EMI-Caused EOS Sources in Automated Equipment

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Abstract
Electrical overstress causes damage to sensitive components, including latent damage. A significant source of EOS is high-frequency noise in automated manufacturing equipment. This paper analyses sources of such noise, how it affects components and how to mitigate this problem.

Introduction
Electrical Overstress (EOS) has been reported to be the number one cause of damage to IC components[1]. While most manufacturers are concerned with electrostatic discharge (ESD), not enough attention is paid to the much more damaging EOS phenomenon.

Significant source of EOS in manufacturing environment is high-frequency noise (often called EMI - Electromagnetic Interference). High-frequency noise is present in most manufacturing tools such as pick-and-place machines, lead trimmers, wire bonders and many others. This noise is caused by operation of various electric and electronic equipment, both inside the tool and by the tools nearby or even far away. Understanding the sources of EMI and how to mitigate EMI-caused EOS exposure is important for safe handling of sensitive components.

Sources of EMI in Tools
Every electrical and electronic equipment generates some sort of artifacts on power line and ground during its operation. Different types of equipment generate different types of noise.

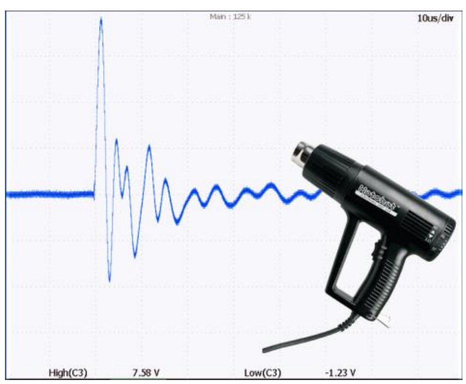

Figure 1. Power line transient from turning on heat gun.

Commutation of Power
Commutation of power, such as turning equipment on and off causes strong transient signals. Figure 1 shows typical voltage spike caused by turning on a regular heat gun. The more powerful the load, the stronger the spike. This type of transient noise does not easily follow an observable pattern and often is difficult to diagnose, in part because the spike can originate quite far away from the source and propagate via power lines and ground.

It doesn't take an entire tool to be turned on or off in order to produce a significant transient signal - all it takes is to have heating element, solenoid or other load within the tool to be turned on or off. The resulting transient signal propagates throughout the tool via common power and ground.

Dimmers/Gradual Heat Control

Common power line dimmers that control light brightness, such as in microscope light, or temperature of certain heating elements produce periodic spikes synchronized with the power line frequency. Typical waveform of noise from dimmer is shown in Figure 2.

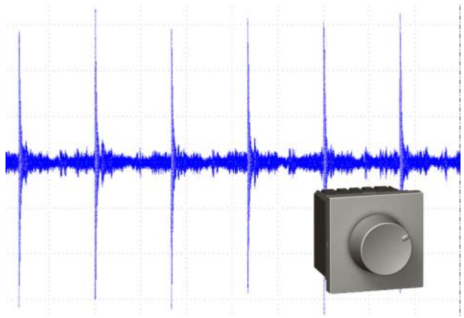

Figure 2. Noise from the dimmer

Switched Mode Power Supplies (SMPS)

While many power supplies provide small manageable level of noise, there are enough SMPS in use that skip on noise suppression and serve as a major source of electromagnetic interference. Switch mode power supplies generate DC voltage from AC mains using high-frequency pulses (typically between 40 and 200kHz). These pulses have sharp edges which are the main culprits in generating undesirable noise. This noise may have rather complex waveform as illustrated in Figure 3. It is important to know that SMPS generate noise both on DC output and on AC mains.

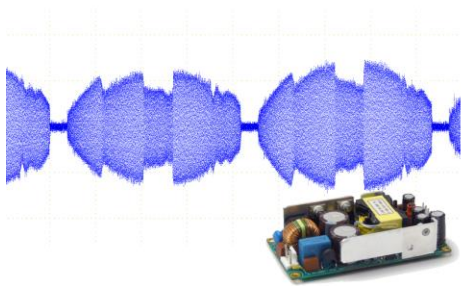

Figure 3. Noise on AC mains generated by several switched mode power supplies

Uninterruptable Power Supplies (UPS)

UPS provide AC power to your equipment when main AC power either fails completely or when its key parameters fall below acceptable levels. In such cases UPS reconstructs AC mains power from its internal battery. The output power in case of mains failure, however, is far removed from the expected sinewave. It is most likely a square wave with sharp edges that cause significant high frequency noise at the output. Figure 4 shows AC output of a typical UPS (blue trace) and resulting high-frequency pulses on power line (red trace). Power conditioning in absolute majority of UPS does not include noise filtering and, in those that do, it is mostly sub-standard.

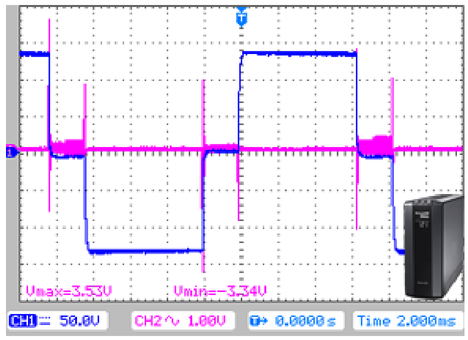

Figure 4. Noise from UPS

Servo and Variable Frequency Motors

Almost every equipment with moving parts utilizes either servo or variable frequency motors. They are a workhorse of today's automation. Unfortunately, they are also the strongest source of EMI in the tools. These motors are driven by the pulses ranging typically between 8kHz and 20kHz with sharp edges only a few nanoseconds long. This pollutes the entire tool, especially its ground, with strong sharp transients with repetition rate of that of drive pulses.

