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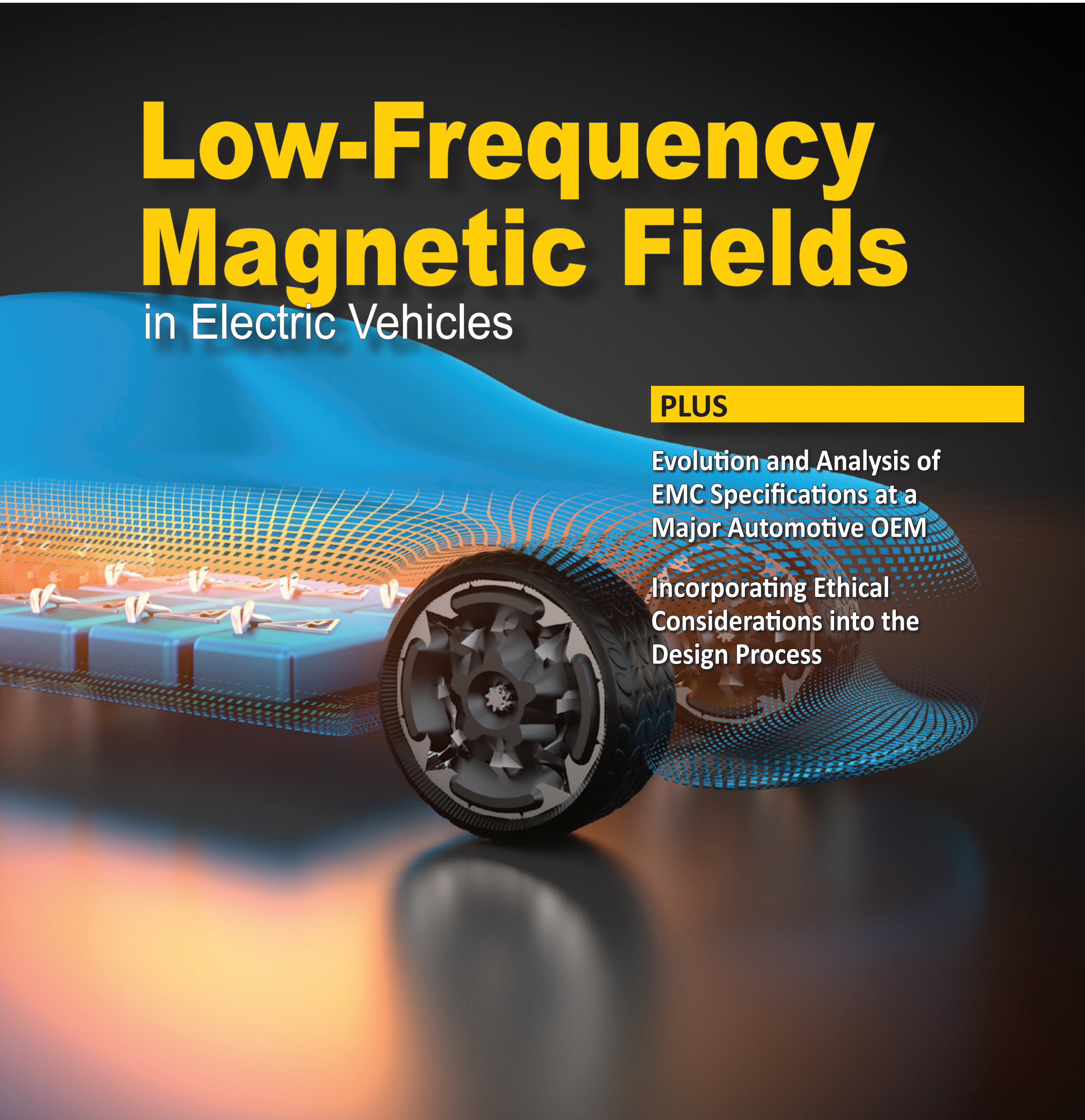

Low-Frequency Magnetic Fields in Electric Vehicles

PLUS

Evolution and Analysis of EMC Specifications at a Major Automotive OEM

Incorporating Ethical Considerations into the Design Process

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FCC Upholds Fine for Use of Signal Jammer

The U.S. Federal Communications Commission (FCC) has upheld a civil penalty issued against a Texas warehouse employer for using a signal jammer to prevent employees from using their mobile phones at work.

The $22,000 fine against Ravi's Import Warehouse in Dallas, TX was originally levied in April 2018, following a 2017 visit to the company's facility by an FCC field agent, who was responding to complaints of interference in the vicinity of the warehouse. During that visit, the owner of the business reportedly acknowledged the use of the jammer on the company's premises but said that it had been disposed of before the FCC's visit. The owner declined to voluntarily retrieve the disposed device but then offered to sell the jammer to the FCC agent.

Section 301 of the Communications Act of 1934 prohibits the operation of "any apparatus for the transition of energy or communications or signals by radio…unless such use is licensed or authorized." Further, Section 333 of the Act states that "no person shall willfully or maliciously interfere with or cause interference to any radio communications…licensed or authorized."

EU Commission Extends Transitional Provisions for In Vitro Diagnostics

The Commission of the European Union (EU) has amended key transitional provisions for certain in vitro diagnostic medical devices under Regulation (EU) 2017/746 (also known as the IVDR), in an effort to ensure the supply of qualified devices during the COVID-19 pandemic.

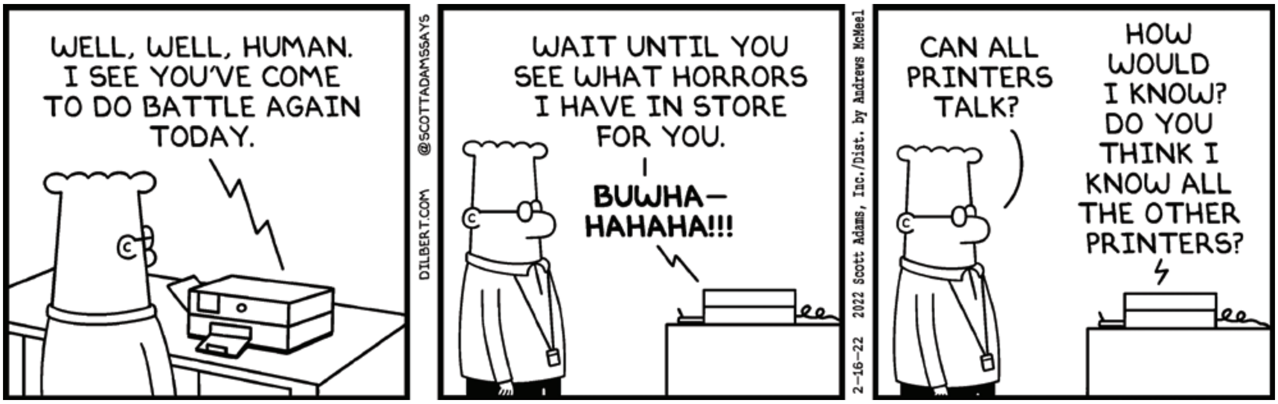
Published in the *Official Journal of the European Union*, Regulation (EU) 2022/112 extends for one year the date by which existing in vitro devices that have been reviewed and certified by an EU Notified Body in accordance with the provisions of EU Directive 98/79/EC must comply with the requirements of the IVDR. Manufacturers of these in vitro devices now have until May 27, 2025 to achieve compliance with the updated requirements.

In addition, most in vitro devices that do not require an assessment by a Notified Body will have even more time to bring their devices into compliance with the requirements of the IVDR. Manufacturers of Class C devices will have until the end of May 2026 to affirm compliance with the IVDR, while Class B and Class A devices will have until the end of May 2027.

Fitbit Recalls 1 Million Smart Watches Due to Battery Overheating

The company behind the widely popular Fitbit smartwatch product line has issued a national recall of one of its smartwatch models due to the potential risk of burns linked to overheated batteries.

According to a notice posted on the website of the U.S. Consumer Product Safety Commission (CPSC), Fitbit LLC is recalling four models in its line of Fitbit Ionic Smartwatches following reports the watches' lithium-ion battery overheated. The company has reportedly received at least 115 reports in the U.S. and 59 reports internationally of battery overheating. Of these, 78 reports in the U.S. and 40 reports internationally indicated that smartwatch wearers suffered burn injuries as a result of battery overheating, including two reports of third-degree burns and four reports of second degree-burns.



FCC Reissues Enforcement Advisory on Using Radio Equipment for Criminal Acts

The U.S. Federal Communications Commission (FCC) is reminding amateur radio operators not to use radios or radio equipment to commit or facilitate criminal acts.

The FCC's Enforcement Advisory reiterates the Commission's prior messaging on this issue that licensees of amateur and personal radio services are prohibited from using radios "in connection with any activity which is against Federal, State or local law." Further, the Advisory states that licensees cannot transmit "communications intended to facilitate a criminal act" or "messages encoded for the purposes of obscuring their meaning."

Under FCC regulations, those found using amateur or personal radio services to commit or facilitate criminal acts are potentially subject to penalties, ranging from fines, seizure of their radio equipment, and even criminal prosecution.

Havana Syndrome Could Have Been Caused by EMP

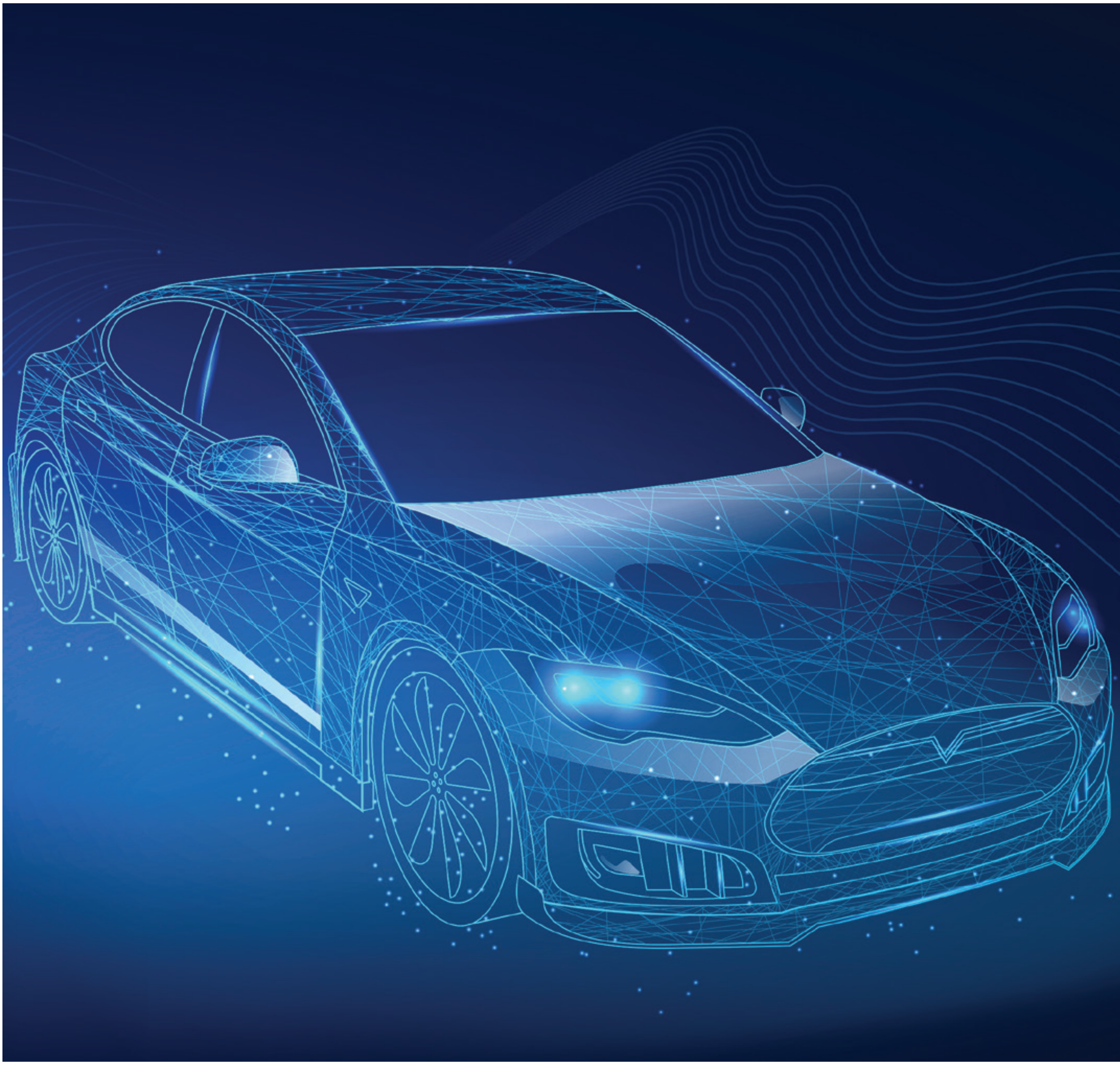
A recent report by the U.S. Central Intelligence Agency (CIA) has raised the specter that electromagnetic pulse (EMP) energy may have been one of the potential causes of the symptoms associated with the so-called Havana Syndrome.

According to Reuters, *The New York Times*, and other news outlets, a report prepared by a panel of experts convened by the CIA indicates that some of the 1000 U.S. diplomats and intelligent officers posted to Havana, Cuba in 2016 who experienced ear pain, vertigo, and other medical symptoms generally referred to as the Havana Syndrome may have been the target of "pulse electromagnetic energy, particularly in the radio frequency range."

