EMC Testing Goes the Extra Mile

Written by Tom Lecklider, Senior Technical Editor

EMC standards strike a balance between extremes. Emissions must be controlled, but equally, there is a need to harden a design against interference, whether from internal or external sources. Reducing emissions and their effects requires appropriate design effort but doesn't necessarily mean a higher product price.

Any additional cost associated with EMC often results from corrective actions taken late in the development phase. Even at an early hardware prototype stage, an EMC engineer's options may have become more limited and expensive. Product development is most successful if EMC is considered from the outset and included at each step in the design process.

Two actual test cases illustrate the range of situations that EMC test labs may encounter.

King of the Steroid Trucks

The word truck falls short by a long way when it comes to describing Komatsu America's latest Model 930E with electric drive shown in **Figure 1**. This is a monster mining machine that holds 320 tons of rock, stands over 24 feet tall, and uses 53/80 R63 tires that weigh 9,482 lb each. And, it's electric—well, diesel-electric to be accurate.

Figure 1. Komatsu Model 930E Mining Trucks
Courtesy of Mining & Equipment Journal

General Electric (GE) makes the separate in-wheel motors and AC induction motor drives. A 2,700-hp Komatsu diesel engine drives a type GTA-41 GE Alternator that is the source of power. According to GE, "Compared to mechanical drives, diesel-electric drive systems offer lower operating costs and higher haul productivity. The elimination of wearing components such as torque converters, drive shafts, transmissions, and differentials reduces maintenance, improves truck availability, and lowers life cycle cost.

"Electric drives require no gear shifting. Current and voltage to the traction motor control torque and speed, providing smooth application of power to the wheels. Built-in traction-control algorithms further enhance performance. Electric drive systems also offer continuous retarding. Dynamic retarding reduces wear on the primary braking system."[1]

Even huge mining trucks have to meet EMC specifications, and it was with regard to onsite compliance testing that Komatsu contacted National Technical Systems (NTS). NTS Marketing Director Tom Wetzel picks up the story, "We were awarded a contract to test large Komatsu earth-moving trucks and loaders for radiated emissions, radiated immunity, and ESD. Testing inside a shielded enclosure wasn't possible because of the immense size of the equipment.

"Although ESD testing was relatively straightforward, performing radiated emissions and 100-V/m immunity testing required a suitable test site. Komatsu uses part of an abandoned copper mine in Sahuarita, AZ, as a proving ground, and this also turned out to be a suitable EMC test site. The mine depth and the amount of copper surrounding the test site ensured relatively low background noise although the desert's cold mornings and very hot daytime temperatures added challenges."

With the test site identified, the next challenge was to develop a test method to operate the large equipment, protect the test personnel, and arrange for all test equipment to be brought onsite within Komatsu's schedule. NTS suggested using a trailer as an office/storage/test control room, and Komatsu agreed to supply power. The trailer would be lined with aluminum foil and evaluated to ensure that test personnel would be protected. The trucks and loader would be placed on blocks to allow the engines to run at a predetermined rpm for immunity testing. The trucks then would be driven past antennas mounted within the test facility to take the radiated emissions measurements.

This unusual assignment was successfully completed in large part due to the careful planning that occurred up front. Also key was the cooperation from both parties, without which the job couldn't have been undertaken.

Big Dump Truck Noise

Electric drive systems, especially for huge equipment such as Komatsu's mining trucks, often involve gate turn-off (GTO) thyristor- or insulated gate bipolar transistor (IGBT)-based inverter technology. GTO designs are older and require extensive snubber circuits and more expensive gate drive compared to later IGBTs. Both inverter types allow AC induction motors to be used that eliminate the commutator-related limitations of DC machines.

An inverter produces an AC sine-wave digitally using pulse-width modulation. Typically, big mining machines use three-phase motors and a number of IGBTs in series-parallel combinations. Brands and types of IGBTs differ in detail, but from an EMC point of view, all the usual high-voltage, high-current, and fast switching concerns are encountered in a large AC inverter design.