Figure 5 shows how rising edge of servo motor drive pulse (red trace) is synchronized with ground current inside the tool (blue trace). This current was measured using a production current probe and with its 5mV/mA ratio the ground current peak-to-peak measure is almost 2A with width of pulses of under 100nS.

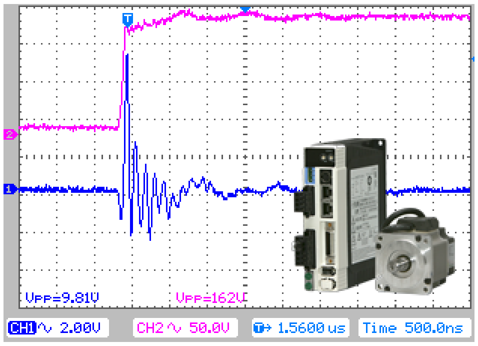

Figure 5. Effect of Servo Motor Pulse on Ground Noise

A typical production tool has several servo/variable frequency motors, sometimes more than 10. Combined electrical noise from all motors can significantly pollute the ground of the entire tool.

How does EMI Turn Into EOS?

EMI-caused electrical overstress occurs when a device, such as an IC, is in a contact with grounded parts of a different potential which causes current through the device. While it is fairly easy to establish equipotential environment inside the tool at DC and at 50/60Hz, at high frequencies it becomes very difficult. One of the reasons for that is that at high frequencies conductors behave differently. Even a straight wire becomes an inductor with noticeable impedance and a phase shift.[2,3] Metal parts that are not in physical contact can still conduct current because of parasitic capacitance between them. This creates unanticipated current paths and further phase shift. Actuators of robotic arms with associated wiring have substantial inductance and high capacitance to the tool's frame. The result is that high-frequency voltage on the robotic arms is not the same as on the tool's frame. This leads to a possibility of current through the devices.

While for DC and 50/60Hz metal-to-metal contact is required for current passage, at high frequencies parasitic capacitance offers low impedance to current even without physical contact. Consider as an example an IC suspended on a nozzle of a pick-and-place machine (or, similarly, an IC handler) as shown in Figure 6.

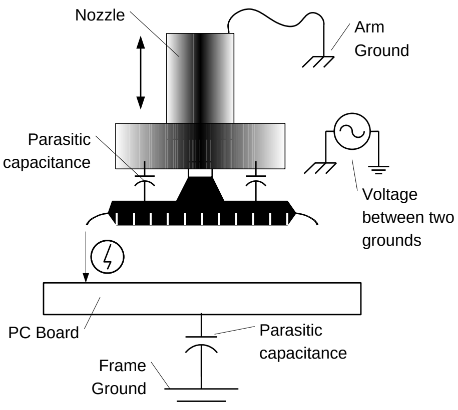

Figure 6. High-frequency current path through the device in pick-and-place

The silicon die of the IC and its leadframe form one plate of a capacitor and the nozzle forms another. Close proximity of these plates provides big enough capacitance and resulting low impedance between the IC and ground of the robotic arm.

The copper of PC Fab which may not be galvanically connected to the tool's grounded frame nevertheless forms even bigger capacitance with the tool's frame and other metal parts of the tool.

Once the IC is placed on the copper pads of the PC Fab, the metal-to-metal final contact closes the circuit and the current now can flow. Strong current with high repetition rate is a viable cause of EOS.

Figure 7 depicts actual measurements made in an IC handler. The blue trace shows drive pulses of a servo motor; red trace - current through the device. As seen, current pulses are synchronized with the drive pulses. Other (non-synchronized) pulses are associated with other servo motors in the tool (there were total of 6).

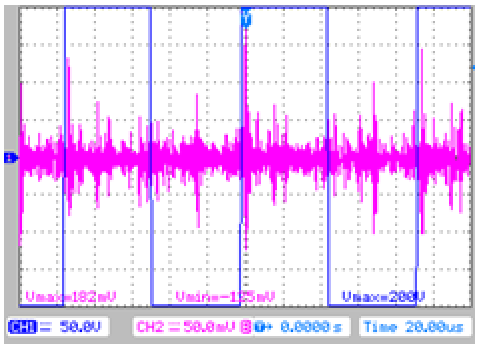

Figure 7. Current through the device in an IC handler

It is important to note that these current pulses are continuous -they "hit" the device up to 20,000 times a second every second. This weakens the device structure and can cause latent damage which is more pronounced due to EOS than to ESD exposure[4].

Not surprisingly, such current pulses weaken not only the device structure but the tool itself - just like dripping water often causes more damage than an occasional pour. The most wide-spread phenomenon is damage to ball-bearings of servo and variable frequency motors[5]. Figure 8 shows typical damage to the bearings from ground transient pulses caused by EMI. If such damage occurs to hardened steel, what would it do to small silicon structures of the devices?

