Measurement, Simulation and Reduction of EOS Damage by Electrical Fast Transients on AC Power

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Abstract – It is shown that electrical fast transients (EFT) on the AC power line can result in electrical overstress (EOS) damage to a Class 0 ESD sensitive device connected to the output of AC powered equipment. A methodology for measuring EFT and EOS transients is described and simulations are used to understand coupling mechanisms. Finally, several techniques for reduction of the EOS transient are tested and analyzed.

I. Introduction

It is well known in the field of electromagnetic compatibility that transients can be present on an AC power system. These so-called electrical fast transients (EFT) conduct into equipment via the power cord and can upset their operation. A test standard (IEC 6100-4-4) exists for the generation and susceptibility testing of equipment due to EFT [1].

Power line transients are quite common in manufacturing, where there are many types of high-current AC-powered equipment in close proximity. One common cause of power line transients is sparking that occurs whenever an AC power cord is plugged in, equipment is switched on/off, or when relays are opened or closed. Other frequent sources of power line transients are from inductively-loaded brushed or stepper motors, variable-frequency drives, and certain transformers, dimmer switches and UV light sources.

Figure 1 shows a simplified system consisting of two pieces of equipment that are AC powered. One piece of equipment is called the "Aggressor" because it generates an EFT transient, say when it is turned on. The other piece of equipment is called the "Victim", because it receives the EFT pulse generated by the aggressor through its power cord. Although the incoming EFT pulse is generally attenuated within the victim equipment, a surprisingly large fraction of the incoming EFT current can wind up flowing through
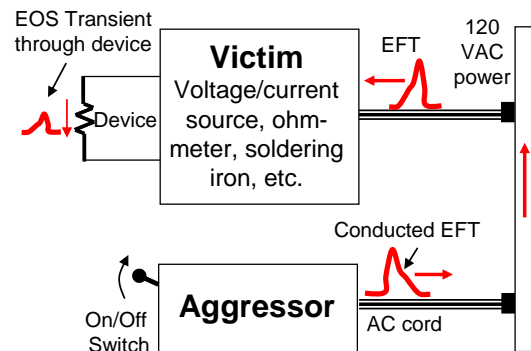

Fig. 1. AC-powered equipment with an "agressor" that generates an outgoing electrical fast transient (EFT) on its power cord when it is turned on, and a "victim" with a device that experiences a transient due to the incoming conducted EFT from the agressor.

the device as a current transient. Electrical overstress (EOS) damage to a device results when the amplitude of this attenuated transient exceeds the energy or voltage damage threshold of the ESD sensitive device.

The goal of this paper is show for the first time that EFT transients on AC power can easily result in severe EOS damage to an ESD sensitive device connected to AC-powered equipment. Measurement techniques for the detection of EFT transients on the power line and the resultant EOS transient through the device are described. Three practical cases that result in EOS damage to a Class 0 ESD sensitive device are studied. SPICE modeling is used simulate the generation and transmission of the EFT from the aggressor and through the victim and device. Finally,

several methods to reduce the amplitude of the EOS transient at the device are explored.

II. Experimental

Figure 2 shows the measurement methodology for the detection of EFT pulses on the power cords and EOS transients at the device. The goal is the measure the voltage and current waveforms of the EFT and EOS transients.

On the power cords, a Fischer Communications F-65 clamp-on current probe was used to measure the EFT transient current. Also, custom common-mode and differential-mode transformers were used to measure the voltage transients on the power line.

At the device, an HP 1142A differential voltage probe was connected across the two terminals of the device to measure the voltage transient at the output of the victim equipment. For current, a TEKTRONIX CT-1 current probe (1GHz) was used to simultaneously measure the current transient through the device.

A LeCroy 5005A digital oscilloscope was used to measure the output of any of the current and voltage probes in both the time and frequency domain (FFT). The minimum system bandwidth was 1 GHz.

Three different types of equipment were used as the "Victim". The first was an AC-powered, high-quality Keithley 2400 Source/Measure Unit (K2400). The K2400 is commonly used to supply a bias voltage or current to two terminal ESD sensitive devices. The second type of victim was an AC powered multimeter, often used to measure the resistance of ESD sensitive devices. The third victim was an AC powered soldering iron for making solder connections to ESD sensitive devices.