As **Figure 2** shows, turn-on and turn-off times are in the submicrosecond range with much higher frequency ringing on the gate-emitter waveform. For this turn-off waveform, the maximum slew rates are approximately 4,000 V/µs and 6,000 A/µs. These signals were recorded from a 1,700-V ABB device developed for traction applications. Several IGBT chips are mounted, interconnected, and encapsulated to form an E2 module measuring 140 mm x 190 mm.

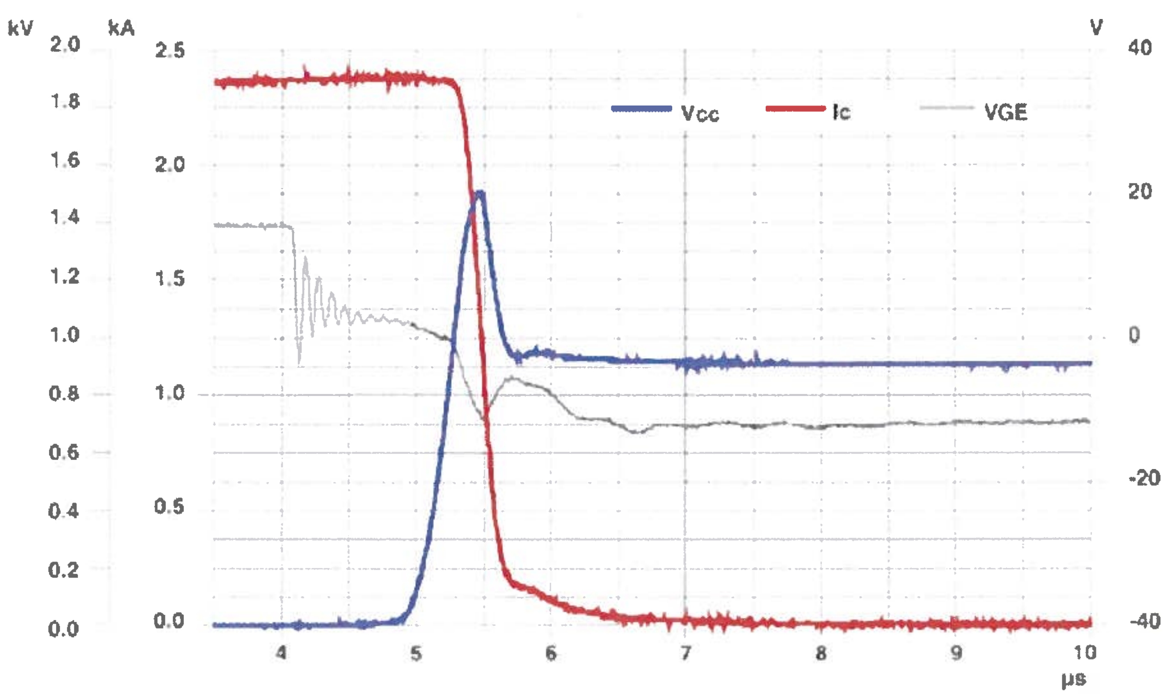

Figure 2. IGBT Turn-Off Waveforms
Courtesy of ABB

ABB's device testing included turn-on/turn-off measurements as well as induced 10-µs short-circuit faults at greater than 10,000 A. An interesting comment by the test report authors put some of the parameters into perspective. "In high-power modules…a large number of IGBT chips are paralleled, and the derivatives of the current slopes (di/dt) are multiplied by the number of paralleled IGBTs. Such high di/dt in conjunction with the stray inductance can cause relatively large overshoot voltages…."[2]

A couple of interesting aspects of Komatsu's EMC environment were discussed in an *Engineering and Mining Journal* article about Rio Tinto's Pilbara mine in Australia. As part of a major Rio Tinto initiative to develop more efficient operations, Komatsu will configure a fleet of its trucks to run under control of a remote operations center.

"Komatsu America's manufacturing facility in Peoria, IL, will produce the 320-ton-capacity 930E Electric-Drive Trucks equipped with the FrontRunner Autonomous Haulage System, a navigation system developed by parent company Komatsu Ltd. and integrated by Modular Mining Systems ….In addition, Komatsu…equips its construction-class vehicles with Komtrax, a satellite-assisted machine status and location system that employs GPS technology to keep track of a machine's location."[3]

Clearly, GPS, a communications system capable of meeting the safety aspects inherent in autonomous operation of million-pound trucks, and numerous built-in wireless maintenance sensors must coexist with the vehicle's AC drive inverter. Typically, different ranges of frequencies are involved, but autonomous operation and GPS location monitoring are further reasons that mining trucks need stringent EMC control and testing.