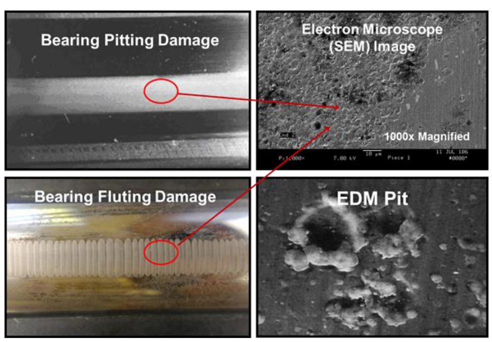

Figure 8. Damage to bearings due to high-frequency currents[6]

Places of Likely EMI-Caused EOS Exposure

Every place in automated equipment where there is a metal-to-metal contact is a possible source of EMI-caused EOS. Among the tools liable to produce such exposure are:

PCB Assembly	Device/IC Manufacturing
• Pick-and-place tools • Lead formers • Lead trimmers • Wave soldering • Testers	• IC handlers • Wire bonders • Singulators • Lead formers • Testers

Acceptable EOS Limits

How would a responsible specialist assess current EMI levels in the tool and how would they specify the "safe" limits? The only document today that specifies maximum acceptable EOS levels in PCB assembly is IPC-A-610[7]. In its section 3.1.1 it states that "equipment must never generate spikes greater than 0.3 volt." For semiconductor device manufacturing ITRS (International Technology Roadmap for Semiconductors - www.ITRS.net) in its Factory Integration Tables[8] recommends essentially the same levels today and even lower levels for the near future.

Once your factory has conducted an EMI audit of its tools it would become clear where EMI needs to be mitigated and to what levels.

Other Effects of EMI in Manufacturing

Besides causing electrical overstress noise on power lines (AC and DC) and ground infiltrates data lines. The most frequent result is errors in test. It is not uncommon to test the same board or the device several times until it passes. While such problems are not fatal, they reduce productivity and may lead to a bad board erroneously passing the test and be shipped to a customer.

Mitigation of EMI-Caused EOS

While it is appealing to have inherently low EMI levels generating by electrical equipment, in practice factory specialists have to deal with noise-generating equipment all the time. Sometimes improvement in wire routing can help a bit in some circumstances. However, the most practical way to effectively suppress EMI in the tools is implementation of properly-designed EMI filters[1]. The difference between commonly-found generic EMI filters and specialized filters for factory level EMI suppression is outlined here[9]

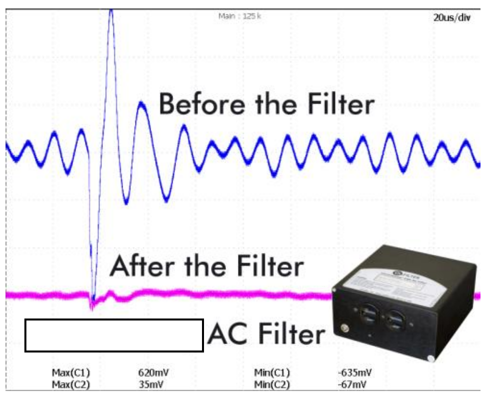

Figure 9. Reduction of noise on AC power line using stand-alone AC Filter

Specialized AC power line filters help to stop noise on power lines from reaching the tool as shown in Figure 9. This filter which is "plug-and-play" and requires no special installation effectively blocks noise on power line and ground in both directions.

Figure 10. Ground Line Filter prevents propagation of noise via facility ground

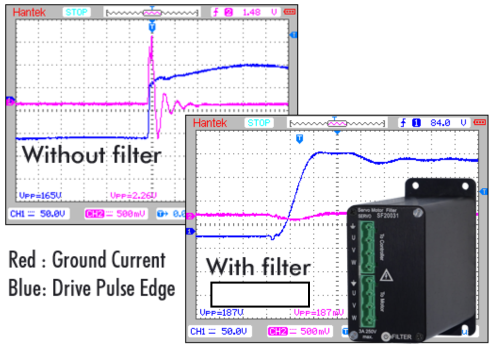

Figure 11. Ground current (red trace) with and without servo filter

Some factories use separate facility grounding throughout the facility. This separate ground serves as a pipeline for noise delivering it to every tool in the facility. Figure 10 shows installation of ground line filter with ground bars. Installation with ground wire under the floor is very similar. Connecting ground filters every 2...3 meters in dense tool environment effectively stops propagation of noise while maintaining required ground quality. Servo and variable frequency motors require specialized servo filters such as one shown in Figure 11. The specific filter shown is installed between servo controller (also called "servo pack") and the motor. By processing drive pulses while preserving their driving ability this servo filter reduces ground noise by more than 20dB in this particular example. The resulting current through the device as was shown in Figure 6 is now reduced even more - 45 times as shown in Figure 12. As a positive "side effect" servo filter also improves reliability of motor's ball bearings by reducing erosion-causing ground current.

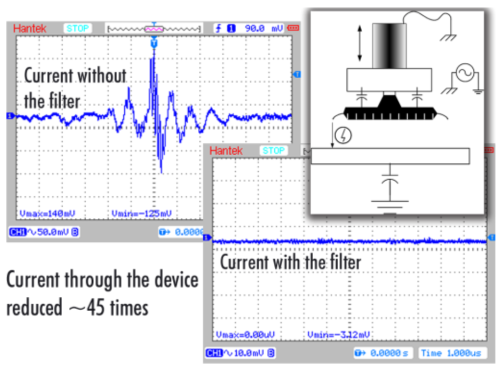

Figure 12. Current through the device with and without servo filter

Conclusion

Electrical overstress is a serious and increasing threat to sensitive devices. Reduction of EOS exposure in assembly is an important way to improving yield and to reduce latent damage to the devices. High-frequency noise (EMI) in automated equipment is a significant source of electrical overstress.

Proper analysis of EMI environment in the facility and inside the tools, setting EOS limits for your process and proactive mitigation of EOS exposure improves yield and reduces EOS-caused failures.

References

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3. Introduction to Electromagnetic and Microwave Engineering, By Paul R. Karmel, Gabriel D. Colef, Raymond L. Camisa, 1998 John Wiley and Sons).