While the report did not delve into possible sources of the EMP, it did acknowledge that EMP associated with radio waves, microwaves, and X-rays could have been generated "using non-standard antennas and techniques" and that such "signals could be propagated with low loss" through the air and building materials.

LOW-FREQUENCY MAGNETIC FIELDS IN ELECTRIC VEHICLES

Challenges, Shielding, and Design Considerations



Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd, a UK-based engineering firm that specializes in EMC consulting, troubleshooting, and training. His in-depth knowledge in power electronics, digital electronics, electric machines, and product design has benefitted companies worldwide. Zhang can be reached at info@mach1desgin.co.uk.

By Dr. Min Zhang

***Editor's Note:** Readers may also be interested in Zhang's other* In Compliance Magazine *articles addressing EMC issues with electric vehicles, "EMC Design Techniques for Electric Vehicle Powertrain Modules" (February 2021), and "EMC Design Techniques for Electric Vehicle DC-DC Converters" (December 2021).*

Most electromagnetic interferences (EMIs) in the field are conducted emissions/immunities, radiated emissions/immunities, electric fast transients (EFT), and electrostatic discharge (ESD). There are, however, other types of EM-related disturbances, including low-frequency magnetic fields, the subject of this article.

The power-frequency (50-60 Hz) magnetic field is a direct result of currents flowing in power networks. When low-frequency currents flow in the entire power network, depending on the size of the current-circulating loop, the impact on equipment/products in the environment can be significant. A typical case is an equipment with a cathode ray tube (CRT) screen. The display on a CRT screen would appear to wobble due to the presence of a nearby low-frequency field[1]. Professional audio equipment such as electric guitars, tape recorders, and loudspeakers are also sensitive to external magnetic fields. EN 61000-4-8 defines the test method for basic power-frequency magnetic fields[2].

In recent years, many low-frequency magnetic field issues have been identified in new product applications, such as products using electron-beam technology and electric vehicles (EVs). Products such as additive manufacturing equipment using electron-beam technology are also sensitive to power-frequency magnetic fields and poor immunity could lead to inaccuracy in the manufacturing process. In the case of EVs, traction motors generate fluctuating currents up to 2 – 3 kHz, and wireless power transfer (WPT) systems for battery charging are operated at about 85 kHz[3].

The issue with low-frequency magnetic fields in this case is often related to health and safety. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines 2020[4] describes the potential health and safety impacts of human exposure to electromagnetic fields. According to the Guidelines, the main physiological effects of electromagnetic field exposure include the electro-stimulation of the nervous system, resulting from electric fields being induced in biological tissues under exposure to time-varying magnetic fields with frequencies up to 10 MHz.

Not only can low-frequency magnetic fields pose health hazards to human beings, but they can also affect some electric control units (ECUs) in a vehicle. An ECU that consists of Hall-effect sensors located near the battery pack or powertrain modules could be affected by the low-frequency magnetic field if no sufficient shielding is provided.

In this article, the discussion of low-frequency magnetic fields is based on applications where the frequency range is below 500kHz. The low-frequency magnetic field challenges in EV applications are discussed. Low-frequency electric fields and plane waves are outside the scope of this article, as are low-frequency magnetic fields produced during the EV charging process.

First, some basic theory about low-frequency magnetic fields is in order.

THE PHYSICAL LIMITATION OF LOW-FREQUENCY MAGNETIC FIELD SHIELDING

Shielding techniques, which are widely used for radiated emissions, are effective because they work in the far-field. Since the wavelength is physically small, the attenuation of a shielding material combines both absorption loss and reflection loss[5].

In many situations, manufacturers perform a risk assessment of their product during the design phase to identify potential hazards, the probability that they will occur, and the consequences or severity of the injury, damage, or loss associated with them.

As shown in Figure 1, the laws of physics dictate that the wavelength is large when the frequency is low (900 kHz), hence the same distance becomes near field for lower frequency noise. In this case, the shield cannot provide sufficient reflection loss. The absorption loss is also reduced and is at a low-frequency. As a result, low-frequency magnetic field shielding can only be achieved by the following techniques:

1. Using thick conductive metal material such as steel, which often works well, but the drawback is the weight. Aluminium or magnesium are much lighter than steel, but they have insufficient low-frequency shielding properties and, therefore, cannot be used in this application.
2. Using a magnetic material such as mu-metal to increase the absorption loss. However, this technique doesn't work for low-frequency electric fields or plane waves (see Endnote #5). Another drawback of magnetic materials is that their permeability decreases with frequency.
3. Active shielding techniques to cancel out the low-frequency field[6], which works in applications where the product suffered from power-frequency (50-60 Hz) magnetic fields and is not constrained by size.

LOW-FREQUENCY MAGNETIC FIELDS IN EV APPLICATIONS

Low-frequency magnetic fields are often generated by the four primary high-voltage modules in an EV, namely, the powertrain module, the on-board charger (OBC), the battery pack, and the DC-DC module.

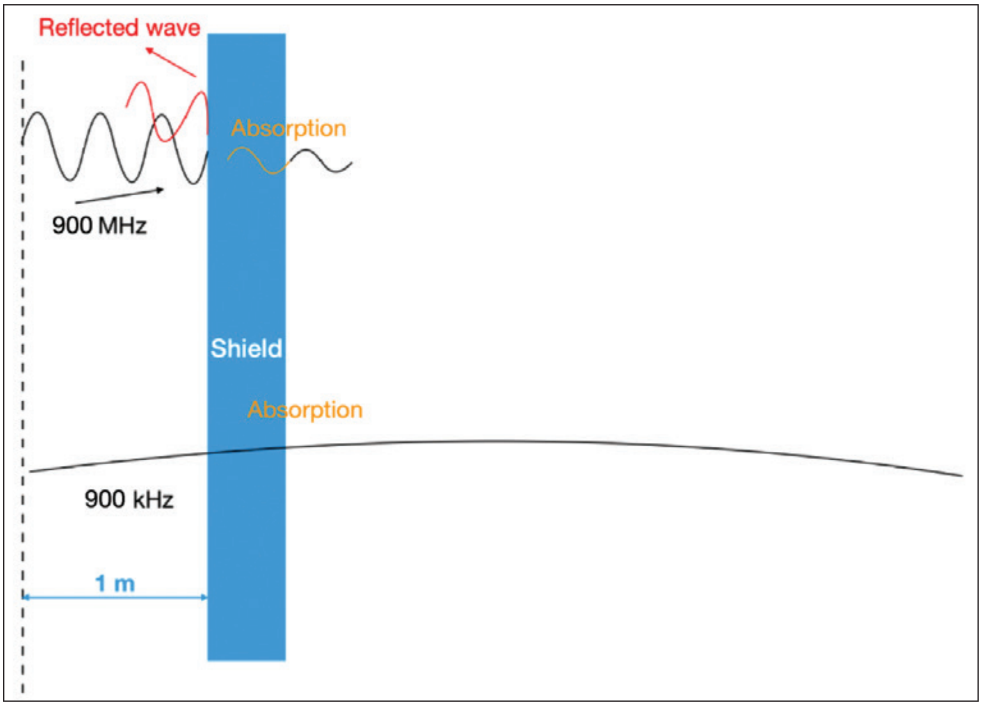


Figure 1: In near field, low-frequency noise can only be absorbed but the absorption loss is also reduced.

A simplified system diagram is shown in Figure 2. Often there is a high-voltage (HV) junction box between the HV battery pack and other HV loads. For demonstration purposes, the junction box and other HV loads are not shown.

When the traction motor is in motoring mode (that is, when the motor is in cruising mode), currents are drawn from the battery pack. The currents can reach a much higher level when the vehicle accelerates as the motor demands more power. When an EV is in braking mode, the motor starts regeneration and large amounts of currents are fed back to the battery pack. In this case, the HV wiring and harnessing determine the current-circulating loop area. Hence, the low-frequency magnetic field depends on the motor speed, the motor drive switching frequency, its operating mode, and the impedance of the cables.

The HV bus bar currents consist of many frequency contentsHere is the frequency contents breakdown:

1. From 1 Hz to a few kHz, static magnetic field noise is often generated by the battery pack and DC bus bar current flow.
2. In the frequency range of a few kHz, noise is generated by the electric frequency of a rotor, which depends on the mechanical speed and the number of poles of the rotor.
3. From tens of kHz to a few hundred kHz, noise is generated by the switching frequency of the motor drive.
4. The sharp rise time of the motor drive generates noise in the high-frequency range between a few MHz and a few hundred MHz.
5. Partial discharge of HV cables and bearing currents of the traction motor generate noise beyond hundreds of MHz.
6. The battery pack, HV cable, and the traction motor forms a C-L-C circuit; resonances could occurdepending on the geometry of the structure.

Generally speaking, it is in a design engineer's interest to shorten the cable length between the battery pack and the motor drive unit. Any extra length of an HV cable connection means an increase in loss (i^2R) and is, therefore, not desired. But the vehicle design often decides the layout of HV subsystems. When it comes to overall vehicle design, it is safe to say that trade-offs need to be made between vehicle design and safety, efficiency, and thermal effects.

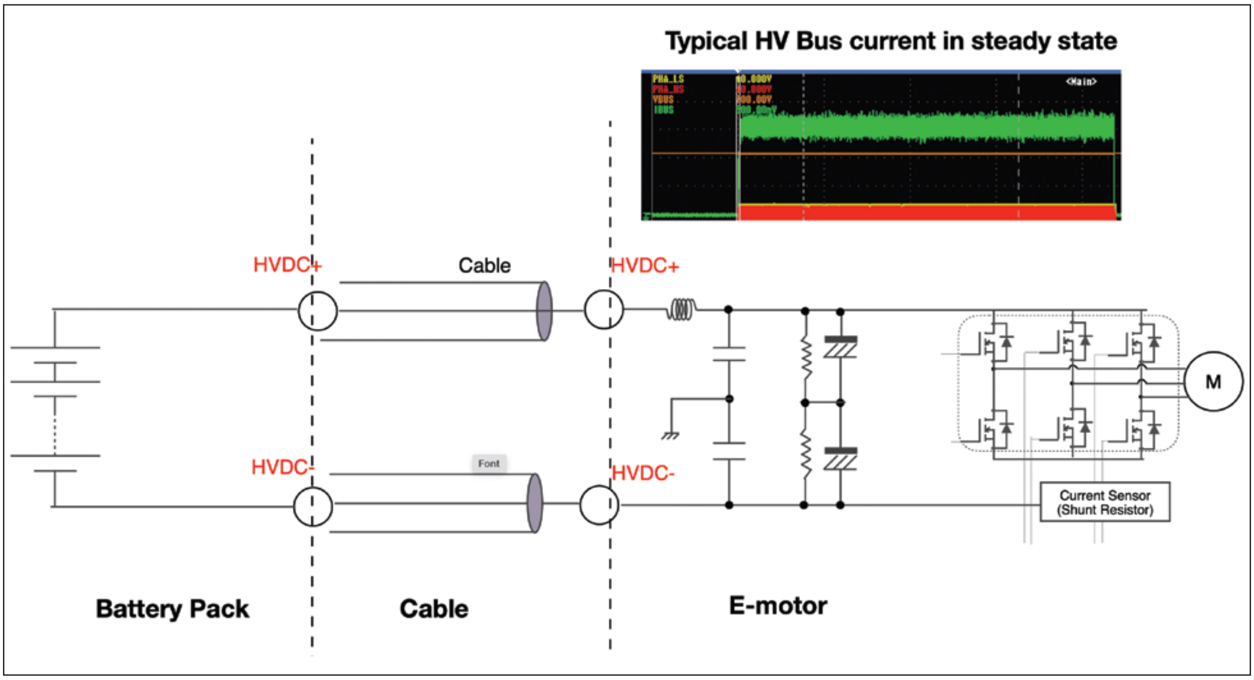


Figure 2: A simplified system diagram of a battery pack supplying power to a traction motor

As stated previously, the time-varying, operation modes-dependent traction currents lead to rapidly changing magnetic fields that can potentially disrupt Hall-effect sensors and pose electro-stimulation hazards to human tissues.

Test standards are being developed to test against low-frequency magnetic fields. The aim of these tests is to place a limit on the magnitude of the electromagnetic fields generated by a unit to ensure that compliance to the human exposure reference limits detailed in ICNIRP Guidelines can be achieved during vehicle level testing. Unless specified in the approved test plan, testing is often performed in the frequency range from 1Hz to 500 kHz using a 100 cm^2 three-axis sensor, though there can be proximity errors in the test set-up[7].

DESIGN TECHNIQUES FOR LOW-FREQUENCY MAGNETIC FIELDS

Because automotive applications are a volume manufacturing business, cost is often at the top of the list during the design stage. High-tensile steel is used to shield the 100s of kHz noise generated by the traction motor in the example shown in Figure 3.

Considered as a cost-effective solution, this approach also has the benefit of being mechanically strong, which is great from the battery pack safety point of view. It does, however, have the disadvantage of being heavy, which could be a big drawback for an EV application. One of the pain points of modern EVs is their limited mileage, which could be extended significantly when the weight of the vehicle is reduced.