Bang! Bang! Rat-A-Tat-Tat!!

Chances are your latest design job was less exciting than a two-seat video arcade game with mock machine guns and accompanying vibration and sound effects. Nevertheless, this was the DUT that Underwriters Laboratories (UL) was asked to test for EMC.

At the heart of the game was a 60-inch plasma display with two chairs facing it. Each chair had a toy machine gun with built-in speakers, vibrating solenoids, and lights to give the user the sensation of firing a real 0.50 caliber machine gun. Internally, the system consisted of mostly off-the-shelf parts, and the cabinet was made of wood.

The most serious problem with the unit, according to Michael Windler, operations manager, North American EMC and NEBS at UL, was the failure of exposed metal parts to withstand direct ESD hits. The system would lock up, or sometimes parts of the machine guns would stop functioning. Because of the game's size, several metal supports mounted to the wooden enclosure were relatively long distances from each other. This design made effective grounding difficult although the designer had provided heavy 14-Ga safety grounding from exposed metal parts to a central point.

All that could be done in the short term was replace some of the wires with low-inductance wide metal straps. This solution made the grounding more effective at high frequencies, reducing the impedance seen by the very fast ESD transients. Longer term, the number of exposed metal parts could be reduced to make the grounding job easier.

Straps vs. Wires

You may be familiar with the use of wide straps for lightning protection. The need for low inductance is the same in this application or the arcade game. Equation 1a gives the self inductance of a wire with length (X) and a circular cross section of diameter (d).

$$L(\mu H) = 0.002X\left[ln\left(\frac{4X}{d}\right) - 1\right]$$

(1a)

Equation 1b relates to a thin flat strap of length (X) and width (w) with a rectangular cross section.

$$L(\mu H) = 0.002X\ ln\left[\left(\frac{2X}{w}\right) + 0.5 + 0.2\frac{w}{X}\right]$$

(1b)

All dimensions are in millimeters.

It turns out that a flat strap as wide as a wire's diameter has about the same self inductance. The key is to use a wide strap with the same cross-sectional area as a round wire. As **Figure 3** shows, a regular polygon's perimeter asymptotically approaches the circumference of a circle as you increase the number of sides. The error is <1% for 14 sides and <0.1% for 41 sides. This means that for a given area the shortest perimeter is a circle. At the other extreme, a flat, thin strap is the shape having the greatest perimeter for a given cross-sectional area.