The "device" connected to the output of the victim was either a 300Ω ½ watt carbon composition resistor, or a Class 0 ESD sensitive device. The ESD sensitive device was a two-terminal, 300Ω tunneling magnetoresistive (TMR) recording head used in today's hard disk drives. This device is an extremely ESD sensitive Class 0 device that is damaged by a 1ns-wide transient voltage (current) at a level of only 1V (3mA) [2].

III. Results

Figure 4 shows some typical current transients when the Kepco current supply was turned on. Figure 4(a) shows the current transient on the Keithley 2400 power cord. Figure 4(b) shows the current transient through the device resistance at the output of the K2400. Note that the similar shapes of the two current transients confirm that the transient through the load resistor is entirely due to the conducted EFT transient incoming on the power cord. The current transients have an initial pulse width of about 40ns, with subsequent ringing at a frequency of about 3 MHz.

While the peak current of the incoming EFT pulse is 300mA, the peak current of the transient through the resistor is a much lower 12 mA. Thus, the incoming
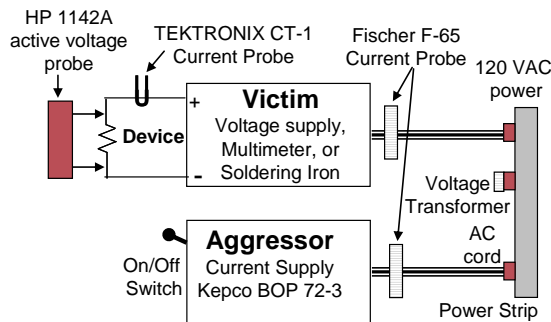

Fig. 2. Voltage and current probe setup for measuring EFT transients on the power cords and EOS transients at device.

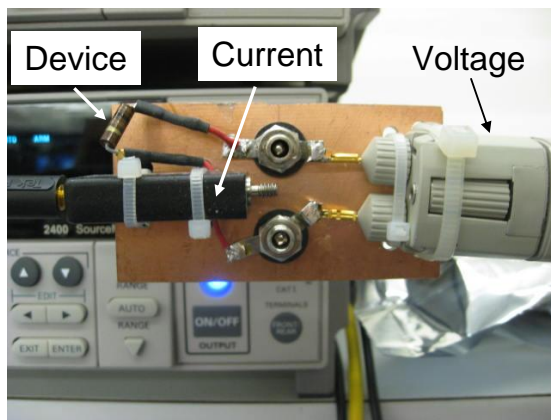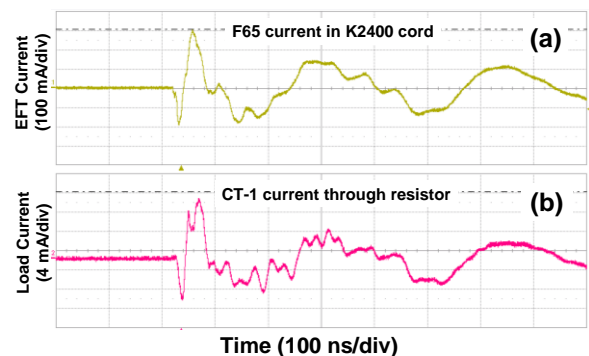Fig. 3. Photo of the current probe (left), voltage probe (right), and load resistor at the output of the Keithey 2400 Source/Measure Unit. These probes measure the EOS current and voltage at the device.

Fig. 4. (a) Incoming EFT currnet transient on the power cord and (b) current through a 300ohm load resistance at the output of the K2400 (bottom), vs. time.

EFT current is attenuated by a factor of 25 as it passes through the K2400.

A number would be useful in order to characterize the ability of equipment to reject the incoming EFT pulse on its power cord. To this end, an attenuation factor for EFT, AF_{EFT}, is defined as

$$AF_{EFT} = 20\log\left(\frac{I_{out}}{I_{in}}\right), \qquad (1)$$

where I_{out} is the peak differential-mode current through the device at the output of the victim equipment, and I_{in} is the peak incoming common-mode current of the EFT pulse on the victim's power cord. Thus the EFT AF for the K2400 is -27 dB.

