dc current flow. The switch is abruptly opened. If the switch risetime is fast enough to be in the 50 Ω frequency domain of the LISN, and the LISN provides a reliable 50 Ω at all frequencies of interest above the knee frequency, the calculation is once again straightforward. (An extended frequency – 100 MHz – LISN is important for this test.)[2] The LISN 50 μH inductor tries to maintain the 4 Amp current flow through itself. It does this by raising the voltage at the output of the LISN relative to the input. (Incidentally, this phenomenon answers the oft-raised question about spike tests: "Does the specified spike amplitude include the line voltage, or is it superimposed on the line voltage?" The line inductance superimposes the spike voltage on the power line voltage, or it would not have the desired effect of maintaining the current through the inductance). If the inductor were the only element to consider, the spike induced by turning off the load would be infinite in amplitude. However, reality imposes line-to-line and other stray capacity which would tend to snub the spike. A benefit of the 50 Ω LISN is that the 50 Ω dummy load provides a stronger snubbing effect than any stray capacity, yielding repeatable, predictable spikes. Per our assumption, we are in the 50 Ω frequency domain of the LISN; then the spike voltage is just the switched current multiplied by 50 Ω. In our case, we should see a 200 Volt spike (50 Ω x 4 Amps). The time constant is independent of the load impedance, it has been switched out of the circuit. The time constant is the ratio of the 50 μH inductor and the 50 Ω dummy load, or one microsecond. The source impedance is 50 Ω. A qualitatively predicted waveform is shown in Figure 1.

It is interesting to calculate the spike amplitude, duration and source impedance as a function of a varying dummy load impedance. If the dummy load were, for instance, 5 Ω, then the spike amplitude (for the same switched 4 Amps) would be 20 Volts, the time duration would be 10 microseconds, and the source impedance would be 5 Ω. A figure of merit related to spike energy may be calculated as follows. Take the product of spike amplitude by spike short circuit current by spike time constant. This is Volts times Amps times time duration. In the above 50 Ω and 5 Ω cases, we get an unvarying 0.5 millijoule. This is intuitively reassuring: the amount of *energy* stored in an inductor is

$$\frac{1}{2}LI^2$$

and only the rate of discharge should be affected by the parallel resistance.

Summary of Switching Transient Characterization and Comparison to CS06 Spike Generator Characteristics

Before proceeding to test data to verify the foregoing analysis, it would be valuable to summarize the predictions made. Figure 1 serves as a graphical summary and comparison of our predictions to the common spike immunity requirement, MIL-STD-461 CS06. A negative-going transient due to a load coming on-line will have a maximum amplitude excursion near zero, the source impedance of the switched load, and a time constant related to the LISN inductance and load capacitance and resistance. A positive going transient will have an amplitude of the switched current multiplied by the LISN bypass resistance, a source impedance equal to the bypass resistance, and a time constant given by the ratio of LISN inductance and bypass resistance. The MIL-STD-461 CS06 10 μs spike has fixed amplitude, time duration, and 1 Ω or less source impedance, regardless of polarity.[3]

Test Data

Figures 4 and 5 show turn-on (negative slope) and turn-off (positive slope) transients generated by switching a 4 Amp load powered from 28 Vdc. The circuit for performing the switching function is shown in Figure 6. A 100 μF capacitor lengthens the turn-on transient, but has no effect on the turn-off transient. Precise correlation between the qualitative waveforms of Figure 1 and the measured transients is achieved. Figures 4 and 5 are open-circuit measurements. While the turn-on transient is low impedance and difficult to load, the 50 Ω turn-off transient is easily loaded (reduced amplitude, increased duration) by another load on the LISN (such as the EUT). Figures 7 and 8 show turn-on and turn-off transients generated by switching a 4 Amp rms load powered from 120 Vac (60 Hz). The circuit for performing the switching function is shown in Figure 9. A 10 μF capacitor replaces the function of the 100 μF capacitor used in the dc case; less hold-up capacity is needed on a higher voltage bus.