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EMI-Caused EOS Sources in Automated Equipment

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Outline

- What is EOS and its importance
- EMI as a significant cause of EOS
- EMI Sources in automated equipment
- How does EMI turn into EOS
- Acceptable EMI limits
- Mitigation of EMI-caused EOS

What is EOS?

- EOS is **E**lectrical **O**ver**S**tress
- EOS is excessive voltage and current applied to sensitive devices
- Unlike ESD (Electrostatic Discharge), EOS is caused by voltages and currents in the tools, not by static charge
- Unlike ESD, EOS can provide very significant continuous energy into the device causing damage at much lower exposure levels than ESD

3 ESD/EOS

Manufacturing Enabling Guide

May 2010

ESD/EOS

3.2 Electrical Overstress

3.2.1 Electrical Overstress

EOS is the number one cause of damage to IC components. This section describes EOS and how to prevent it.

Reference: Intel Manufacturing Enabling Guide

EMI as a Significant Cause of EOS

- High-frequency noise is always present in a manufacturing environment
- This noise is often called EMI – **E**lectro**M**agnetic **I**nterference
- Presence of unwanted voltages and currents in production environment provides potentially damaging exposure to sensitive devices
- While ESD is tightly controlled by responsible manufacturers, EOS is seldom addressed or even acknowledged

Sources of EMI in Tools

- Commutation of Power
- Dimmers/Heat Control
- Switched Mode Power Supplies (SMPS)
- Uninterruptable Power Supplies (UPS)
- Servo and Variable Frequency Motors

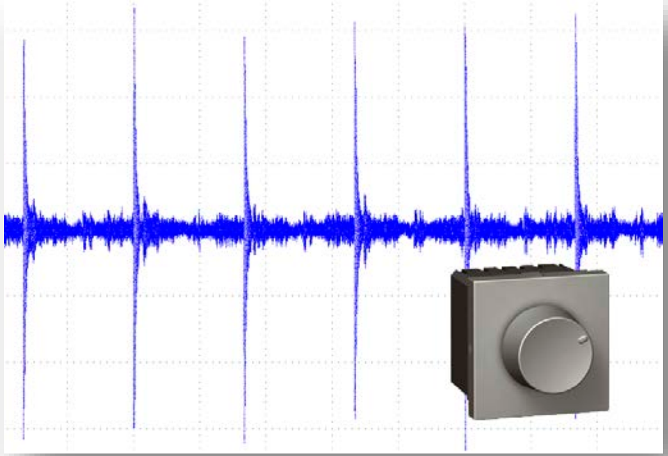
Commutation of Power

- Turning equipment on and off causes significant current and voltage changes
- Power and ground networks adjust to these changes
- The result is voltage spikes on power lines
- These spikes propagate throughout the tool and the facility
- The higher the power consumption the stronger the spike
- Manufacturing facility has many tools that turn on and off all the time

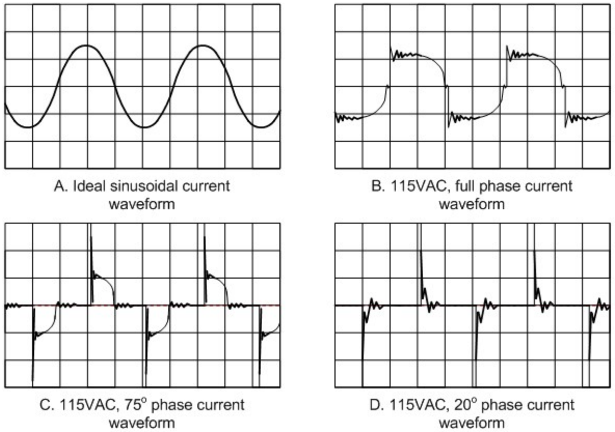
Voltage transient on 110VAC mains from turning on and off common heat gun. Peak is 7.58V

Dimmers/Heaters

- Brightness control of lights and some heating elements are controlled by adjustable phase angle control thyristor circuits also known as dimmers
- While being effective in gradually controlling RMS voltage, they provide sharp transients synchronized with the ignition time of thyristors and mains frequency
- The highest peaks are when the dimmer is set ~half way

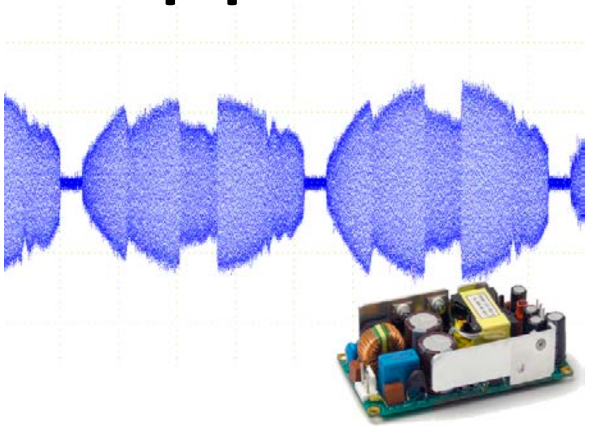


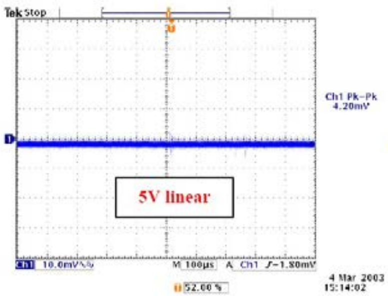
Voltage transient from a typical dimmer

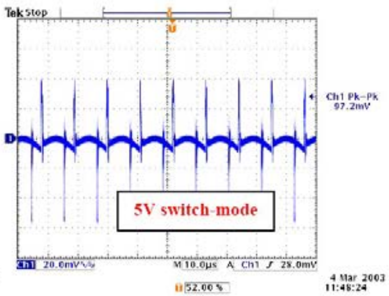


Switched Mode Power Supplies

- Switched mode power supplies (SMPS) work on pulse principle
- They convert typically AC voltage (mains - ~110 to 250VAC) to desired DC voltage by converting AC voltage into high-frequency pulses with typical frequency of 60 to 200kHz and then transform these pulses into DC voltage
- Edges of these pulses “seep through” and cause noise pollution in the equipment
- While some SMPS are properly filtered, many are not