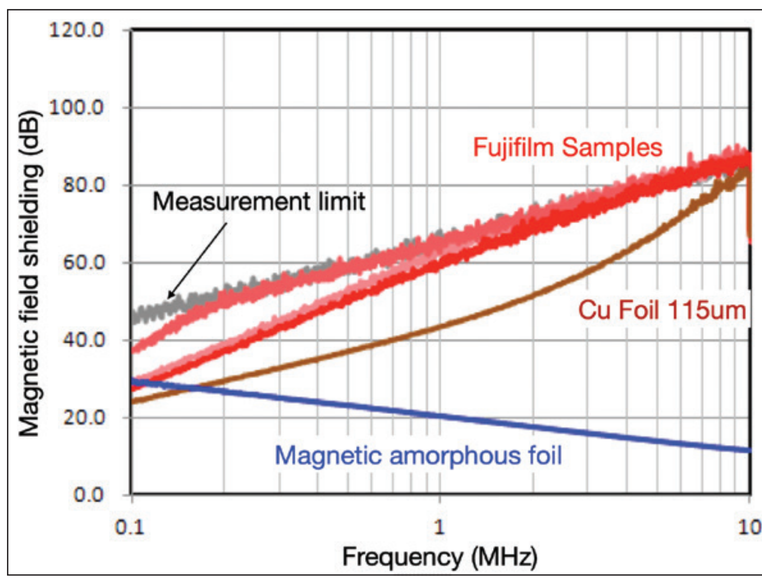


Figure 3: The low-frequency magnetic field shields developed by Fujifilm showed great shielding properties between 100 kHz and 10 MHz. (Graph courtesy of Fujifilm)

A similar application is electric aircrafts where weight is even more important. Currently, the solution there is to use aluminium material for the battery pack. But even aluminium material is considered heavy, so carbon fibre composite material is preferred. Layers of copper sheeting need to be added for shielding and to protect against lightning strikes.

There is a strong demand for better low-frequency magnetic shielding materials that have higher shielding properties, that are lightweight, and can potentially be moulded through additive manufacturing processes. As shown in Figure 3, some new materials have shown great potential in this regard. It should be pointed out here that the reference is a 115 μm copper foil, rather than high-tensile steel. Generally, below 100 kHz, steel achieves much greater attenuation than copper. From 100 kHz up to 10 MHz, copper becomes a better shield than steel. Therefore, it can be expected that this material would work well for shielding motor drives and DC-DC converters. In terms of the lower frequency performance (1 Hz to 100 kHz), such as the traction currents discussed previously, there is still a question mark. On top of that, cost is also an important factor to consider.

Because of the limited options to shield low-frequency magnetic fields effectively, a better approach is to control the magnetic fields at their source, and avoid or minimize generating them[8].

Magnetic fields depend on the loop size and the current level. Since the current level cannot be reduced, efforts should be made to reduce the loop size. Reducing loop size for low-frequency magnetic fields mainly involves:

1. Planning battery housing, which includes battery cells module layout, battery management system (BMS) wiring layout, and battery bus bar layout. The good news here is that safety, thermal, and system efficiency requirements all require an optimized wiring structure.
2. HV junction boxes also need to adopt smaller/improved conductor rail designs. This is often an area that can be overlooked by design engineers. A typical case is that bus bar/wiring can be separated by the larger contactors. In Figure 4, two examples are shown to demonstrate the point.
3. Optimizing the wiring and harnessing in the HV power network. An optimized system is often achieved by integrating multiple modules.

SUMMARY

In this article, low-frequency magnetic fields below 500 kHz in EV applications were discussed. The shielding capability of low-frequency magnetic fields is limited by the laws of physics. As a result, design engineers are left with limited options.

Reducing the magnetic field loop size and using advanced materials should be considered in the

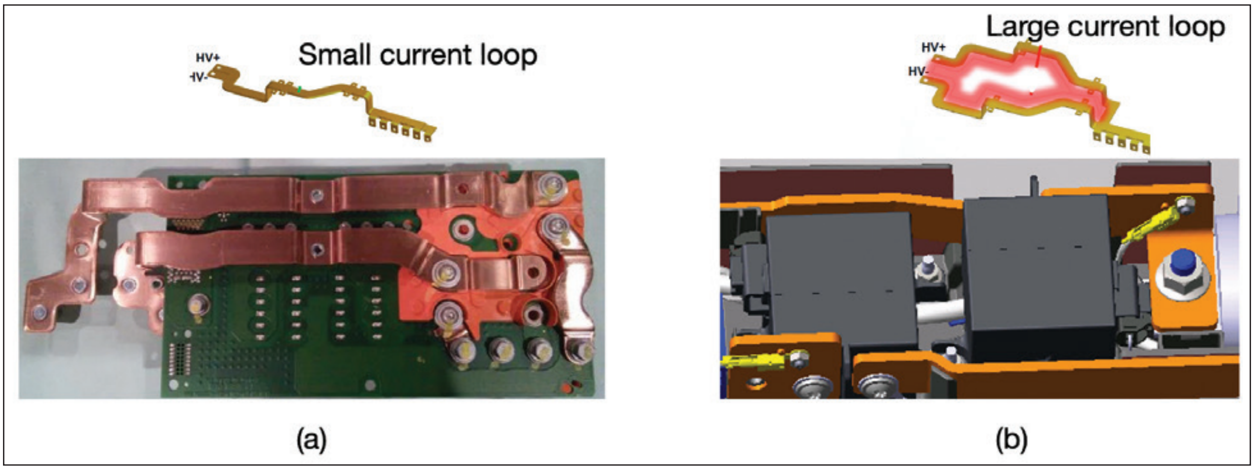


Figure 4: An HV junction box developed by Tesla (shown in Figure 4a) demonstrates the small current loop (Figure 4b). Another HV junction box has a larger current loop because of the HV contractor's layout.

vehicle design stage. Due to its superior attenuation at very low frequencies (<10 kHz), steel might still be a preferred choice for vehicle manufacturers. Integration of power modules should also reduce the risk of emitting low-frequency magnetic fields. Active shielding may be used for such applications but require further study.

ENDNOTES

1. K. Armstrong, "A Practical Guide for EN 61000-4-8 Power-frequency magnetic field immunity test," REO UK LTD.
2. EN 61000-4-8:2010 Electromagnetic Compatibility (EMC) - Testing and Measurement techniques. Power frequency magnetic field immunity test, 2010.
3. A. R. Ruddle, "Proximity Errors in Quasistatic Magnetic Field Measurements on Line Sources Using Coil Probes," *Proceedings of the 2019 International Symposium on Electromagnetic Compatiblity*, Barcelona, 2019.
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5. H. W. Ott, *Electromagnetic Compatibility Engineering*, New Jersey: Wiley, 2009.
6. Aldo Canova, Juan Carlos de-Pino-López, Luca Giaccone and Michele Manca, "Active Shielding System for ELF Magnetic Fields," *IEEE Transactions on Magnetics*, Vol. 51, No. 3, 2015.
7. See Endnote #3.
8. See Endnote #5.

EVOLUTION AND ANALYSIS OF EMC SPECIFICATIONS AT A MAJOR AUTOMOTIVE OEM

Using Insights from the EMC Specification Evolution to Make an Informed Analysis of Test Results

Arnold Nielsen has many decades of experience in the automotive electronics industry. He has worked as an instrumentation engineer, powertrain (engine, transmission) hardware/software design engineer, and as a Senior Technical Specialist in Reliability, Product Assurance, and EMC. After retiring in 2005, he has been consulting on a wide variety of products (Arnie Nielsen Consulting LLC). He is an iNARTE certified Master EMC design engineer and can be reached at arnienielsen@gmail.com.

By Arnold Nielsen

The purpose of this article is to give some history and insight into how the EMC procedures evolved at one OEM. Although other OEMs have had different paths leading to their present-day EMC specifications, they are more similar than different mostly due to the extensive reference to international standards which they have taken part in developing (e.g., EMC committees).

The EMC specifications have been developed over approximately 40 years, mostly as a compilation of actual lessons learned (some based on old issues that no longer apply) and test procedure refinement. They are all idealized simulations of the real world. Many specification setups and limits create a situation that is much worse than what would be experienced in a vehicle (could be considered as overtesting to maintain a big safety margin).

Different people looking at the same data can come up with quite different conclusions depending on their background and insight. Knowing the specification history can help EMC practitioners, especially those new to the discipline, gain insight into the implementation and the limitations of test procedures. The test evaluator should have a sense of the nature of the test and what it is trying to simulate. The goal should be to know when to "hold or fold."

CHRONOLOGICAL SUMMARY OF EMC DEVELOPMENTS

The 1970s

- Minimal electronics
- Mostly concerned with ignition system interference with radio and radio FCC certification.Europe more critical (long distances for AM)1977, Electronic Division dedicated EMC efforts started in electronic engine control (EEC)
- 1978-1981, a preliminary version of EMC component specifications being developed.
- 1978, EEC-1 was first-generation complex powertrain electronic system
- Initial vehicle EMC testing (no dedicated corporate EMC test facilities available at the time)

The 1980s

- Electronics increasing such as more complex EECsMany EMC field issues
- Only a few dedicated EMC people
- Lots of flexibility (large EMC organizations not yet established). Test procedures could change very quickly (invention stage).
- EMC design rules being developed (vehicle and component)
- 1981, the value of PCB ground planes is realized (single most important rule)
- 1982, Electronics Division first EMC specification release (43 pages)
- 1982, Electronics Division EMC component test facility on-line
- 1982, Vehicle EMC test facility on-line
- 1983, EEC-4 was the first "clean sheet" for EMC design rules application

The 1990s

- The explosion of automotive electronics technology
- Design practices, test standards/procedures maturing
- Large EMC organizations and facilities in place, large inertia (makes difficult and slow to change), perspective limited (often doesn't cross discipline boundaries).
- 1995, radio example, overcame old ingrained PCB ground myth, proved that one good ground plane much better than many
- Various specification updates led to the 1998 version where the specification was harmonized as much as possible to international standards such as ISO and CISPR

The 2000s

- Specifications maturing, similar throughout industry. Follow international standardsMinimal EMC field issues (if established design guidelines followed), most EMC contemporary issues are conducted immunity (e.g., microprocessor lock-up)
- New challenges - electric and autonomous vehicles

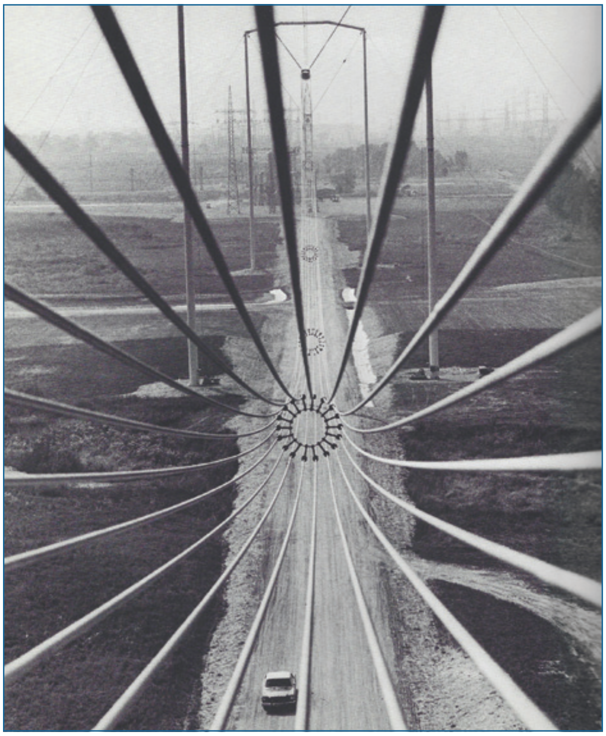

Figure 1: High voltage experimental transmission line

VEHICLE EMC TESTING

Although this article focuses mainly on component EMC testing, here is a brief history of vehicle level testing.

Early (the 1970s): Vehicle testing examples (no dedicated corporate EMC vehicle facilities available)

- Voice of America, Mason Ohio, 250kW curtain antenna
- American Electric Power research project, Indiana, 2.255 kV (see Figure 1)
- Port Austin Michigan Air Force radar station, 5 Megawatts (20us)
- Install different frequency 110-watt transceivers and antenna locations in a vehicle
- Vehicle electrical system EMC testing (reverse battery, load dump, etc.)Vehicle AM/FM radio interference (mostly ignition noise), FCC compliance

1982: Original dedicated EMC vehicle test facility (see Figures 2a and 2b)

- TEM cell with dynamometer, 60Hz/lightning pulse, 5000v/m; 10kHz-20MHz, 200v/m max
- Anechoic chamber with dynamometer rotating table, 20MHz-18GHz, 200 v/m max

2010 - Present: New corporate EMC vehicle test facility

It should be noted that the anechoic chamber method of testing the vehicle is not totally representative of the real event. For example, with radiated immunity,

Figure 2a: Vehicle transverse electromagnetic (TEM) cell

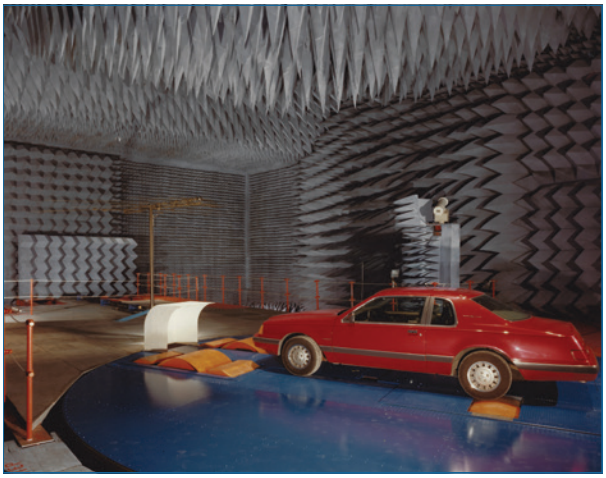

Figure 2b: Vehicle anechoic chamber

under most situations, the "real-world" source of the field is from an antenna on or near the vehicle, and the field strength rapidly falls off with distance from that antenna. However, for vehicle testing, the whole vehicle is immersed in a fairly uniform field. This is an accepted compromise for testing efficiency that is common practice today throughout the industry and can indeed identify potential"real-world" concerns.