What is the effect on filtering requirements of imposing the spikes of Figures 4 and 5 rather than CS06? For the turn-on transient, the emphasis shifts from snubbing a short duration spike, to providing hold-up capacitance. If the turn-on transient duration has been correctly specified, then this provides valuable information to the equipment designer. To evaluate the effect of the change in turn-off transients, a 0.1 μF capacitor was placed across 5 Ω and 50 Ω resistors on the output of the transient generating LISN and the parallel output of the Solar 8282-1 transient generator. Across the LISN, the capacitor with 50 Ω resistor brought a 228 Volt spike (plus dc) down to 50 Volts (spike plus dc). Across the Solar device, at a 10 µs setting, the capacitor was totally ineffective whether placed across a 50 Ω or 5 Ω resistor. Reduction of a 200 Volt Solar generated spike to 50 Volts was achieved using the 0.15 µs setting. The RC time constant of the loads, assisted by the higher source impedance of the spike, could average the shorter spike.

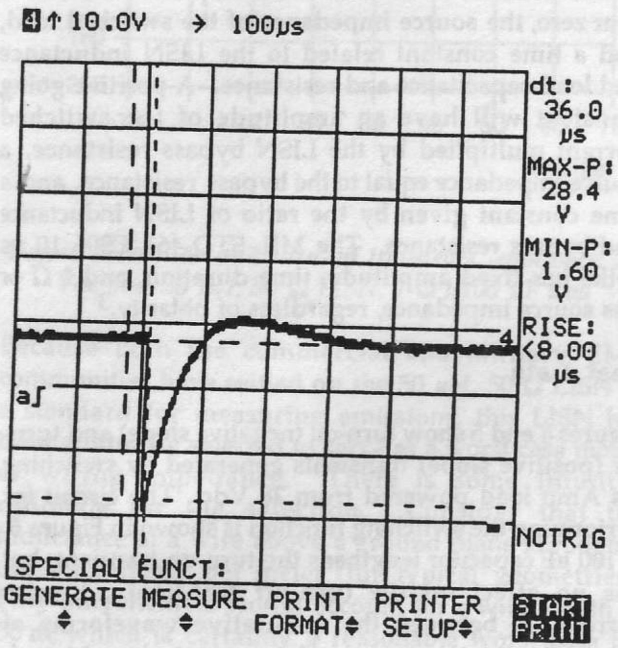

Figure 4: *Turn-on transient (turning on 4 Amp load in parallel with 100 µF capacitor)*

A Note About the Switch

In order to assure waveform repeatability, it is necessary that the switch transition time spectrum be in the 50 Ω region of the LISN. While other methods may be possible, the author needed a MOSFET and FET driver circuit in order to achieve the desired transition time. For ac loads, the rectified ac line connects to the load. A voltage divider reduced ac line voltage may be squared up and inverted by digital logic circuitry. Adjustable voltage division allows for selecting the portion of the ac waveform at which to switch the load. The inverter output drives the monostable 555 oscillator, and the rest of the switching circuitry is as before. Figure 9 shows a circuit for spike testing an ac load. The ac switch differs from the dc switch in that it is synchronized with the peak of the ac waveform. The 555 timing circuitry here is only used to limit the pulses-per-second to 1 - 10 pps rate; otherwise, the circuit would generate transients at the line frequency, which is a considerable over test.[4] A minor modification to this circuit would allow for synchronization with any portion of the waveform. However, the amount of switched current, and therefore transient characteristics will vary according to waveform amplitude at the switching point. Because of this variation, this type of *peak-sensing switch* is valuable when measuring transient on/off emissions from an ac powered EUT. Without it, the measurement of a worst case transient is hit-or-miss.