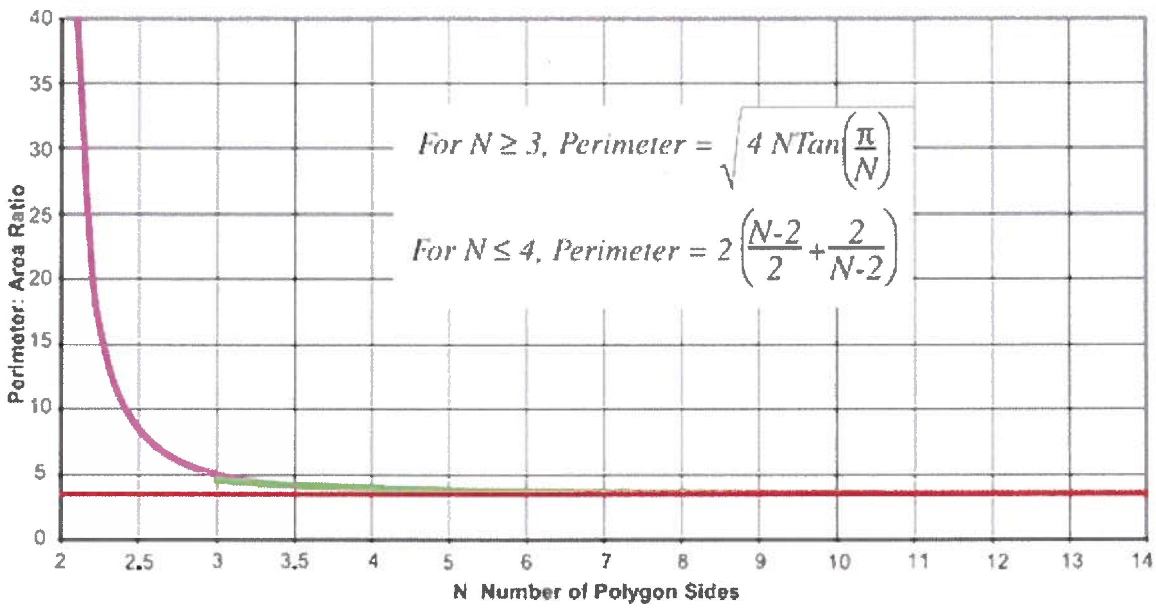

Figure 3. Cross Section Perimeter vs. Area

As an aside, Figure 3 obviously holds at integer values of N, but what about for intermediate values? The shape that corresponds to 4.5, for example, is a five-sided spiral with 80° included angles instead of 90° that a square would have. This means that only one half of the fifth side is required to form a 360° closed shape. The two equations coincide at N = 4. For N<4, the violet line interprets (N-2)/2 as the rectangle height and 2/(N-2) as the width.

Taking the arcade game's 14-Ga wire as an example, the 6-foot lengths used to ground some parts of the game each have about 15-m? resistance at room temperature. For a 25-A ground bond test current, and allowing a little more resistance for the connections to the wire, a 0.4-V drop would occur. The fusing current level for the wire is about 150 A so there doesn't seem to be a problem with the wire's size from a safety point of view.

The wire's diameter is 1.65 mm, the length 183 mm, and the cross-sectional area 2.13 mm^2. From Equation 1a, the wire's self inductance is 2.7 µH. At the 1-GHz frequency Mr. Windler says should be considered when running ESD transient tests, the wire's impedance is 17 k?.

Let's see what happens when a flat strap having the same cross-sectional area is used instead. Straps with 10-, 25-, and 50-mm widths have self inductances of 1.5, 1.18, and 0.93 µH, respectively. The strap thickness does have some effect on inductance, but it's minimal compared to length and width.

This exercise shows that forming the same amount of copper into a different cross section achieves at least a 44% to 65% impedance reduction. It also is clear that you don't have to go to extremes to make a big difference. Even a 5-mm wide strap reduces the inductance to 1.76 µH, a 35% change.

A large improvement would occur if the ground wires or straps were shorter. Equations 1a and 1b include conductor length both as a linear and a logarithmic term that are multiplied together. Reducing the conductor length has the greatest effect on inductance even if 14-Ga wire is used rather than flat straps.

For example, halving the length of the wire results in 0.81-µH self inductance—a 70% reduction from the 6-foot length. This shows the reasoning behind Mr. Windler's suggestion that some of the game's exposed metal parts be eliminated. Especially if the widely separated parts were eliminated, low-cost 14-Ga ground wiring could be retained but with even better high-frequency characteristics than the wide 6-foot long straps.

Ensuring EMC Test Success

Both of the examples presented achieved EMC compliance. Komatsu and GE have extensive experience in building heavy machinery that also meets EMC specifications so they have developed system integration approaches that are known to work well. On the other hand, the arcade-game grounding required modification to become compliant. Future game designs could be considerably improved based on the experience gained from tests on this one.

How should you deal with EMC on your next design project? Helpful guidelines are explained in "A More Efficient Approach to EMC Compliance," a white paper available from Intertek.[4]

The first requirement is to know the specifications your product must meet. This seems obvious, but, as an example, in the United States, the FCC does not require immunity testing for domestic products. It is mandatory for products sold in Europe. Broadly, you need to know what standards apply in the countries where the product is likely to be sold.

This is an area where test labs can be helpful even before a design starts. EMC standards are constantly evolving, so unless your company frequently tests items and you remain up to date with the EMC requirements, consulting a test lab at the start of the development process could save considerable time and expense. It's also a good way to begin a dialogue that will help to ensure success later when the final product tests are run.