The energy coupled into a particular system is a function of much more variability than the component testing. Table 1 shows some of the differences.

VEHICLE	COMPONENT
Complex coupling mechanism	Controlled coupling mechanism
Harness length and routing varies for individual circuits	Constant harness length and routing for all circuits
Many harness branches	Any harness branches would be different and relatively small loop areas compared to the vehicle
Many individual circuits are not "shielded"by other wires in the bundle	All circuits are within same bundle (with a few exceptions)
Distance over ground plane (sheet metal) varies	Controlled distance over ground plane
Resonances of vehicle cavities	Any cavity resonances would be different
Many circuit and wiring resonances	Limited circuit and wiring resonances

Table 1: Vehicle and component level comparison

It is easy to see that trying to correlate vehicle and component test results on a direct frequency and field strength basis does not make sense. Also, directionally, it can be seen that the vehicle test levels will be lower than the component test levels. The best approach is to ensure compliance under the controlled conditions of the component testing at a level high enough to ensure a high probability of vehicle success.

EMC COMPONENT SPECIFICATION, GENERAL

For this article, I will concentrate on component tests that offer some insight that may be useful to the automotive EMC community. European Union Regulation No 10, "Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility," is much less severe than most automotive specifications and not discussed here. Also, DC stress (overvoltage, reverse battery, etc.) is not addressed in this article.

Here's a brief summary of SAE and international standards (see References 1-6):

- SAE J1113, single document, 1975 version, revised in 1987, included Radiated Immunity (RI), Conducted Immunity (CI), Electrostatic Discharge (ESD), but no Radiated Emissions (RE)/ Conducted Emissions (CE).
- SAE J1113 series, 17 standards originally (most first published in the mid-1990s to early 2000s), 10 were subsequently canceled and replaced by ISO 11452 series.
- ISO 11452 series, 11 parts starting in 1995.
- ISO 7637-2 was originally published in 1984 (latest edition in 2011, new version being developed).
- ISO 16750-2, originally published in 2003 and does not cover many aspects of EMC (e.g., RI, RE/CE, many ISO 7637-2 transients). However, it does cover power line conducted immunity more comprehensively.
- CISPR 25, first published in 1995 (latest revision in 2021).
- ISO 10605, ESD, first published in 2001, latest revision in 2008 (confirmed in 2013).

There is also a good summary of present-day automotive EMC testing standards in the February 2016 issue of *In Compliance Magazine*.

Table 2 shows an overview of how the component EMC specification has changed over the years. It can be broken down into two periods. Before the year 2000, many new concepts were tried, such as:

- Development of many new test methods (e.g., stripline, tri-plate)
- Development of realistic load dump simulator although not used in later specifications
- RI/RE acceptance criteria quantified deviations although not included in later specifications
- Later 1990s, as can be seen in the brief summary above, standards were first becoming common.

From 2003 to present (only shows to 2016 - public domain, more recent specifications similar) reflects the maturing of corporate, SAE, and international standards. For example:

- RI: Stripline and tri-plate dropped, reverberation method added (preferred), small antenna over the device under test (DUT) to address cell phones, 14 bands (434 discrete frequencies), deviations subjective
- RE: Many specific bands and limits (was three or four continuous segments), deviations subjective
- CE: New test for low voltage (< 60v) current
- CI: Realistic transients implemented (ref 14), load dump changed to ISO pulse 5 with 0.7/0.5 Ω in parallel with the DUT
- ESD much more refined

QUALITY OF EVENT, CORRELATION

Even though the component specification tests are under very controlled conditions, it is unrealistic to expect them to act as a catchall for all potential concerns for a number of reasons, such as:

1. Many tests are idealized versions of the actual event, only an approximation to the real vehicle. They are good at comparing different components.
2. Some malfunctions only occur when the stress (e.g., transient) lines up with a certain point in software execution.
3. Impractical to test at different temperatures, components such as electrolytic capacitors can change dramatically over temperature.
4. Impractical to test some products in all their modes of operation.
5. Impractical to monitor all possible functions in detail.

Test	1. 1982	2. 1989	3. 1995; 1996	5. 1998	6. 2003	7. 2009	8. 2016
Detailed Test Plan Template				Yes	Yes	Yes	Yes
Radiated Immunity (RI), (a) Cover 1-3100M, 14 bands (434 frequencies)							
Stripline	1M-1G	1M-1G	Same	1-200M			
Tri-plate		1M-1G	Same	Same			
BCI		0.03-220M	1-400M	1-200M	1-400M	Same	Same (a)
ALSE				200M-2G	400-3100M	Same	360-3100M (a)
Reverberation					400-3100M	Same	360-3100M (a)
RI deviations	(1)	(2)	(3)	(3)	Discretion	Discretion	Discretion
Magnetic field			0.06-10kHz	0.05-10k	Same	0.05-100k	Same
Coupled immunity	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Radiated Emissions (RE), C = CISPR 25 Procedures, S = Segment							
NB, ALSE	10k-1G, 2S	10k-1G, 3S	10k-1G, 4S	150k-2G, C, 3S	150k-2.5G, C, many bands/ limits	150k-1.5G, C, many bands/ limits	530k-1.6G, C, many bands/ limits
BB, ALSE	10k-1G, 4S	NB - 10db	89/336/EEC; 150k-1G, 4S				
RE deviations			(4); (5)	(6)	Discretion	Discretion	Discretion
Conducted Emissions (CE), C = CISPR 25, V = VDE 879-3							
Time		100v p-p	+/-100v pk	Same	+100, -150v	+75, -100v	12v:+75/-150 24v:+150/-450
Frequency, NB		V, class 4	V, class 4/5	C, class 3	Similar	Similar	Similar
Conducted Immunity (CI), ISO = 7637-2, 16750-2, R = Realistic version, M = Modified, S = Sine ramp offset							
Sine	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transients	Custom	ISO 1-3, 6, 7	ISO 1-3	ISO 1-3	ISO 1-3+R	ISO 1+R	12v: ISO 1+R 24v: ISO 1-3
Load dump, P = Parallel load	Custom	ISO 5	ISO 5; ISO 5, P=0.7	R, P=0.7Ω	ISO 5, P=0.7Ω	ISO 5, P=0.7Ω	ISO 5, P=0.5Ω
Power cycling		ISO 4	ISO 4, M+S	Same	16750-2, no S	Same	Same
Power dropout			Yes	Enhanced	Same	Same	Same
Battery recovery, Groundshift (GS)		GS only	GS only; Both	Yes	Yes	Yes	Yes
ESD +/- kV P = Powered U = Unpowered		P, U = 15 Air discharge	U = 10 P = 15 Air	Same	(7)	Same	Same

Table 2: EMC component specification history summary

Table 2 Notes:

1. Minor malfunctions at 200v/m if OK at 150v/m
2. OK at 50 or 75 % of limit (many caveats). See RI Acceptance Criteria section, option 1.
3. Must comply over 90% of any 100MHz span and must comply at 50% of limit (many caveats). See RI Acceptance Criteria section, option 2.
4. Z = (statistical limit - average) / standard deviation. See RE Acceptance Criteria section.
5. SCFM = SCFM = (∑ Xi 2) 1/2 (N/Span). See RE Acceptance Criteria section.
6. PSD = ∑ (X / L) 2 / (Frequency Span / Resolution). See RE Acceptance Criteria section.
7. ESD = U, contact = 4, 6; U, air = 8; P, contact = 4, 6, 8; P, air = 4, 6, 8,15, 25 (some applications)

6. Impractical to test all subsystem component interactions. Often, EMC testing is the first time a DUT is setup up in a subsystem configuration.

The later versions of the EMC specification (starting in 1998) require a detailed test plan template to be filled out and approved before testing starts. It cannot be overemphasized how important such a test plan is at achieving meaningful test results. In addition, the quality of the test facility must be verified, for which most OEMs have a process and procedure.

CHANCE OF SUCCESS

Successfully meeting the EMC requirements with a minimum of expense and time is highly dependent on the up-front work. Going to a commercial EMC lab without this preparation and hoping for the best is risky. If you look at all the specifications throughout the industry, they are all similar but why are some outcomes better than others?It's the things that are not in a specification - the whole design and validation process. The up-front work consists of:

1. Analysis, focus on contemporary issues.
2. Verify EMC design guidelines implementation.
3. Early development testing using internal company EMC facilities.
4. If these facilities are not readily available, use low-cost methods (see Reference 7 example).
5. Failures are good (early in the design process) - information theory, maximize information.

Keep in mind that the responsibility for meeting EMC requirements is the product design (PD) engineer. Considering how EMC testing is done (test setup and limits are much more severe than in the real world) some degree of flexibility should be allowed (more on that later in this article), especially when one considers that most EMC issues are 3-6 Sigma events. EMC groups are typically a separate community and can have a narrow view. This may be in conflict with some of the realities of the PD engineer, including:

1. Limited time on each project, must keep on schedule.
2. Must address many other design and manufacturing aspects.
3. Keep costs down (weigh cost/benefit) and make a profit.

RADIATED IMMUNITY (RI)

When RI testing was first started (vehicle and component level) there were many concerns since cost-effective design techniques were not yet developed. In fact, the first EEC had developed a $100 filter connector (see Figure 3) to solve unique RI field issues (e.g., police vehicles with 110-watt transceivers). The cost was so high due to limited volume and having to pass automotive environmental specifications. Fortunately, other cost-effective methods were found before large scale production. The RI test limits max levels basis was higher power on-board transceivers which was common at the time.

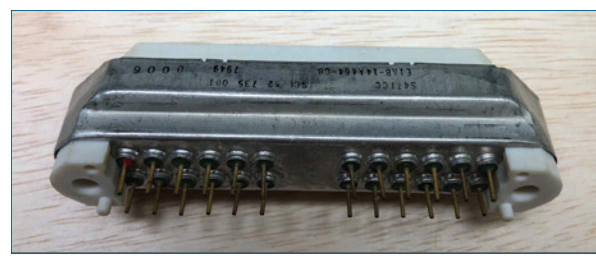

Figure 3: Filter connector

The vehicle EMC facility (1982) was also justified and built during this era of many RI concerns. However, today the number of RI actual field concerns is minimal.

Stripline (Reference ISO 11452-5): Actually, this is a microstrip but the name stripline somehow stuck. It was the first method for exposing DUT and harness wiring to RF energy with a fairly uniform field over a wide frequency range. Since many RI concerns are due to harness pickup, a stripline is good at recreating actual vehicle concerns. However, it has a limited test volume and cannot expose larger DUTs. This shortcoming was first illustrated by instrument clusters. Pre-production testing at the vehicle level showed immunity concerns (switching power supply malfunction caused damage) but the stripline did not show this effect. The tri-plate line overcame this limitation and recreated the concern by providing more test volume to insert the cluster itself within the test volume.

Tri-plate line (TPL) (Reference SAE J1113-25): The term tri-plate line (TPL) was coined by Myron Crawford who invented the TEM cell. The TPL is basically an open-sided TEM cell that has a uniform field to a higher frequency than the TEM cell since it avoids the resonances inherent in a closed structure like a TEM cell. In addition, the TPL configuration allows a wider plate separation (more test volume) and narrower width than a stripline while maintaining a reasonable impedance (70Ω). The narrower TPL width for a given plate separation translates into a higher frequency cutoff since the cutoff frequency is inversely proportional to the width. The TPL also provides a more uniform field than a stripline since the field is more contained within its volume.

Bulk current injection (BCI) (Reference ISO 11452-4): Bulk current injection (BCI) was developed in Europe as an outcome of the Falklands war (e.g., H.M.S. Sheffield's sank due to EMC issue) and its use rapidly spread because it is relatively inexpensive and easy to set up. It also does not require a lot of power (RF power amps are expensive).

Absorber lined chamber (ALSE) (Reference ISO 11452-2) *and* ***Reverberation chamber (Reference IEC 61000-4-21):*** An excellent paper that compares these two methods (Reference 8) shows there are differences in the test results between the two. However, the reverberation method is preferred since it is faster, requires less power, and provides more complete illumination of the DUT and wiring harness without the need for multiple DUT orientations and antenna polarizations.Either method will show immunity concerns.

Magnetic field: This test was developed to represent the magnetic fields set up by high current loads to which certain devices (e.g., Hall sensors) are sensitive.

Coupled Immunity, Ignition: This test simulates crosstalk (from mutual capacitance and inductance) to DUT wiring caused by secondary ignition wires. This test was deleted in newer specifications since vehicles no longer use such ignition wires.

Coupled Immunity, Transients: This test also simulates crosstalk to DUT wiring caused by other noisy wires in the same wiring bundle. The noise sources are mostly from inductive loads being mechanically switched (solenoids, motors, etc.). The waveforms are very complex and have fast rise/fall times that efficiently couple. The coupled noise has such high-frequency components and low energy that normal filtering in the DUT is usually sufficient to mitigate any concerns with this. However, some circuits cannot have much filtering, or it will affect the normal signal and may require special measures such as shielding.