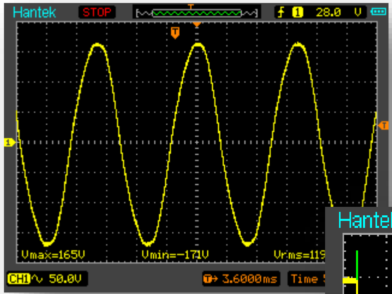




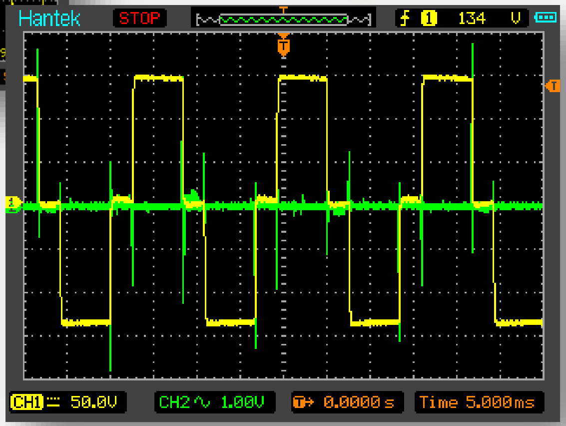


Uninterruptable Power Supplies (UPS)

- Installed in many tools and servers to prevent power outage, brownouts and alike
- Fundamentally similar to switched mode power supplies – operate in pulse mode
- When "good" AC power is present, they simply pass mains' voltage through to the load
- In case anything is wrong, they generate their own substitute
- This generated voltage is often anything but sinusoidal

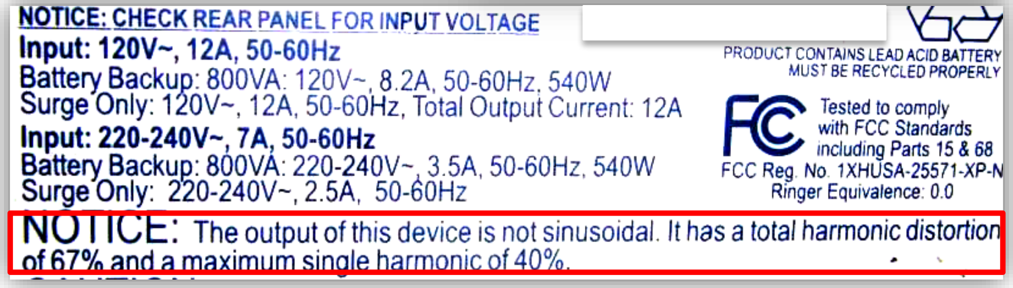


Original Mains Voltage



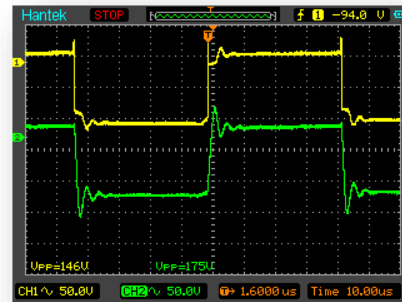
Generated output voltage (yellow trace)

Green: transients caused by pulse edges

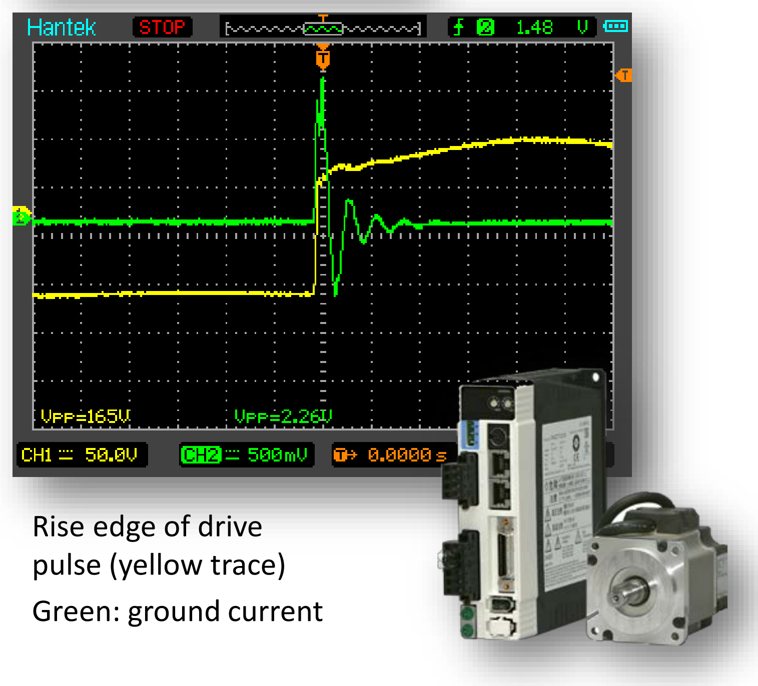


Servo and Variable Frequency Motors

- Almost every tool with moving parts uses servo or variable frequency (VFD) motors
- These motors are driven by pulses with frequency of ~6 to 20kHz
- Edges of these pulses can be as short as few nanoseconds
- This produces significant current pulses in ground (often more than 1A peak magnitude)
- Typical tools use several servo motors or VFD – this pollutes power and ground significantly