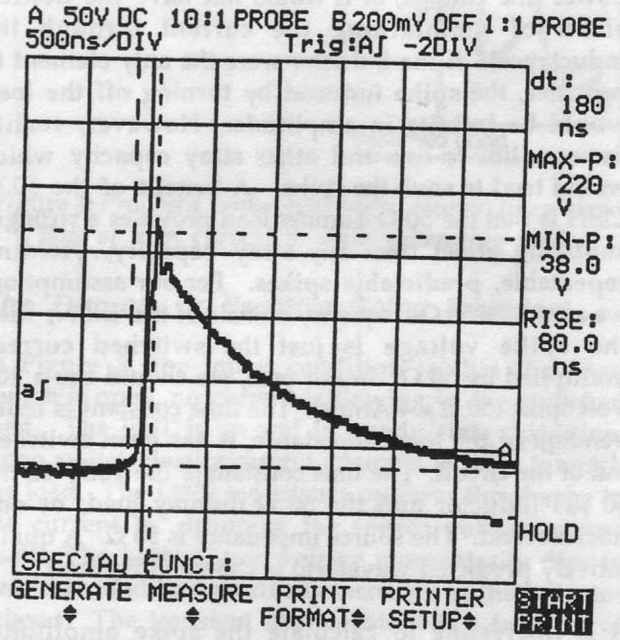

Figure 5: *Turn-off transient (turning off 4 Amp load on 28 Vdc bus*

An Important Note About Power Source Current Rating

The necessary current sourcing capability of the power source is the amount of current drawn by the switched load, multiplied by the on/off duty cycle. The line-to-ground capacitance on the input side of the LISN assists in this derating. This is why Figure 3 shows the high current path bypassing the power source. For a dc power source, any amount of capacity may bypass the LISN input to further augment the derating. In this investigation, a 0.2 Amp current limit allowed for switching the full 4 Amps required to yield a 200 Volt spike. Power dissipation of the switched load and transistor is also derated, proportionally to the square of the switched current. A duty cycle of 1% is reasonable, since an "ON" time of 1 ms is more than adequate to achieve steady-state current draw, and a pulse repetition rate of 1 - 10 pps is traditional.