For the simulator, the waveforms are best duplicated with an actual inductive load being mechanically switched. The chattering relay as described in the following section on transients is an excellent source of noise. In an actual vehicle, these transients are usually single events and very random in amplitude and duration. If these single event transients were attempted for this test, the time involved to detect a possible malfunction would be excessively long. Therefore, the noise created by this test provides a continuous series of random transients for ease of detecting a malfunction.

RI Acceptance Criteria

For the aforementioned reasons, there is not necessarily a one-to-one frequency correlation between the vehicle and component test results. However, the overall number of malfunctions, if they occur, is about the same for vehicle or component testing. The following acceptance criteria should be considered for certain RI tests since it allows some flexibility. Some older versions of the component specification made some attempts, but they never caught on. There are many reasons for this, including the intent to be conservative, the risk of litigation, and ensuring close adherence to the requirements of international standards. Newer versions allow some discretion as to what passes but are still subject to who is looking at the data, and putting a specific number on the data would help this decision.

These examples of acceptance criteria options provide minimal risk and allow some degree of flexibility in evaluating test results while ensuring that the device meets the intended design requirements. It has been empirically determined over many years of comparing component level and vehicle level test results. In addition, the specification limit already includes a big safety margin.

Also, this is just one EMC test among many. If a module passes RI with these acceptance options in addition to all the other RF tests which indirectly give an indication of RI (e.g., RE, ESD, etc.), it is highly likely to meet the intent.

Option 1: During this time frame (the late 1980s), there were limited communication bands to worry about:

- Deviations allowed at 50% of the limit, and the frequency range over which the deviation occurs is $\leq$ 5MHz. No more than three of these may occur (no more than one in a given radio communication band).
- Deviations allowed at 75% of the limit, and the frequency range over which the deviation occurs is $\leq$ 5MHz. No more than five of these may occur (no more than one in a given radio communication band).

Option 2: For all function importance categories (1, 2, 3) (References ISO 11452-1 or SAE J1812), the DUT must:

- Comply with all functional performance status requirements (i.e., I, II, III, IV) over a minimum of 90% of any 100 MHz span (sliding window).
- It may degrade no more than one functional status classification over the remaining portion of that span.
- Furthermore, it must comply with its intended functional class when tested at 50% of the specified limit.

RADIATED EMISSIONS (RE)

As is the case for RI, this test is also very dependent on the test setup. For example, a University of Kentucky study, “EMC Radiated Emissions Analysis Through Computer Modeling,” found that moving the DUT harness near the termination test fixture can result in a 20db difference in emissions at higher frequencies (influences common mode current).

There are many papers that evaluate the setups for RE (similar concepts would also apply to RI) which show how the setup is not truly representative of the actual vehicle, and differences between test labs can be high (References 9 and 10). This gets to the degree of flexibility addressed in the acceptance criteria sections later in this article.

Present-day RE limits are very complex. Having a lot of bands/limits is not realistic since it is only good for the specific component test configuration. Levels will be amplified or attenuated differently in the vehicle. It’s more important to control the total energy emitted.

Narrowband (NB) and Broadband (BB)

This distinction between narrowband and broadband has caused much confusion and test complexity over the years. By using the CISPR 25 test methods with bandwidths that represent the "real-world" receiver bandwidths (e.g., AM and communication FM = 9 KHz, Entertainment FM = 120 KHz), these concerns are minimized. In addition, the need for a separate broadband test is eliminated.

RE Acceptance Criteria

In the context of the automotive industry, the present method of using a limit line for determining module radiated emissions acceptance is too simplistic and is not the most effective way to make competitive business decisions. The limit line approach does not address many real issues.

It is very difficult if not unpractical to get the same results at each frequency from different test labs for radiated emissions due to the many variables involved. However, it is possible to establish a correlation between different testing laboratories on a statistical basis. Some technical papers (References 11 and 12) have suggested a solution. For example, if only the highest emission levels are compared independent of the emission frequencies, a higher degree of correlation is possible. Such an approach may be justified under the assumption that the test facility design does not significantly affect the total emissions power but mainly leads to the radiated power spectrum redistribution.

The simplistic approach of being below a limit line can result in chasing a red herring and overdesign, needlessly increasing the cost. For example, even if the RE is consistently below a limit line, it is more probable that a real-world concern would exist if there were many spectral lines close to and under the limit (i.e., the spectral density would be high). Another situation would be to fail a module that only had a few data points slightly over the limit but otherwise showed little emissions.

There are many differences between the module test setup and the vehicle configuration (see Table 1) and it is unlikely that there is a one-to-one correlation between the testing laboratory and the vehicle (at each frequency). For example, even if a module was below a limit line using the bench test configuration, there would be an entirely different configuration in the vehicle so that those frequencies that were below the limit line are now connected to a system that more effectively radiates, resulting in customer concerns.

Newer versions of the specifications have some discretion as to what passes, but the ultimate decision is subjective and depends on who is looking at the data. With that in mind, consider using a limit line (not applicable to legal requirements) as only one part of a decision for acceptance.

Z score: This was included in the 1995 spec version. If emissions are above the limit, apply a statistical limit 5dB above the preferred spec limit. Within each antenna range, compute the average, standard deviation, and resulting Z score. Z shall be > 1.3. Use linear values (not log).

$$Z = (\text{statistical limit} - \text{average}) / \text{standard deviation}$$

Spectrum content figure of merit (SCFM):

$$SCFM = (\sum Xi^2)^{½} (N/Span)$$

Xi = Emission peak value (linear units), N = Number of spikes in chosen frequency span,

Span = Frequency span

PSD: Another option that was included in early versions of the component specification was radiated emissions narrowband data analysis – power spectral density (PSD), (Reference 13). An important parameter to consider is the total amount of power available to excite the vehicle wiring – PSD addresses this concept.

$$PSD = \Sigma (X / L)^2 / (\text{Frequency Span} / \text{Resolution})$$

Where X is the value of the data point in linear terms (uv/m) and L is the preferred limit at the frequency of the data point.

The PSD was automated for a time, just to see if the concept works. Basically, it is the same as an EMC expert looking at it and saying it is OK or not. Figure 4 shows an example. All of these emissions change around with harness lengths so you're just looking for how much energy is there. It's energy because you square the voltage and divided by a certain bandwidth. With a little experience, you learn what is good or not. When this concept was presented to the EMC community (SAE J2556), I thought it would be accepted as a more reasonable approach. However, it never caught on for the same reasons stated in the RI Acceptance Criteria section.

CONDUCTED EMISSIONS (CE)

Time Domain: The limit of, for example, +/- 100 volts is deceptively simple. When this test was first being developed, a complicated peak voltage vs. pulse width specification limit was considered.However, by just specifying the peak voltage, a number of things are

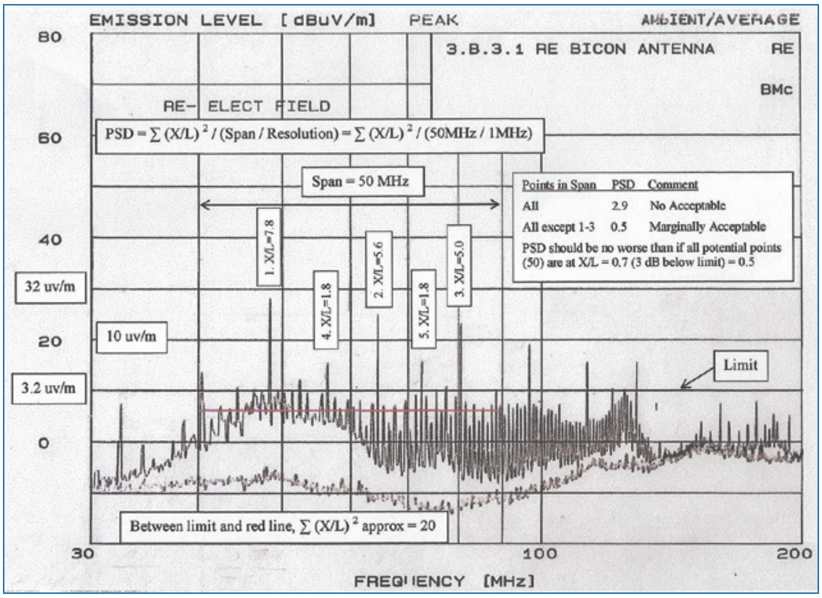

Figure 4: PSD example

implied; it simplifies testing, and arcing and glow discharge are controlled. It is important to get a good clean break of the current to get the peak voltage since you don't want switch bounce where you get a series of smaller voltage peaks.

Frequency Domain: This test addresses controlling continuous or long-duration emissions on power leads (e.g., commutator brush noise, pulse width modulation). Early specification versions used VDE 0879-3 procedures and limits. All subsequent versions (starting in 1998) use CISPR 25. The purpose of this test is similar to that of the radiated emissions test. However, in the radiated emissions test, the wires are bundled together which may give a radiation canceling effect due to the flow of current in adjacent wires in opposite directions. This test addresses systems that draw current through large loop areas (e.g., power feed from fuse panel and ground through sheet metal) where this canceling may not occur.

CONDUCTED IMMUNITY (CI)

General

These tests are applicable to active electronic DUT circuits connected to the vehicle electrical power system directly such as power input, keep alive memory, monitoring inputs (i.e., circuits which are connected to the electrical system when activated such as A/C clutch coil, neutral drive switch, brake switch), or indirectly such as an output connected via load to power.

The two relevant international standards are ISO 7637-2 and 16750-2. ISO 7637-2, originally published in 1984, had many pulses/waveforms (1-7) but have been reduced to only pulses 1-3 (2004), Pulse 4 (power cycle) and Pulse 5 (load dump) now reside in 16750-2, Pulses 6 and 7 were outdated and deleted.

Sine

Represents worst-case noise (i.e., non-fault conditions) created in the vehicle electrical system at lower frequencies. Also represents faulted conditions such as the engine running with the battery out of the circuit (e.g., loose connection or frozen battery after jump start).

Transients

ISO 7637-2 Pulses 1-3 do not identify contemporary field concerns because they do not replicate the actual mechanism creating the transient. Their main attraction is that they are very repeatable. However, they are not representative of the actual vehicle.

A more representative version of vehicle transients is given in newer versions of the EMC specification (starting in 2003). Reference 14 gives a detailed analysis.

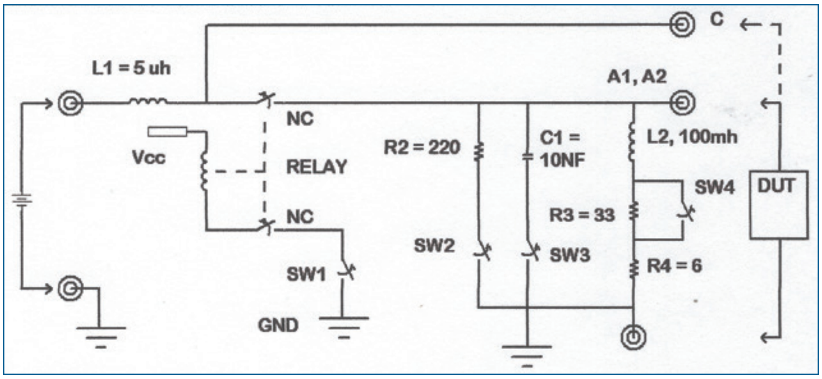

Figure 5: Chattering relay dropout and transient example

A key element of these newer, more realistic transients is the chattering relay. The chattering relay test simulates these transients and interruptions by configuring a single relay in a unique fashion. The configuration consists of placing the normally closed (NC) set of contacts for the relay in series with the DUT power input. Figure 5 shows a simplified example where selectively closing SW1-4 can achieve different types of dropouts and transients.

The relay has a 12 VAC coil operated from 12 VDC (AC coil resistance much lower). This gets the correct current to create the right degree of contact arcing. Since this relay is a mechanical device, it creates a unique combination of transients and interruptions every time the contacts open or close that is very effective in determining if the DUT has a conducted immunity concern. The chattering relay test is superior since it generates a random series of events. This randomness is extremely critical for microprocessor type DUTs since the transients must often line up in time with a certain point in software execution to have an effect. Newer versions of ISO 7637-2 include these chattering relay transients.

Load Dump

In early versions of the EMC specification (1996 - 1998), the load dump simulator circuit was based on data taken from a special load dump test stand consisting of an electric motor that drives an actual alternator. The load dump open circuit condition is set up with the load current in the range of 100 amps - both the battery and approximately 0.15 ohms across the alternator output. The open-circuit voltage is developed when this load is suddenly removed.

The actual test condition with the DUT in the circuit is set under similar conditions except that a load is placed in parallel with the DUT (0.7 represents the minimum vehicle electrical loading such as fuel pump and engine control, 14 v / 20 amps).

This test is among the most severe tests and potentially destructive and gets a lot of attention since it often involves adding cost. However, analysis has shown that ISO Pulse 5 load dump simulators were not realistic and could result in overdesign. An important parameter that must be duplicated in a realistic simulator is the action integral (integral of I^2 dt) imparted to the DUT. This is the parameter that causes damage to many devices. Tests were conducted comparing the results of three different methods of subjecting a Metal Oxide Varistor (MOV) to a load dump, as follows:

1. A commercial simulator, ISO pulse 5, 38 A^2 sec, which resulted in permanent damage.
2. Actual alternator is driven by electric motor as mentioned above, 8 A^2 sec, which resulted in no damage.
3. Custom-designed electronic simulator based on 2. above, 10 A^2 sec, which resulted in no damage.