Motor drive pulses. Only two out of three phases shown

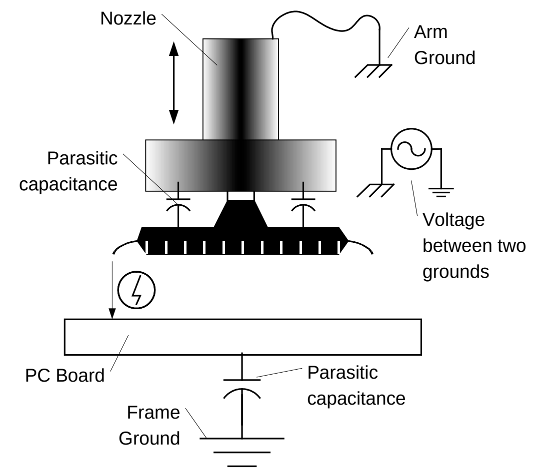


Rise edge of drive pulse (yellow trace)

Green: ground current

How Does EMI Turn into EOS - an Example

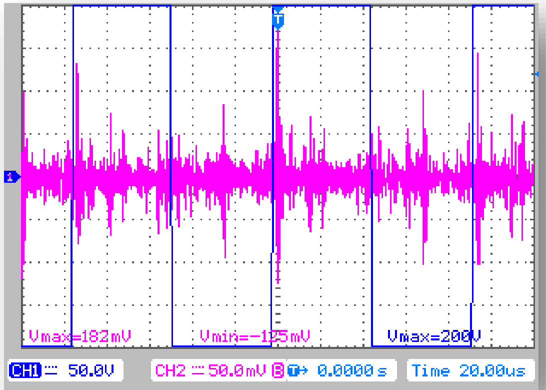
- An IC is suspended in a vacuum nozzle
- While it has no galvanic connection to the nozzle, its capacitive coupling provides low-impedance connection
- There is high-frequency noise in the tool causing different voltage on the nozzle and elsewhere in the tool
- When IC touches the board (or shuttle or test socket), there is a flow of high-frequency current through the device



Blue trace: motor drive pulses

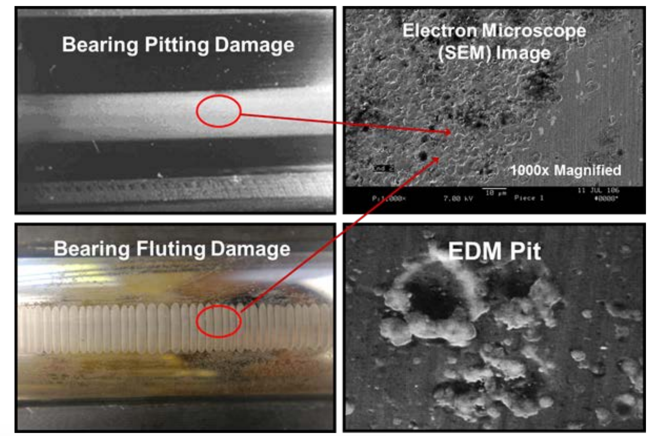
Purple trace: current through the IC

In this example current is ~36mA



Isn't 30mA Too Little to be of Importance?

- While the max. amplitude of each noise pulse may be low, these pulses occur ~20,000 times per second, every second
- Just like a small river carves a canyon in a hard rock, small persistent pulses cause damage to even hardened steel bearings of the motor
- Damage to bearings due to EMI in VFD and servo motors is a well-known and an expensive phenomenon
- The devices in process are affected by these pulses as well




Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages
Jay Erdman, Russel J. Kerkman, Dave Schlegel, and Gary Skibinski

Inverter Driven Induction Motor Bearing Current Solutions
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Paper No. PCIC-2002-08
R. F. Schiferl, Senior Member, IEEE
M. J. Melfi, Senior Member, IEEE
J. S. Wang, Member, IEEE

Capacitively coupled discharging currents in bearings of induction motor fed from PWM (pulsewidth modulation) inverters
AdamKempski*

Influence of High-Frequency Leakage Current on Motor Position Control in PWM Inverter-Fed Servo Drives

Generation, Control and Regulation of EMI from AC Driv
G. Skibinski, J. Pankau, R. Sladky, J. Campbell
Rockwell Automation

The Effects of PWM Voltage Source Inverters on the Mechanical Performance of Rolling Bearings
Doyle Busse, Jay Erdman, Russel J. Kerkman, Dave Schlegel, and Gary Skibinski