To measure the frequency content of the EFT transients, the FFT math function in the LeCroy scope was used. Figure 5 shows an FFT of a typical power cord EFT current transient due to powering up the Kepco supply. The dominant frequency is 3 MHz, with other lower amplitude peaks extending out to 16
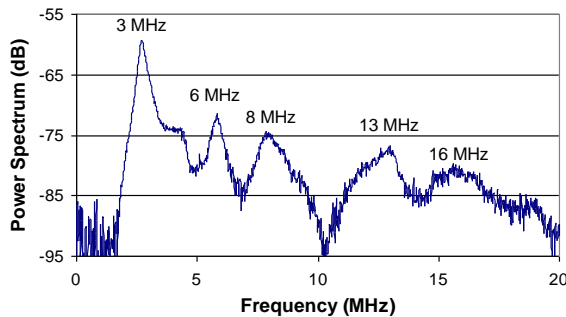
Fig. 5. FFT of a typical power line EFT current transient, showing discrete frequency peaks between 3 to 16 MHz.

MHz. This information is critical in designing a filter for reducing EFT transients.

In one experiment, the resistor at the output of the K2400 was replaced with an ESD sensitive device. The resistance of the TMR head dropped from 300 Ω down to 30 Ω when the Kepco was turned on the first time. In this device, any resistance decrease is an indicator of ESD/EOS damage, and the larger the resistance decrease, the greater the damage. This serious damage is expected based on the previous measurements shown in Fig. 4(a): the failure current of the TMR head is only ~ 3mA for a 1ns-wide transient, and the measured EOS current from the EFT is 12mA for 40ns. Thus, the energy in the EOS transient is 4 times greater than that required to begin to damage the TMR head.

Two other examples of EFT propagating through the equipment are a soldering iron and a line-powered multimeter. The source of disruption on power lines in both cases below was a 1600W heat gun often used in electronic assembly to heat-shrink tubing.

Figure 6 shows the signal on the tip of the soldering iron (Hakko 936) when a heat gun was turned on. As seen, the peak signal can reach 12V which is often sufficient to damage or, at least, to weaken the component this tip touches at that moment.
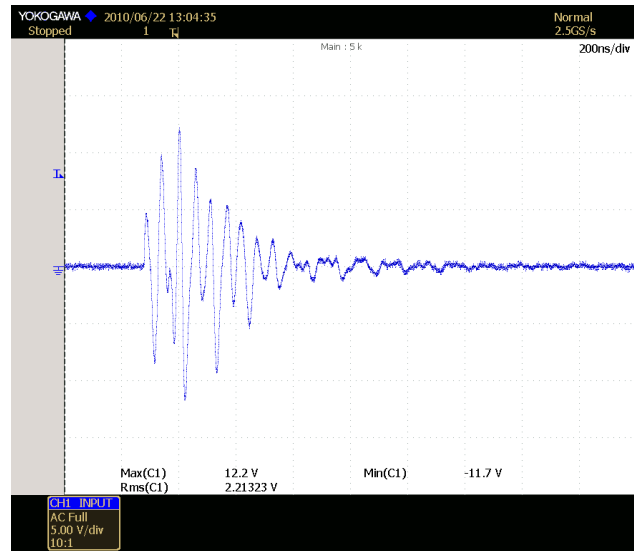
Figure 6. Signal on the tip of soldering iron at the moment of commutation of heat gun connected to the same power line