Dana Craig, division manager at TÜVRheinland, commented, "You'd be surprised how many people show up at the lab ill-prepared to test. They don't even know what standard they want the product tested to. Ideally, a client will contact us during the design phase. We have experienced staff that can be consulted throughout the product development.

"We always advise working closely with the client's marketing department to understand their plans. With that information," he concluded, "we gain insight into which EMC requirements the product needs to fulfill and which tests are relevant."

This advice was echoed by ETS-Lindgren's Jari Vikstedt, principal RF engineer, with regard to precompliance testing. "Our recommendation is to be knowledgeable about the certification test process: what tests are conducted, how they are performed, and what limit levels are specified. Can the manufacturer self-certify, or must the measurements be made in an approved or authorized test lab?

"Even if final measurements must be made in an approved or authorized test lab, if manufacturers understand the test process, they can conduct precertification testing that will increase the chance of success," he continued. "If manufacturers are not familiar with the precertification test process, they should consider hiring a recognized industry consultant to bring them up to speed."

Another suggestion is to perform early testing of those parts of the design thought most likely to have EMC implications. If you can make the necessary changes early in a project, the cost will be minimal. Stopgap measures taken at the end of development generally are more difficult to implement, cost more, and aren't as effective.

Finally, as figured prominently in the Komatsu-NTS work, make a comprehensive test plan. It needs to clearly set out the requirements and the tests necessary to prove they have been met. This also is the document that will follow the product through its production life, addressing new EMC requirements as they develop. The documentation must be updated to reflect the latest version of the product and/or revised standards.

According to Greg Kiemel, director of engineering at Northwest EMC, "The most economical use of test time can be achieved through the use of a test plan. The information in the plan will allow the test lab to provide more competitive rates, better preparation in advance of testing, and consequently, more effective use of test time."

One of the ways in which a good plan saves money and time was explained by TÜVRheinland's Mr. Craig. "When we perform EMC tests, we can run one main test for all of the harmonized markets and then any extra tests required by varying global markets. In the end, we have all the test data the client needs for all of its market requirements."

Summary

The Intertek white paper concludes with 13 specific recommendations. Here are the main points:

1. Map out which standards relate to your product with regard to the area of application and target market.
2. Apply EMC compliance as a project goal and a natural part of the development program.
3. Maintain an active dialogue with your test laboratory regarding EMC, standards, editions, interpretations, documentation, and tests.
4. Plan and budget for prototype tests in several turns to achieve invaluable design input during the development phase.
5. Plan for design reviews, with or without your test laboratory, where the design and associated documentation are reviewed during the development phase. This affords you the opportunity to make changes at an early stage of the project.
6. Document the development work and ensure that all the documentation is present, right up to the final test.

Perhaps the most important of these actions is number 3 because, once a dialogue has been started with a test lab, a manufacturer has access to EMC experts. They can assist at all stages of a project, initially providing guidance about which tests to perform and later helping to resolve performance issues.

Information and assistance are available in several forms. For manufacturers with their own EMC test lab, Northwest EMC offers lab management services. Northwest will operate a client's internal lab, staff it, and obtain the necessary accreditations.

ETS-Lindgren offers clients access to a test lab at the company's Cedar Park, TX, headquarters and carries out design and installation of EMC test facilities ranging from small, precompliance to large, full-compliance chambers and fully integrated test systems. So-called product tour videos that show how the company's products are used also are available.

TÜVRheinland's Mr. Craig stressed personal involvement by his company's test engineers. "We send our engineers to the client to review the proposed testing with them and, of course, also do that during the precompliance testing. By doing so, the lab's experts can review everything and make sure the client really is ready for testing."

UL's Mr. Windler gave similar advice. "One of the most important, problem-minimizing things a customer can do is to engage UL fully from the start of the design process. UL's expert engineering staff can review designs and often anticipate potential issues, ultimately saving manufacturers time and money."

EMC compliance test success can't be guaranteed, but you can be confident that following the suggestions of industry experts will minimize the risk of failure. Know what standards the design must meet, design for them, and involve a test lab throughout the development process.

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May 2009

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