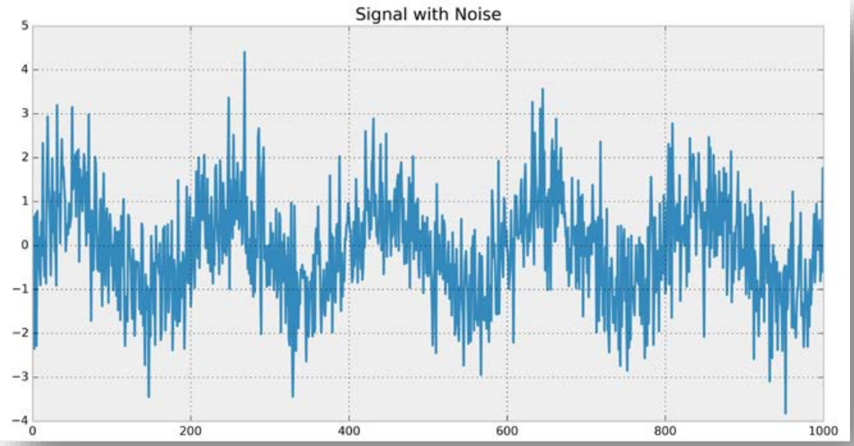
Overcoming Motor Bearing Failures in AC Motor Drive Systems
By
Hans-Joachim Pöss, Manager IT/EMC, Magnetec GmbH
Gary Van Schaick, V.P. Engineering, MH&W International Corp

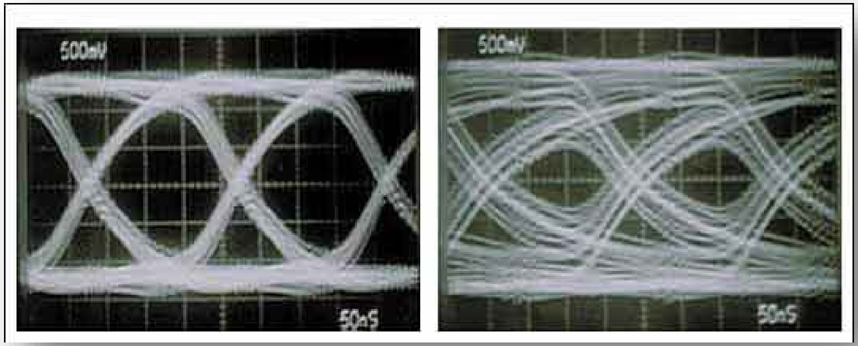
Places of Likely EMI-Caused EOS Exposure

PCB Assembly	Device/IC Manufacturing
Pick-and-Place Tools	IC handlers
Lead formers	Wire bonders
Lead trimmers	Singulators
Wave soldering	Lead formers
Testers	Testers
Wherever metal-to-metal contact is present	Wherever metal-to-metal contact is present

Is EOS the Only Problem with EMI?

- High-frequency noise has non-destructive effects as well
- The most common is added noise to useful signal
- In electronic manufacturing the most common victim is test
- Noise alters useful signals, especially low-level ones
- It is not uncommon to test and re-test the same board or device multiple times until it passes
- What about erroneously passing failed board?
- Without EMI this won't happen





Eye diagram without and with the noise

Acceptable EMI Levels

- The only two commonly-accessible documents set similar levels of noise in electronic manufacturing environment are IPC-A-610 and ITRS (International Technology Roadmap for Semiconductors)

IPC-A-610E-2010

Acceptability of Electronic Assemblies

April 2010
Supersedes IPC-A-610D
February 2005

A standard developed by IPC

3.1.1 EOS/ESD Prevention – Electrical Overstress (EOS)

Before handling or processing sensitive components, tools and equipment need to be carefully tested to ensure that they do not generate damaging energy, including spike voltages. Current research indicates that voltages and spikes less than 0.5 volt are acceptable. However, an increasing number of extremely sensitive components require that soldering irons, solder extractors, test instruments and other equipment must never generate spikes greater than 0.3 volt.

ITRS 2013

Table FAC10 Facilities Technology Requirements

Year of Production	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
DRAM ½ Pitch (nm) (un-contacted Poly) (f) [2]	**28.3**	**26**	**23.8**	**21.9**	**20**	**18.4**	**16.9**	**15.5**	**14.2**	**13**	**11.9**	**10.9**	**10**	**9.2**	**8.4**	**7.7**
Continuous Conducted Emission Limit Allowable Continuous Noise (9kHz - 30MHz) Level (dBuV)	90	90	90	90	90	90	80	80	80	80	70	70	70	70	70	70
Transient Conducted Emission Limit Allowable transient signal Level (V) for regular environment	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Transient Conducted Emission Limit Allowable transient signal Level (V) for sensitive environment	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1

Mitigation of EMI-Caused EOS

- The most practical, most expedient and most cost-effective way to reduce EMI-caused EOS exposure in the tools is to implement proper EMI filters
- Electrical and electronic equipment produces high-frequency noise as a part of its normal operation
- Properly designed EMI filters block this noise from propagating throughout the tool and the facility

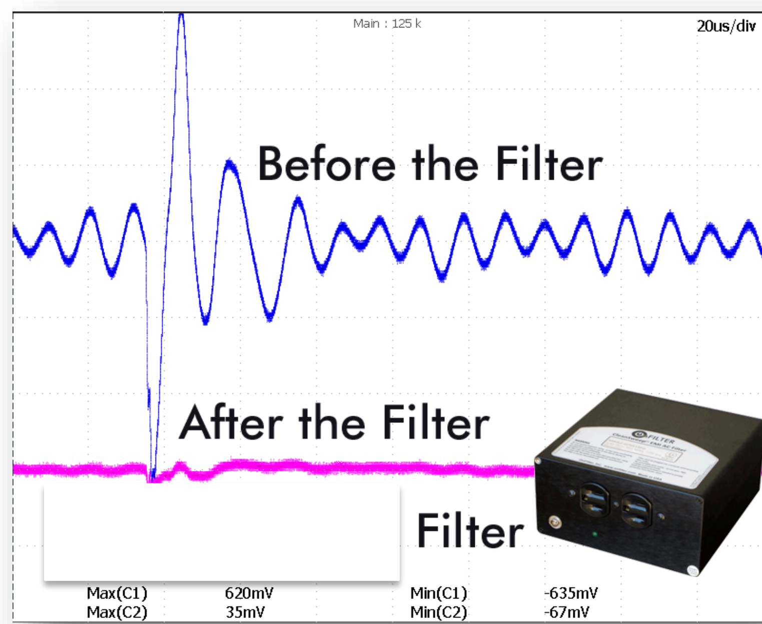
Reference: Intel Manufacturing Guide

ESD/EOS

3.2.4 Prevention of EOS

Conduct regular AC supply line monitoring and, if necessary, install EOS line control equipment such as incoming line filtering and transient suppression circuits.