Figure 7 shows the signal across the terminal of a line-powered multimeter set to Ohms measuring a 100 Ohms resistor. As seen, the peak voltage exceeded 2V. While this may seem insignificant for some components, a number of Class 0 components may be affected, as well as the results of measurements this multimeter is performing at the moment.
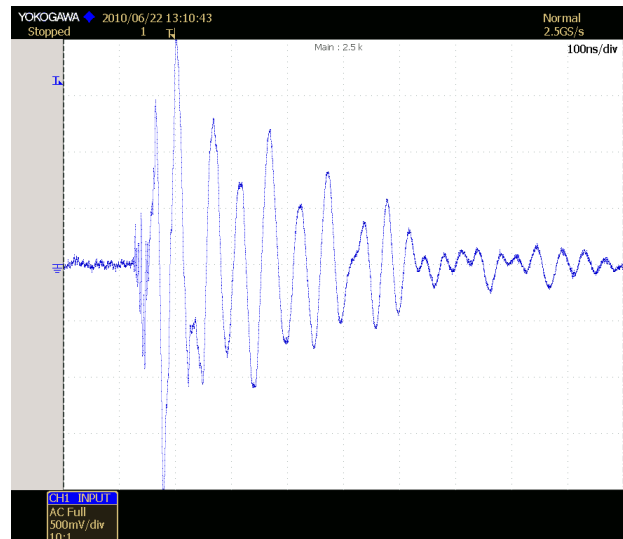
Figure 7. Signal across terminals of a line-powered multimeter at the moment of commutation of heat gun connected to the same power line

IV. Simulation

The EFT problem can be modeled using lumped-elements, with the power cords and attached equipment forming an RLC circuit with a resonance that is excited when there is an abrupt voltage change. Figure 8 shows a simple SPICE model and the EFT current transient that results when there is a voltage change on the power cord. The amplitude of the first pulse is close to the 300mA peak amplitude shown in Fig. 4(a). The fundamental frequency of the simulated waveform is 3.4 MHz, which is very close the to the 3 MHz peak in the measured power spectrum FFT shown in Fig. 5. Thus, lumped-element SPICE simulations show that the EFT pulse on the power cord is consistent with an excitation of an RLC resonance in the power cords, due to an abrupt voltage change on AC power.
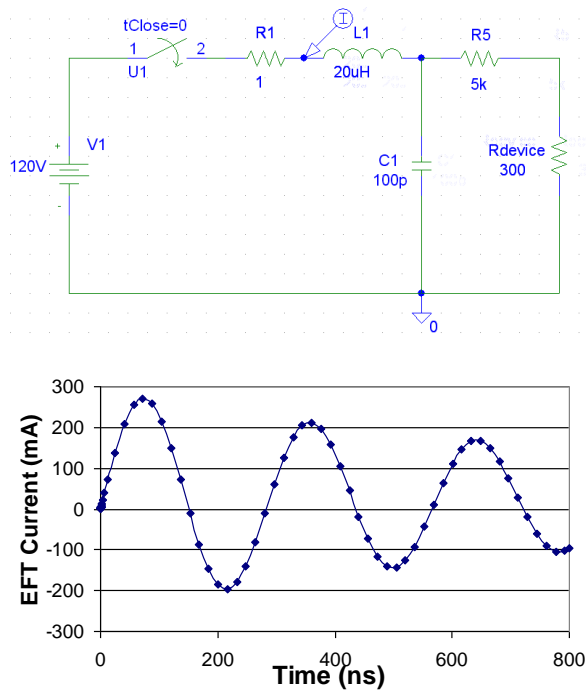

Fig. 8. (top) SPICE model for power cord. (bottom) EFT transient that results when there is an abrupt voltage change on on the power cord.

V. EFT on Power Lines and Their Mitigation

The most frequently used method of mitigating EMI on power lines is use of power line filters. Typical power line EMI filters are designed to bring equipment in compliance with emission regulations (CE, FCC, etc.). As such, these filters perform best in a laboratory setting when the measurements are done with slow regulation-compliant detectors. Performance of these filters in real-life installations and under real-life conditions varies. Reduction of noise on power lines must take into account the properties of the signal that needs to be suppressed as well as properties of the signal conduit in real life. Laboratory test conditions under which the standard filters are tested are quite different from the real-life conditions. Among the fundamental differences are matching impedance, length of wires and the type of signals present.