Even though all three tests transfer approximately the same Joule energy to the DUT, the commercial simulator had a much higher action integral, and the custom electronic version is much closer to the actual electromechanical (alternator) version. Recent versions of the EMC specification have reverted to the use of the ISO 7637-2 Pulse 5 (now resides in ISO 16750-2) due to its wide use in the industry. However, adding a parallel load (e.g., 0.5 Ω) absorbs most of the energy.

It should be noted that the actual load dump waveform (without loading) is much more complex than the waveforms created by these electronic simulators. The real event consists of an arcing period of about 50us to 10ms followed by a positive spike up to 200 volts of about 50 - 100us. After this spike, the alternator voltage decays according to the field coil circuit time constant. During this decay, high alternator ripple is superimposed on the waveform.

POWER CYCLE

This test (similar to ISO 16750-2, starting profile) determines the immunity of a DUT to voltage drops and the sinewave waveform due to cold engine starting. In a cold start, before the starter motor begins rotating, it is in a stalled condition and draws a large amount of current. As an example, assume the battery resistance is 0.03 ohms when cold and the starter draws 300 amps, which would create a battery voltage of less than 4 volts. Once the starter motor rotates, the voltage increases due to lower starter currents after the initial stall condition. The main concern is unpredictable DUT operation.

For this test, the test setup should retain a low impedance. The sinewave portion of the power cycle is meant to represent engine cranking, in which the exhaust and compression cycles present a varying load on the starter motor and result in the sine voltage. Early versions of the specification also had this sine portion offset ramping, which was deleted in later versions to align with international standards. This offset is important since it was derived from field concerns. It's important not to simplify the waveform with a square wave; the sine is more realistic, and using a square wave will not detect concerns related to circuits that are sensitive to hysteresis (e.g., voltage detecting).

Power Dropout

Similar in intent to ISO 16750-2, discontinuities in supply voltage, power dropout tests are meant to represent a number of things and are among the most important tests in the specification with regard to major field concerns. In the late 1990s, there were a lot of microprocessor-related lock-up issues. Enhanced tests were developed to ensure that a DUT was sufficiently robust to minimize power dropout risk from this issue. The test consists of square wave cycling of various periods and single dropout of various durations. These tests don't necessarily represent what is found in the vehicle but rather what would really be a worst-case upset for a DUT with a microprocessor. Software algorithms were developed so that they would always recover, no matter the specific circumstances.

This test also addresses switch bounce and intermittent connections. The real-world waveforms due to these events are very random in nature. One of the mechanisms for intermittent connections is due to connector pin corrosion buildup over time (fretting), a common finding in older vehicles with inexpensive, open connectors. If the pins/wires in the connector shell are not rigidly retained and sealed, the connection can be momentarily broken when the vehicle hits a bump on the road.

For all power dropout tests, the test setup should duplicate the open circuit condition. This is done by inserting a series diode with the simulator. In addition, a resistance is placed across the DUT to represent other vehicle loads between the DUT and the intermittent connection. This resistance bleedsoff the input capacitor charge, as would be the case in the vehicle.

Battery Recovery

Similar in intent to ISO 16750-2 slow decreases and increases of supply voltage, the battery recovery test is based on the following sequence. A vehicle battery becomes discharged (e.g., cold weather cranking didn't start the engine). The vehicle is left overnight, and the battery voltage slowly rises and recovers to some extent. Although there is not enough energy to start the vehicle, the voltage goes through a critical value that causes too many DUT EPROM cycles, which wears it out. This test would only apply to devices directly connected to the battery that draw small currents. Other situations that draw any appreciable current would pull down the battery voltage.

Groundshift/Offset

This test was originally developed to evaluate EEC immunity to noise on the ignition ground circuit between the EEC module and the thick film ignition module (TFI). The TFI is grounded at the distributor, and the EEC is grounded at the battery. Noise between the two (e.g., turn signals, stop light, etc.) could cause erratic operation. Another example is the vehicle speed sensor which is grounded at the transmission and feeds the instrument cluster, which is grounded to the instrument panel. Noise from the ignition system could trigger a speedometer indication even though the vehicle was not moving.

In earlier versions of the specification, the noise was injected via the secondary of a transformer. However, this created problems for modules that drew higher currents since the transformer secondary had an impedance of 0.5 ohms. Recent versions of the specification use a low impedance power amplifier.

ESD

In general, ESD testing has a reputation for being non-repeatable. However, this is really not the case when the mechanisms involved are fully understood. Here are some of the issues that affect ESD testing repeatability:

1. For all ESD testing, the placement/orientation of the DUT with respect to the ground plane is critical. The amount of charge that is transferred to the PCB is proportional to the ratio of the capacitance of the PCB (with respect to the test ground plane – i.e., stray capacitance) to the capacitance of the ESD simulator. Also, the ESD current paths depend on the orientation of the DUT. To illustrate this, for the unpowered handling test, when modules are placed perpendicular to the ground plane with the connector up, they may be damaged by the ESD currents flowing the length of the PCB from the connector pins to the ground plane. This is unrealistic and results in failures that do not occur in the field.
2. The routing of the ESD gun ground strap is critical for repeatability since it radiates. Connect ESD gun ground strap (inductance < 1.5 microhenries) to the ground plane. It should be routed as far as possible from the DUT.
3. The simulator probe should be perpendicular to the test point (+/- 15 degrees). The probe tip should be slowly (approximately 1 cm/sec) moved towards the test point until a discharge is obtained. Variations in the speed of approach can lead to a variation in the rising slope of the current waveform (amps/nanosecond) by a factor of 20 or more. Therefore, a fixture to control the approach speed and angle is advisable to ensure the best repeatability.
4. Completely different DUT responses can occur at different ESD voltage levels. Low-voltage and high-voltage ESD pulses uncover more concerns than medium-voltage pulses. At lower voltages, the rise times are faster and peak currents higher (less corona bleed-off). At high-voltages, a series of multiple discharges can occur. The ESD multiple discharge phenomenon is characterized by successive pulses, each possessing lower energy levels than the previous pulse. Subsequent pulses can be separated by a time period ranging from 10 us to 200 ms. For medium-voltage ESD pulses, multiple discharges are less likely, and the associated corona predischarge will slow down the rise time while limiting the peak current.
5. Pins/terminals should be discharged between ESD discharges via a 1 Megohm resistor to prevent cumulative voltage buildup.
6. Use an ESD static meter to verify that a charge buildup is not occurring between ESD discharges. Such a buildup will make subsequent discharges non-realistic since the ESD gun and the DUT will be at similar charge levels, thereby preventing a discharge. If charge buildup is present (usually the case for DUT with nonconductive housing), use an air ionize to neutralize the charge.
7. In-house-built ESD simulators are not acceptable since construction is very critical. In addition, guns from different vendors are not the same. Studies have shown that, even though the voltage waveform is similar when tested into a standardized termination, there are other events occurring, such as the radiated fields, which vary from one simulator to another. In fact, these emissions can vary with different simulator orientations with respect to the DUT.
8. The voltage and power threat for an IC mounted on a PCB can be much worse than an IC by itself. The voltage rating of an IC is often confused with the module ESD test level. The ESD rating for an IC is under completely different test conditions (e.g., direct discharge to each pin, not air discharge). It is not possible to establish any meaningful relationship between individual ESD immunity levels of ICs, and the ESD immunity level of a PCB as a whole.

TEST COST, EFFICIENCY

With the ever-increasing use of electronics, especially when considering electric and autonomous vehicles, a more efficient EMC testing process is desirable. In addition, if a module maker supplies components to multiple OEMs, the cost (money and time) in meeting various specifications can be very high. Ensuring compliance with each specification can be over $150k per iteration for devices with many modes of operation, such as a radio (e.g., AM, FM, Sirius).

Some options worth considering to address test cost and efficiency include:

1. Follow the approach for analyzing data presented earlier in this article to avoid over-testing (see RI, RE acceptance criteria).
2. Another option that may have some appeal is to use a generic specification, allowing some minor differences unique to an individual OEM. Present specifications are already somewhat generic since they heavily reference international standards. Some generic examples are:
   - A generic automotive (Tier1) EMC test standard, http://www.tridatacom.co.uk/Downloads/Papers/Papers/AutoEMC2006.pdf
   - ZVEI (German Electrical and Electronic Manufacturers Association) Generic IC EMC Test Specification, May 2017
3. Since present-day OEM specifications are very similar, another option is that one OEM could accept another OEM's test results, at least in part, if some criteria are met and are verified at an accredited EMC lab.
4. Module supplier proposing an EMC specification. Since some suppliers deal with many OEMs, they may have a wider, more cost-effective perspective.
5. For some products that meet certain requirements (such as following established EMC design practices, a mature product design with a good track history, or current compliance with similar specifications), only some of the tests may be required.

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INCORPORATING ETHICAL CONSIDERATIONS INTO THE DESIGN PROCESS

Prioritizing Responsible Innovation Via End-User Values

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By John C. Havens

We live in a time during which new products and systems are being introduced at a dizzying pace. Many of these products and systems rely on artificial intelligence and machine learning (AI/ML) techniques for analysis, decision-making, and operation, leading to more functional, autonomous, and capable systems that are used in all spheres of human activity.

We can hardly make a phone call or a financial transaction, perform our work, attend classes remotely, travel, watch television, or do much else without using systems that rely on AI, at least to some degree. As systems using AI are predominant in our daily lives, a level of trust in them is needed, and therefore they must reflect our human values and respect regulatory obligations.

However, the growing use of artificial intelligence systems brings with it a growing potential for misuse and mistakes, which can harm users in disparate ways and lead to a lack of trust in these systems. A reason for this is that AI is driven by algorithms that, while invisible to users, deeply affect end-user data, identity, and values, leading to potential ethical conflicts.

Ethics are the broad principles that govern behavior and drive individuals' interpretations of the world. The ethics related to AI technologies are complex, but they are key to preventing harm and ensuring end-user trust in a system.

Trust is degraded when, despite the best intentions of a manufacturer, inadequate efforts are made during product development and systems design to analyze and test how end-users will interpret a product, service, or system versus end-user values. In these cases, its design will, in all likelihood, prioritize the values of its creators over those of end-users.

THE IMPORTANCE OF VALUES-BASED ENGINEERING IN BUILDING TRUST IN PRODUCT DESIGN

How to construct a rigorous methodology to reduce harm to users, earn their trust, and thereby promote innovation has been challenging. That's because products such as voice assistants in our homes, driver assistance systems in our cars, automated production systems in our factories, and a litany of other autonomous and intelligent systems have become so pervasive that their growth is outpacing society's ability to identify and address the ethical concerns which accompany their perception and use.

Compounding this is the fact that they are also being used by diverse populations and in geographies with differing values and levels of technological sophistication.

Therefore, there is an urgent need to ensure that the design and development of new products and systems take place using a rigorous values-oriented, applied ethics methodology that complements traditional systems engineering practices while also supporting human and social values.

Such a values-based engineering (VbE) methodology will help enable all relevant human-centric, values-driven issues to be defined, prioritized, addressed, and integrated with functional requirements during systems design. It can help ensure that these non-functional requirements are treated as key performance indicators (KPIs), which are just as relevant and important as are traditional KPIs like operating speed, energy efficiency, and so forth.

Further, when values-based methodologies are used as KPIs for success, the opportunity arises to assess and certify conformance based on these kinds of results.

The IEEE Standard Association's IEEE 7000-series of standards and recommended practices encompass various aspects of ethics in engineering such as data privacy, children's/student's data governance, algorithmic bias, privacy, and more.

Thus, in much the same way that people will buy a certain toothpaste because it has a mark from the American Dental Association (in the U.S.), end-users and customers will begin to buy things like voice-assisted audio systems because they have been certified as "trustworthy AI" by an accredited organization.

TOLD BY A MACHINE THAT HE WOULD DIE

An example that illustrates the need for applied ethics in systems design comes from the field of healthcare. Over the past few years, telemedicine has enabled many patients to interact with their healthcare providers remotely and safely. But telemedicine went terribly wrong in March 2019 when 78-year-old Ernest Quintana was taken to a hospital emergency room in Fremont, CA, suffering from chronic lung disease and unable to breathe.

Later, after he had been transferred to the intensive care unit, a robotic machine rolled into his room while his daughter was sitting with him, and a doctor used its video capabilities to tell Quintana matter-of-factly that he would die within days. It was bad enough to be given this news via a machine, but to make matters worse, his daughter had to repeat to him what was said because he was hard of hearing in one ear and the machine couldn't get to the other side of his bed.

The family was devastated. The man's daughter was quoted in local news media as saying, "If you're coming to tell us normal news, that's fine. But if you're going to tell us there's no lung left, and we want to put you on a morphine drip until you die, that should be done by a human being and not by a machine."[1]

In this instance, a simple geofencing technology could have been used to trigger an alert to Quintana's family that a robotic device, and not a doctor, was about to enter their loved one's room, giving them the chance to assert that only minor health-based reports should be given directly to their father.

That way, the family's wishes also could be transmitted to the doctor so that the doctor could recognize them and respond appropriately.