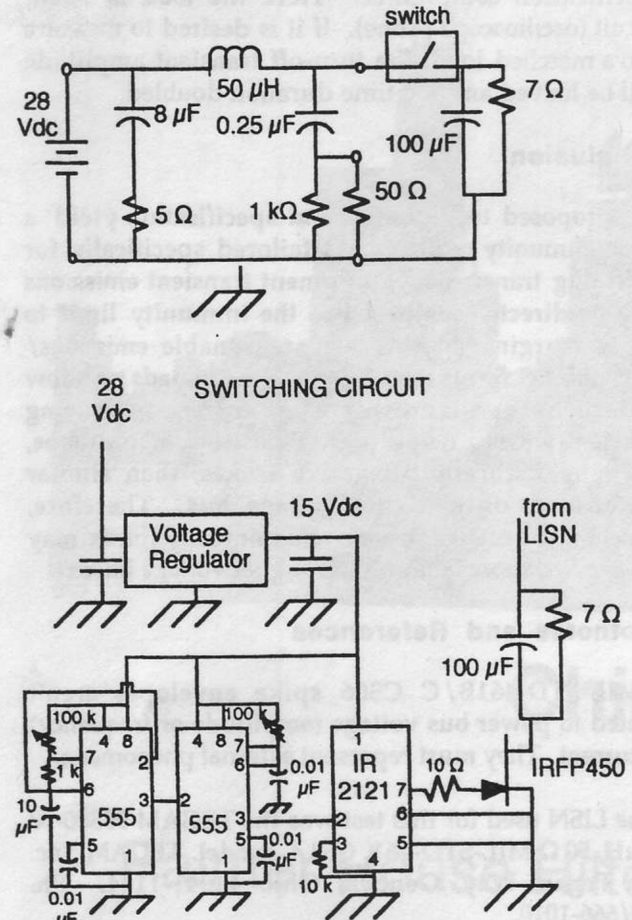

Figure 6: *Transient generating circuit for 28 Vdc loads*

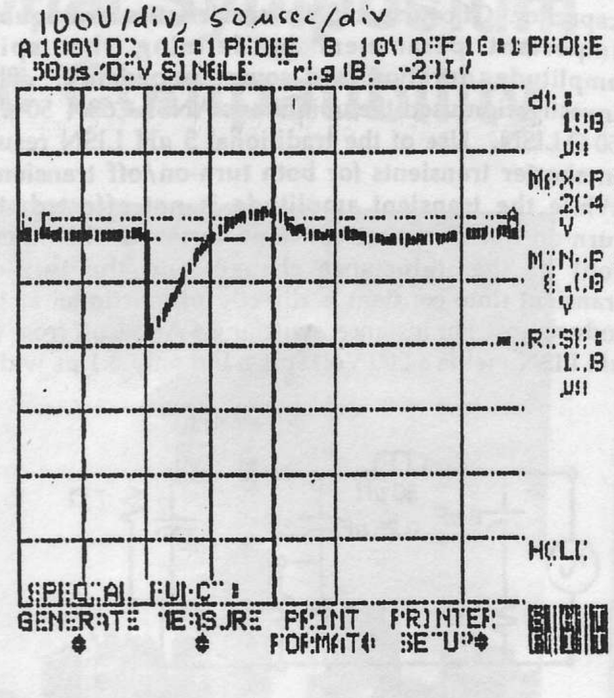

Figure 7: *Turn-on transient (turning on 4 Amp load in parallel with 10 μF capacitor) from 120 Vac source*

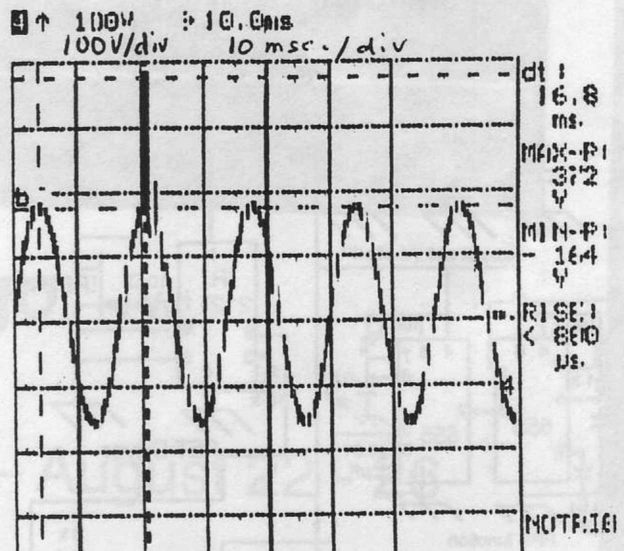

Figure 8: *Turn-off transient (turning off 4 Amp load on 120 Vac bus)*

Test Specification and Procedures

The circuits of Figures 6 and 9 are adequate for any test where peak line voltage (dc or ac peak) plus spike amplitude sum is less than 400 Volts. The amount of switched current depends on both switched load resistance and on/off duty cycle. In this investigation, 4 Amp loads were switched for both ac and dc spikes.

In defining spike immunity limits, both the amplitude and duration inrush and turn-off waveforms must be quantified. Inrush current, provided by a capacitive load, determines the transient duration. The steady-state current is drawn by the parallel resistive load.

The "ON" time must be long enough to fully charge the capacitor. Of course, LISN characteristics are equally important parameters in defining the spike amplitude, duration, and source impedance. This investigation used the ubiquitous ANSI C63.4 50 μH, 50 Ω LISN. Use of the traditional 5 μH LISN results in shorter transients for both turn-on/off transients. While the transient amplitude is not affected, the turn-on transient time constant varies as the square root of the inductance change, and the turn-off transient time constant is directly proportional to the inductance. For instance, switching 4 Amps off from a 5 μH LISN yields a 200 Volt spike, but only 0.1 μs wide.