Most of the troublesome EMI signals on power lines and ground are generated by solenoids, relays, stepper motors, thyristor regulators, switched power supplies and alike. As such, the signals on power lines are largely transient in nature. Unfortunately, this type of signals is not normally taken into account during electromagnetic compliance (EMC) tests for equipment – such tests utilize very slow quasi-peak detector which largely ignores short pulses due to the detector's long time constant [3]. Therefore, it is possible (and common) for the equipment that is fully compliant with CE and FCC requirements to produce very large transient signals polluting power networks.

To aggravate this problem, when equipment is installed in a production environment, long power and ground cables not normally present during the EMC test alter the nature of the noise [4]. Long cables offer distributed inductance and capacitance between the wires and between the wires and ground; skin affect adds to loss of signal at high frequencies.
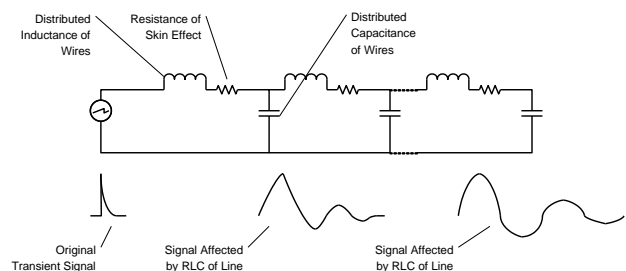

Figure 9. Pulse Transformation on Long Lines

Figure 9 shows the transformation of the short transient signal (EFT) generated by equipment as it propagates through the power lines. Parasitic inductance and capacitance serve two functions – first, they present low-pass filtering function, attenuating high-frequency end of the spectrum. But most importantly, inductance and capacitance of cable present a resonance tank which makes short pulses "ring" with the frequency that wasn't present in the

original signal. As an example, a typical 5m long power cable will have resonance frequency of ~2MHz.

As seen in Figure 9, a short pulse / wide bandwidth original signal is transformed into a very different signal ringing at a relatively low frequency. This presents challenges for conventional filters since they operate better at higher frequencies and are ineffective at lower end of the spectrum where most of harmful signals on power lines reside.

Absolute majority of the strongest signals on power lines, i.e. the ones that cause problems, are not of continuous nature – it is transient signals. Therefore, analysis and mitigation of EFT problems on power lines must focus on time-domain properties of the signal rather than solely on frequency domain. Spectrum analysis using conventional means such as spectrum analyzers would fall into the same trap as regulatory compliance tests where short-duration signals are largely go unnoticed, or, at best, undervalued.

Laboratory compliance tests are done using 50 Ohms terminating impedance as is custom for RF signals. Power lines, however, are anything but that.
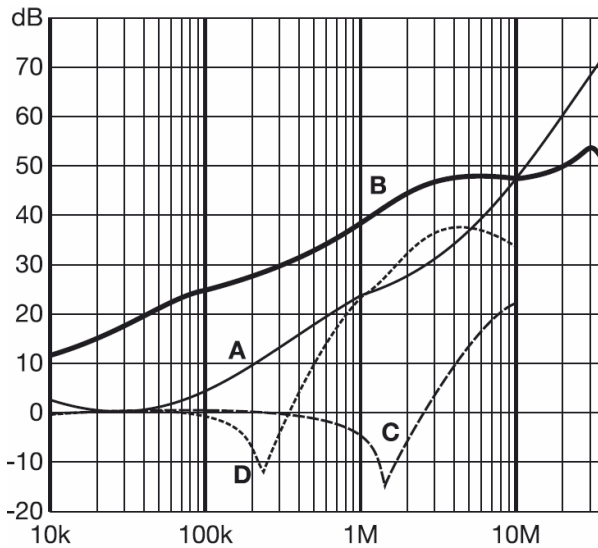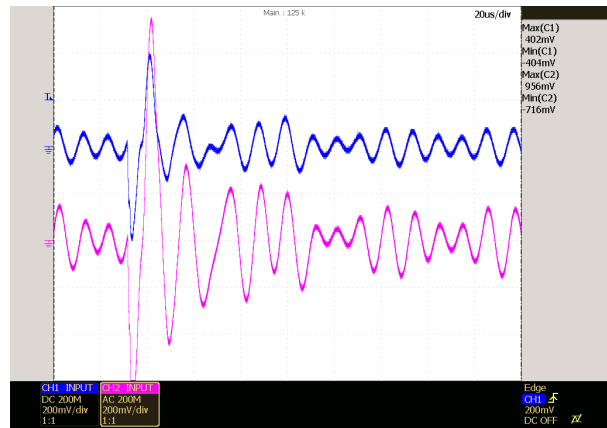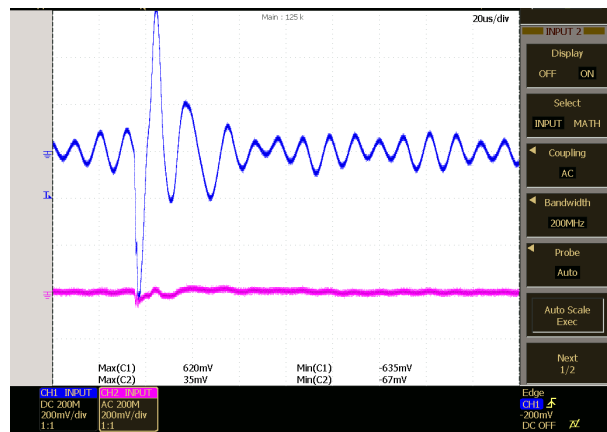