NEW IEEE STANDARD ADDRESSES ETHICAL CONCERNS IN SYSTEMS DESIGN

To provide a path forward to help ensure that such ethical considerations are considered right from the outset in systems design, the IEEE Standards Association has published a new standard, IEEE 7000™-2021, "IEEE Standard Model Process for Addressing Ethical Concerns During System Design."

A first-of-its-kind standard, IEEE 7000-2021 describes how to pragmatically apply a VbE approach to elicit, conceptualize, prioritize, and respect end-user values in system design. It establishes a well-defined process model and a standard approach for integrating human and social values into traditional systems engineering and design; sets forth processes engineers can use to translate stakeholder values and ethical considerations into system requirements and design practices; and details a systematic, transparent, and traceable approach to address ethically oriented regulatory obligations as well.

The standard guides technology developers through an extensive feasibility analysis, consisting of questions and exercises designed to identify the values and ethical biases of the end-users who may buy or use their product or system. Once these answers are identified, they are "translated" into design characteristics and then assimilated into traditional systems engineering and design processes.

The new standard uses the example of airport security scanners as a guide to users who are seeking to address

While more traditional standards focus on technology interoperability, functionality, safety, and trade facilitation, the IEEE 7000-series addresses specific issues at the intersection of technology and ethics.

core issues of identity and privacy in system design. This example was chosen because, in the past, these scanners were built to optimize speed and efficiency over privacy. As a result, scans of people's bodies were often considered invasive by passengers and distasteful by people with gender-normative issues or by physically limited individuals.

PART OF A LARGER ETHICS TOOLSET

IEEE 7000-2021 is one of the latest standards published in the IEEE Standard Association's IEEE 7000-series of standards and recommended practices that encompass various aspects of ethics in engineering such as data privacy, children's/student's data governance, algorithmic bias, privacy, and more. While more traditional standards focus on technology interoperability, functionality, safety, and trade facilitation, the IEEE 7000-series addresses specific issues at the intersection of technology and ethics, with the goals of empowering innovation across borders and enabling societal benefit.

For example, IEEE 7010™-2020, "IEEE Recommended Practice for Assessing the Impact of Autonomous and Intelligent systems on Human Well-Being," establishes well-being metrics relating to human factors that are directly affected by intelligent and autonomous systems. The standard establishes a baseline for the types of objective and subjective indicators these systems should analyze, honor, and include at the outset of their programming and functioning in order to proactively align with and increase human well-being.

The IEEE 7000 series complements the IEEE Standard Association's Ethics Certification Program for Autonomous and Intelligent Systems (ECPAIS), which is creating specifications for certification and marking processes that advance transparency, accountability, and reduction in algorithmic bias in autonomous and intelligent systems. The IEEE CertifAIED certification has great value in the marketplace and for society at large, as it helps consumers and citizens understand whether a system is deemed "safe" or "trusted" by a globally recognized body of experts who have provided a publicly available and transparent series of marks.

The IEEE 7000-series also aligns with the IEEE Global Initiative on Ethics of Autonomous and

Intelligent Systems, the mission of which is to ensure that every stakeholder involved in the design and development of autonomous and intelligent systems is educated, trained, and empowered to prioritize ethical considerations so that these technologies are advanced for the benefit of humanity.

A foundational element of that initiative is the comprehensive report series, "Ethically Aligned Design," that combines a conceptual framework addressing universal human values, data agency, and technical dependability with a set of principles to guide creators and users of autonomous and intelligent systems through a comprehensive set of recommendations.

Created by more than 700 global experts focused on the pragmatic application of human-centric, values-driven design, "Ethically Aligned Design" is intended for a wide range of audiences and stakeholders. The report series content identifies specific verticals and areas of interest and helps provide highly granular and pragmatic papers and insights. It provides guidance for standards, regulation, and/or legislation for the design, manufacture, and use of autonomous and intelligent systems and can serve as a key reference for the work of policymakers, technologists, and educators.

ETHICAL DESIGN AS A PATHWAY TO INNOVATION

A key benefit of IEEE 7000-2021 is that it offers alternative ways to address risk. Whereas traditional evaluations of technological risk may focus largely on areas of physical harm, the VbE methodology at the heart of IEEE 7000-2021 provides a broader lens that can be used to consider potential harms to the ethical values that are associated with product or systems design. This helps make the standard a catalyst for the adoption of applied ethics methodologies in emerging technologies such as AI.

This is a hugely important issue for our times, given the pervasiveness of these technologies. As the "Ethically Aligned Design" report puts it,

> *"Ethics considerations are often treated as impediments to innovation, even among those who ostensibly support ethical design practices. In industries that reward rapid innovation in particular, it is necessary to develop ethical design practices that integrate effectively with existing engineering workflows.*
>
> *Those who advocate for ethical design within a company should be seen as innovators seeking the best outcomes for the company, for end-users, and for society. Leaders can facilitate that mindset by promoting an organizational structure that supports the integration of dialogue about ethics throughout product life cycles."*

SUSTAINABILITY AS THE FUTURE OF ETHICAL DESIGN

Whatever the organization, the future of ethical design must focus on pragmatic ecological sustainability to ensure people and the planet can live safe and meaningful lives. While there are numerous laudable sustainability initiatives designed by and for organizations to utilize, most plans focus on identifying potential harms to the environment after a product, service, or system is created. While these are essential scenarios to plan for, they need to adopt broader metrics of success at the outset of design in the exact same way end-user values must be considered for AI or other ethical considerations as mentioned above.

Fortunately, there is a renewed focus on organizations utilizing environmental, social, and governance (ESG) metrics to specifically identify what areas of their business operations can move from a reliance on fossil fuels to green alternatives. While this may seem like a daunting task, reports like "Winning the Race to Net Zero: The CEO Guide to Climate Advantage," written through a partnership between the Boston Consulting Group and the World Economic Forum, points out that an initial pass at creating a sustainability program is like any other cost-cutting program to eliminate short- or long-term expenses. As the report further notes, examining financial issues around sustainability also means identifying immediate benefits coming from green tax or loan access to longer-term necessities like complying with growing regional and global regulations.

The IEEE has created a standard that provides a "societal impact assessment" methodology for any organization to begin to get a grasp on which ESG and other metrics or indicators that can pragmatically move the needle on their sustainability programs. The previously mentioned IEEE Recommended Practice for Assessing the Impact of Autonomous and Intelligent Systems on Human Well-Being provides an introduction to multiple sustainability (planet and people-based) metrics that should be used at the outset of all technology processes (not just AI systems) to help establish that products, services or systems that are created have KPIs showing how a technology, once released, probably increases environmental flourishing. A key distinction here is to recognize that, just because a technology doesn't harm the environment overtly via established emissions or other standards, without restoring the larger ecological systems and reducing overall carbon emissions, individual products may harm the planet from a systems-level perspective.

Where ethically aligned design prioritizes human values and well-being, sustainability elevates ecological systems to have the same rights as people to protect and increase planetary flourishing now and for the future.

ENDNOTE

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ESTIMATING THE PARASITICS OF PASSIVE CIRCUIT COMPONENTS

By Bogdan Adamczyk, Nick Koeller, and Megan Healy

This article presents a simple method of estimating the parasitics of the three passive circuit components (R, L, C). First, the non-ideal model of each component is presented, followed by the network analyzer measurements. The component (approximate) model serves as the basis for analytical calculations leading to the values of the parasitics.

The PCB used in this study, [1], is shown in Figure 1.

Since the calibration traces are of the same length as the traces leading to the components, the connectors and traces are effectively taken out of the measurements. Thus, the measured parasitics come from the component itself and not from the connecting traces. It should be noted that this approach is not targeting the impedance measurement accuracy but rather provides the simplest way of estimating the component parasitic values. More accurate methods exist [2-5].

1. RESISTOR MODEL AND ITS PARASITICS

Circuit model and the impedance vs. frequency curve (straight-line approximation) for a resistor and its parasitics (with no traces attached) are shown in Figure 2 [6,7].

Figure 3 shows the measurement setup used to obtain the impedance curves for three different resistor values.

Resistor impedance curves are shown in Figure 4.

Each curve shows a 3-dB point corresponding the frequency (shown in Figure 1):

$$f = \frac{1}{2\pi RC_{par}} \quad (1)$$

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Megan Healy is pursuing her Bachelor of Science in Electrical Engineering and Bachelor of Arts in German Language at Grand Valley State University. She currently works full time as an Electromagnetic Compatibility Engineer co-op student at E3 Compliance, which specializes in EMC and high-speed design, pre-compliance, and diagnostics. She can be reached at megan.healy@e3compliance.com.

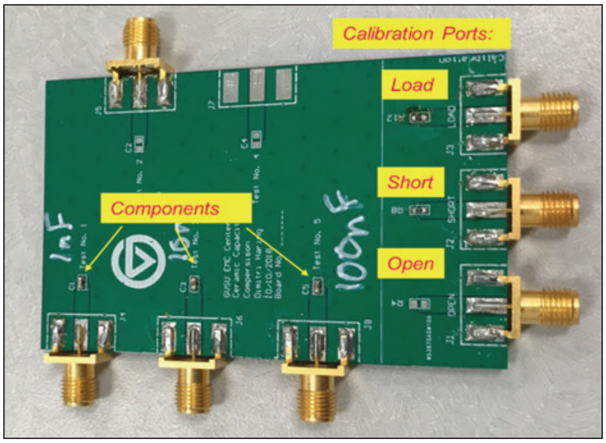

Figure 1: PCB and its details

From Equation 1, the parasitic capacitance can be obtained as:

$$C_{par} = \frac{1}{2\pi f R} \tag{2}$$

The resulting parasitic capacitance values for the three resistors are shown in Table 1.

2. CAPACITOR MODEL AND ITS PARASITICS

Circuit model and the impedance vs. frequency curve (straight-line approximation) for a capacitor and its parasitics (with no traces attached) are shown in Figure 5 [1,2].

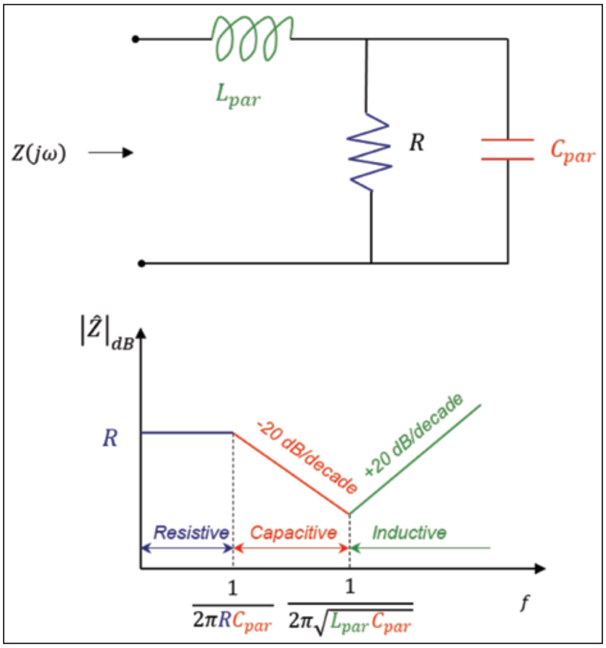

Figure 2: Resistor circuit model and its impedance curve

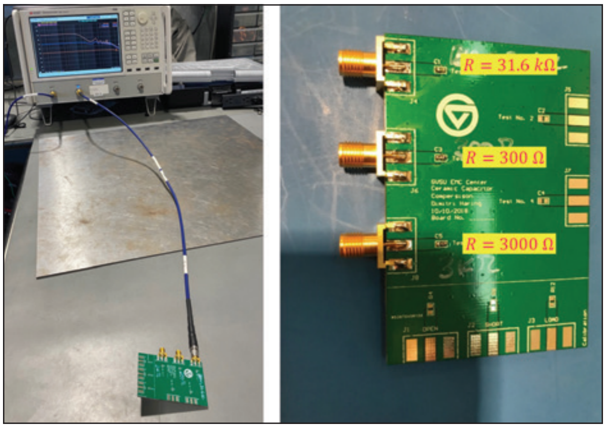

Figure 3: Measurement setup – resistor impedance curves

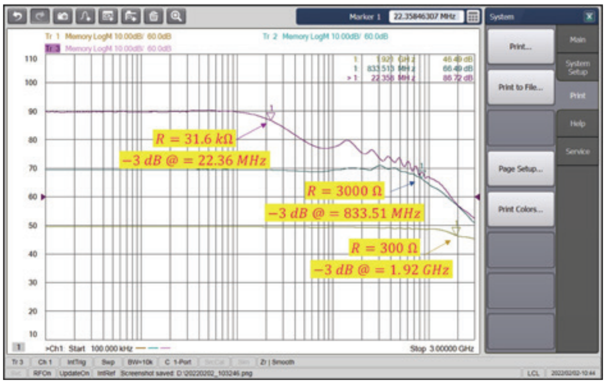

Figure 4: Resistor impedance curves

R (Ω)	f (MHz)	C_{par} (pF)
300	1921	0.276
3000	833.5	0.064
31, 600	22.36	0.225

Table 1: Resistor – parasitic capacitance

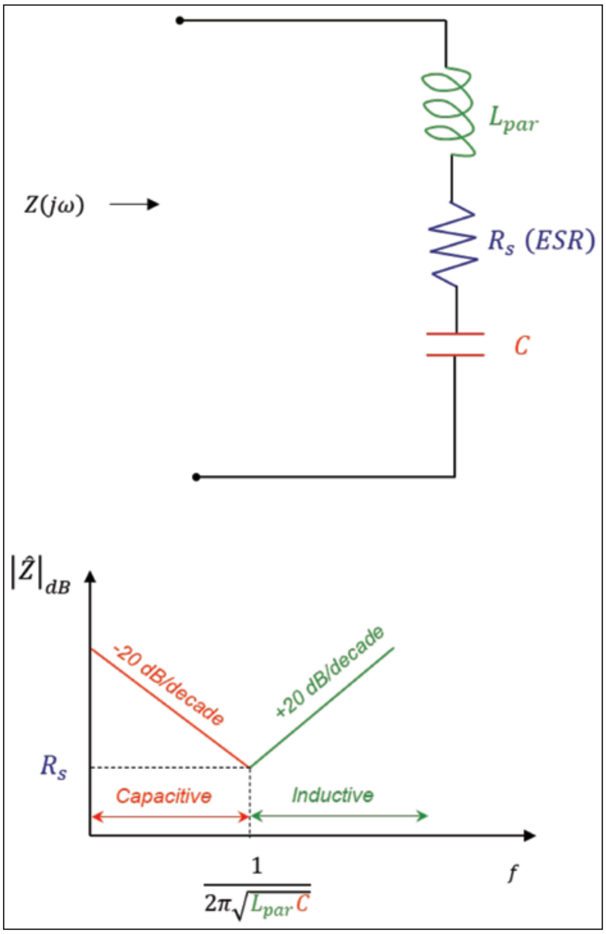

Figure 5: Capacitor circuit model and its impedance curve

Figure 6 shows the measurement setup used to obtain the impedance curves for three different capacitor values.