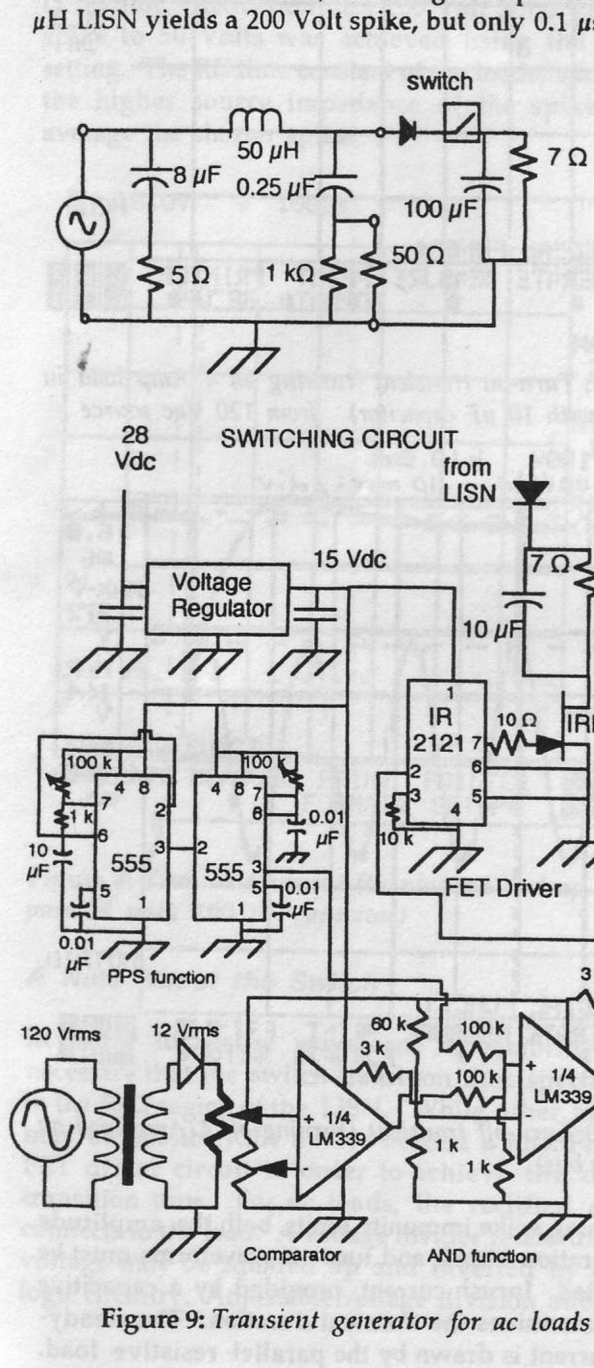

Figure 9: *Transient generator for ac loads*

If different turn-off spike source impedances are desired, this may be achieved by using a different LISN dummy load than 50 Ω. A lower source impedance means more switched current to achieve a given spike amplitude. The opposite effect is achieved by raising the source impedance. If source impedance is raised, one must be careful that the characteristic impedance is achieved at a frequency below that corresponding to the spectrum of the switch rise- and fall-times. Regardless of the amplitude and time duration chosen, it must be specified into what load the turn-off transient is developed for proving specification compliance. Here the load is open-circuit (oscilloscope probe). If it is desired to measure into a matched load, the turn-off transient amplitude will be halved and the time duration doubled.

Conclusion

The proposed test method and specification yield a spike immunity requirement tailored specifically for switching transients. Equipment transient emissions may be directly compared to the immunity limit to assess margins; in this way reasonable emissions/susceptibility limits may be generated. Loads on a low voltage bus will draw greater currents, inducing transient waveforms of higher positive magnitudes, and longer duration negative spikes, than similar power loads on a higher voltage bus. Therefore, switching transient emission and immunity limits may be specified more benignly for higher voltage buses.

Footnotes and References

[1] MIL-STD-461B/C CS06 spike envelopes aren't related to power bus voltage (amplitude or frequency) or current. They must represent external phenomena.

[2] The LISN used for this test was the TEGAM 95300-50 50 μH, 50 Ω MIL-STD-461, C63.4 model. TEGAM, Inc. Ten Tegam Way, Geneva, Ohio 44041-1144. Ph. 800/666-1010.

[3] The Solar 8282-1 CS06 spike generator is specified to have the following output impedances:

$$10\ \mu s - < 1\ \Omega;\ 5\ \mu s - < 2\ \Omega;\ 0.15\ \mu s - < 5\ \Omega.$$

[4] The Solar spike generator built in accordance with MIL-STD-461 basic and revision A did synchronize spikes to the ac line frequency, not just a given point on the ac waveform. The current model 8282-1 corrected this property, allowing for waveform synchronization separately from pulse-per-second selection.