Figure 10. Frequency response of a typical EMI power line filter. Curves A and B are for 50 Ohms termination; curves C and D are for 0.1/100 and 100/0.1 Ohms termination correspondingly

Figure 10 shows typical performance of a power line EMI filter (manufacturer will remain unnamed since such performance is typical for many off-the-shelf filters). As seen, it has reasonable signal attenuation at higher frequencies, but only with 50 Ohms termination – meaning that in actual use where output impedance of power line is extremely low and the

load impedance is only accidentally may be 50 Ohms (curve D), this filter will actually amplify the noise. Figure 11 shows the difference in performance on actual power line between a typical off-the-shelf EMI filter (a) and a special time-domain filter designed for power line applications in the factory environment (OnFILTER single-phase 20A model AED211ATG) (b). As seen, the reviewed off-the-shelf filter actually magnified transient signal on power line more than twice, while time-domain filter attenuated it at least 10 times. This is in general agreement with the filters' own specification (see Fig. 10) and their anticipated performance. Specially-designed filter for real-life installation, however, reduced EFT more than 10 times (>20dB).

(a) Top trace – incidental noise on power line; bottom trace – after regular EMI filter

(b) Top trace – incidental noise on power line; bottom trace – after special time-domain filter

Figure 11. Effect of different filters on real-life transient signals on power line

This emphasizes the necessity of paying more attention to real-life power line noise rather than addressing only EMI compliance needs.

VI. EFT Reduction Within the Tool

The most effective method of reducing EFT is by using properly-designed EMI filter at the entrance of an EMI-sensitive tool. However, additional measures can be taken within the tool to further reduce influence of EFT.

In some applications, such as the one described in this paper, it may be possible to connect a resistor in series with the device under test. This resistor would reduce current going through the device and thus limit the damage from EFT. In this particular example, a 100 Ohms resistor was connected in series with the device described in section II above. This resulted in reduction of current sufficient enough to be below damage level. This tehnique, however effective, may not be applicable to all cases in the field since the resistor cannot always be added in the circut.

In some cases the "aggressor" is located within the same tool where sensitive components are being processed – such as stepper motor, solenoids, etc. In these cases an appropriately-designed DC filter isolating such "aggressors" can be effective.

VI. Conclusion

It is concluded that commonly found EFT transients on the AC power cords can couple through AC-powered equipment and result in EOS damage to an ESD sensitive device that is connected at the output of the equipment. SPICE simulations show that an abrupt voltage change on the AC power cord excites transmission line RLC resonances and results in a ringing transient with a frequency content around 3 MHz. Only transient suppression devices that are tailor-made for the frequency content and time-domain properties of the EFT transient were found to attenuate the EFT transient.

References

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