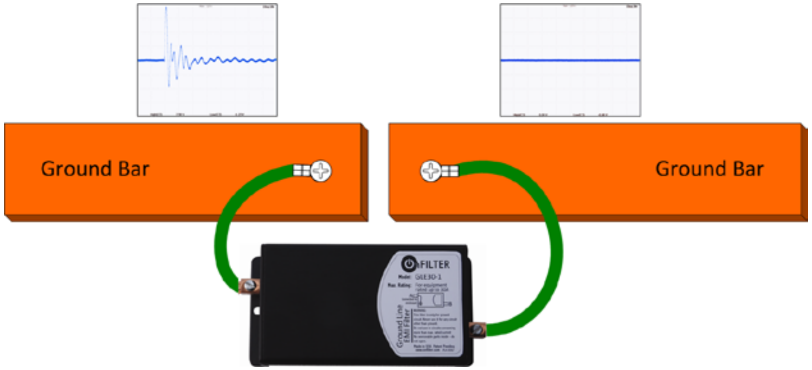
Manufacturing Enabling Guide
May 2010



AC EMI Filter and Noise Reduction

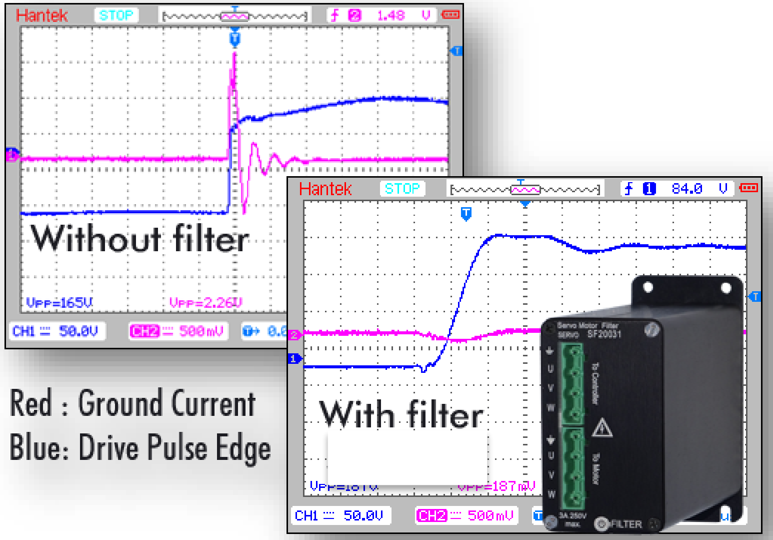
Mitigation of Noise on Ground

- Grounding connects the entire facility together
- Once noise enters ground circuit it may propagate far
- Special ground line filters inserted into ground wiring on intervals of ~3m or wherever noisy equipment is installed block noise while maintaining proper grounding
- Examples include installation with ground bars and with grounding under the tiles as shown

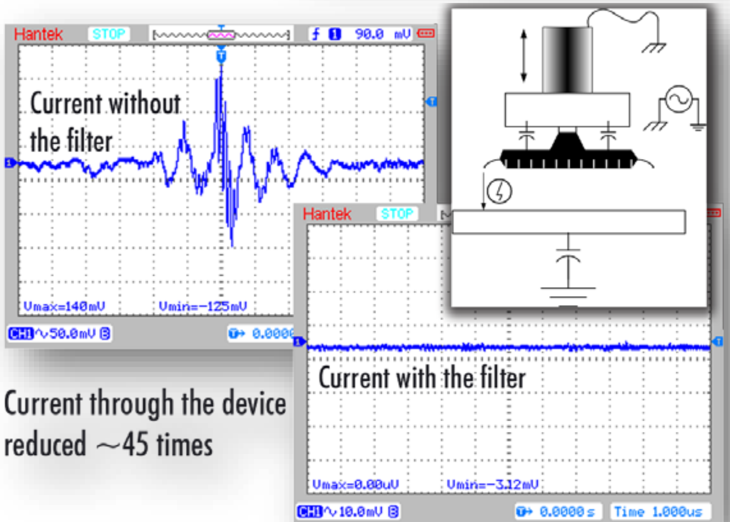


Mitigation of Noise from VFD and Servo Motors

- Special servo motor filters reshape edges of the drive pulses, among other things
- The resulting ground current in motors is reduced by more than 20dB
- Current through the device is reduced by more than 45 times (33dB)
- This also helps to prolong service life of bearings
- Easy installation and no maintenance



Red : Ground Current
Blue: Drive Pulse Edge



Current through the device reduced ~45 times

Conclusion

- Electrical overstress (EOS) is number one cause of damage to semiconductors
- Reduction of EOS exposure in assembly and handling improves yield and reduces latent damage to the devices
- High-frequency noise (EMI) is a significant cause of electrical overstress
- Simple and practical measures, such as special EMI filters, substantially reduce EOS exposure
- Proactive EOS management just like ESD management, improves bottom line

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