Capacitor impedance curves are shown in Figure 7.

Each curve shows a self-resonant point corresponding the frequency (shown in Figure 5):

$$f = \frac{1}{2\pi L_{par} C} \tag{3}$$

From Equation 3 the parasitic inductance can be obtained as:

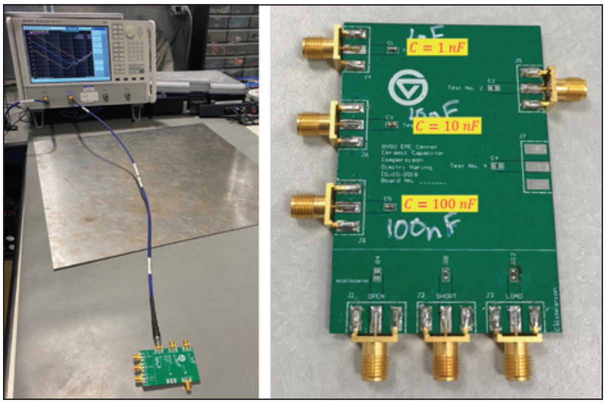

Figure 6: Measurement setup – capacitor impedance curves

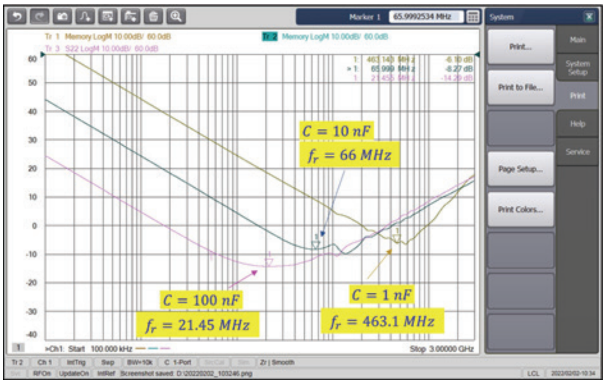

Figure 7: Capacitor impedance curves

C (nF)	f (MHz)	Lpar (nH)
1	463.1	0.12
10	66.0	0.58
100	21.4	0.55

Table 2: Capacitor – parasitic inductance

$$L_{par} = \frac{1}{4\pi^2 f^2 C} \tag{4}$$

The resulting parasitic inductance values for the three capacitors are shown in Table 2.

3. INDUCTOR MODEL AND ITS PARASITICS

Circuit model and the impedance vs. frequency curve (straight-line approximation) for an inductor and its parasitics (with no traces attached) are shown in Figure 8 [1,2].

Figure 9 shows the measurement setup used to obtain the impedance curves for three different inductor values.

Inductor impedance curves are shown in Figure 10.

Each curve shows a self-resonant point corresponding the frequency (shown in Figure 9):

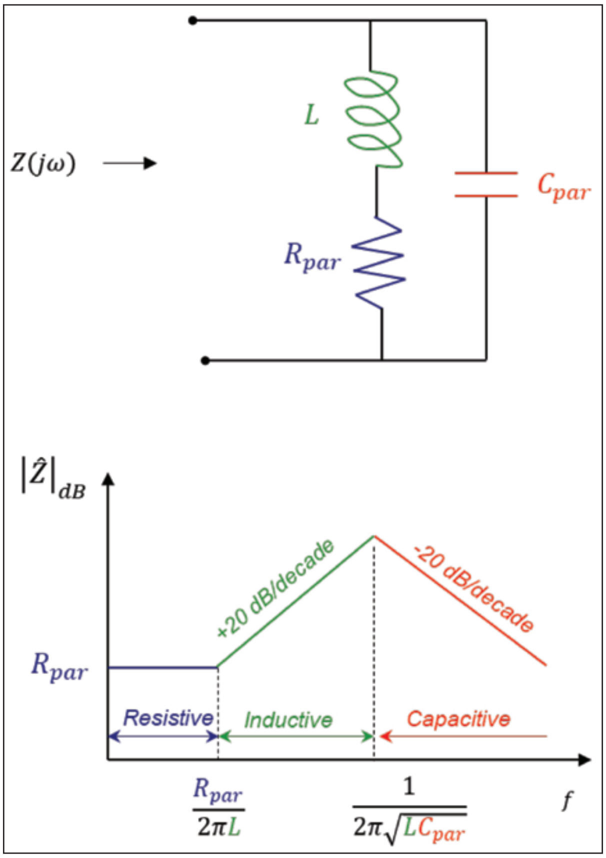

Figure 8: Inductor circuit model and its impedance curve

$$f = \frac{1}{2\pi L C_{par}} \tag{5}$$

From Equation 3 the parasitic inductance can be obtained as:

$$C_{par} = \frac{1}{4\pi^2 f^2 L} \tag{6}$$

The resulting parasitic capacitance values for the three inductors are shown in Table 3.

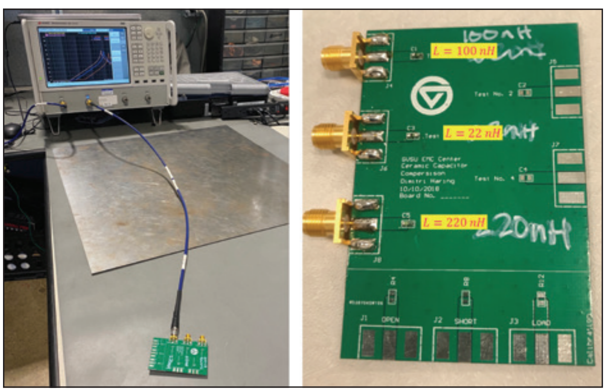

Figure 9: Measurement setup – inductor impedance curves

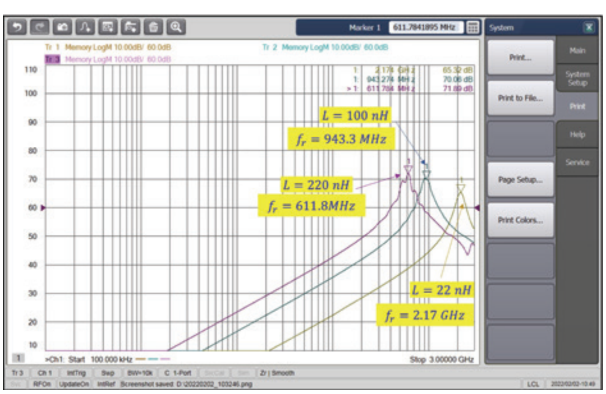

Figure 10: Inductor impedance curves

L (nH)	f (MHz)	C_{par} (pF)
22	2174	0.244
100	943.27	0.285
220	611.8	0.308

Table 3: Inductor – parasitic capacitance

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INDIUM-GALLIUM-ZINC-OXIDE (IGZO) THIN-FILM-TRANSISTORS (TFT) AND ESD

By Marko Simicic for EOS/ESD Association, Inc.

The thin-film transistor (TFT) became commercially available slightly more than 30 years ago in the form of a switch for the Liquid Crystal Display. It all started with an amorphous silicon (a-Si) TFT. Compared to the traditional crystalline silicon CMOS transistor, the a-Si TFT can be produced on large substrates and at low processing temperatures, below 300 ˚C, enabling integration on glass substrates and even flexible substrates.

A-Si TFTs are mainly implemented as simple pixel switches due to their low charge carrier mobility (0.5-1 cm^2/Vs). An alternative semiconductor on glass substrates is low-temperature polycrystalline silicon (LTPS), outperforming a-Si TFTs by a 100x larger mobility (50-100 cm^2/Vs) and often used for high-end displays and imagers. Despite the advantages, fabrication of an LTPS TFT takes more process steps, is limited in substrate size, and requires a larger process temperature. Oxide-based semiconductors as indium-gallium-zinc-oxide (IGZO) fill this gap between a-Si and LTPS nicely, exhibiting low processing temperatures and a decent charge carrier mobility of 10 up to 40 cm^2/Vs [1].

With such characteristics, the IGZO TFTs can be used to fabricate relatively complex circuits on flexible substrates. Consequently, IGZO TFTs are evolving beyond displays and entering the fields of wearable devices and the Internet of Things (IoT). Some highlights include an ultra-flexible circuit for recording electrocardiograms [2], radiofrequency identification (RFID) tags and near-field communication (NFC) tags [1]. Even the memory field has noticed IGZO and its extremely low OFF current and recently demonstrated a capacitor-less IGZO-based DRAM cell with a retention time longer than 400 seconds [3]. We can expect the first IGZO products beyond display applications to emerge in the near future.

Marko Simicic joined the ESD team at imec in Belgium in 2017 with the focus on researching ESD solutions for devices and circuits. He has authored or co-authored more than 35 papers in international journals and conference proceedings and is an active member of the JS-002 ANSI/ESDA/JEDEC joint standard for CDM ESD device sensitivity testing.

Founded in 1982, EOS/ESD Association, Inc. is a not for profit, professional organization, dedicated to education and furthering the technology Electrostatic Discharge (ESD) control and prevention. EOS/ESD Association, Inc. sponsors educational programs, develops ESD control and measurement standards, holds international technical symposiums, workshops, tutorials, and foster the exchange of technical information among its members and others.

WHY ARE IGZO-BASED CIRCUITS A TOPIC OF INTEREST?

As with a large majority of products, electrostatic discharge (ESD) protection is an important concern. If we are to see IGZO products enter the fields of IoT or biomedical engineering, they will have to include ESD protection.

Perhaps ESD protection is not a great concern for wireless products, for example, NFC and RFID tags which have no wired input and output ports. Here the sensitive electronic parts will not be exposed to the user as they are electrically insulated. In this case, like for displays [4,5], a good ESD control program might be enough to protect the IGZO components during assembly. The full display will, in any case, include ESD protection circuits at the system level, even perhaps at the peripherals where the electrical connections leave the display, but not necessarily at the IGZO component level. On the other hand, some wearables like the electrocardiogram patch, might not be able to afford system-level ESD protection circuits fabricated in a different technology other than IGZO. Since the electrodes have direct contact with the end-user, they may require ESD protection circuits at the device level. The same will be true for displays and imagers if their peripheral circuits are implemented using IGZO – to enable a fully flexible display, for example.

IS ESD A CONCERN FOR IGZO CIRCUITS?

Yes, like any digital or analog circuit, also IGZO TFT circuits are susceptible to ESD. Even though the IGZO TFT technology nominal voltage can be as high as 10 V, degradation and breakdown can be observed already at 20 to 30 V [6]. To avoid damage to performance, the IGZO circuit should never be exposed to voltages higher than 20 V. This means the eventual ESD protection circuits should have a clamping voltage lower than 20V, which is only twice the nominal voltage. These limits depend on the IGZO technology and could change as the technology improves.

WHAT ARE THE DIFFICULTIES OF DESIGNING ESD PROTECTION CIRCUITS IN IGZO TFT?

There are several challenges when designing IGZO TFT circuits in general, but perhaps the most prominent one is the fact it is a unipolar technology. Unlike the complementary metal-oxide-semiconductor (CMOS) technology integrating two types of transistors, n-type and p-type, the IGZO TFT only provides n-type transistors. Research on p-type oxide-based TFTs to complement the IGZO n-type transistor exists. Unfortunately, the p-type transistors generally have a much lower charge carrier mobility and would make the complementary design less efficient than the unipolar one [1]. Since ESD protection circuits can rarely dictate the technology evolution, ESD protection designs will most likely have to be made with unipolar circuits too.

The second challenge of the IGZO TFT technology for ESD circuit design is that there are usually no diodes available. Even though it is possible to make diodes in the IGZO TFT technology, it also increases the process cost and is not a commodity in this industry. Therefore, the best next choice would be a diode-connected transistor. The technology options to improve the ESD performance of the diode-connected transistor would be to smartly use the back-gate or to optimize the channel material resulting in larger mobility.

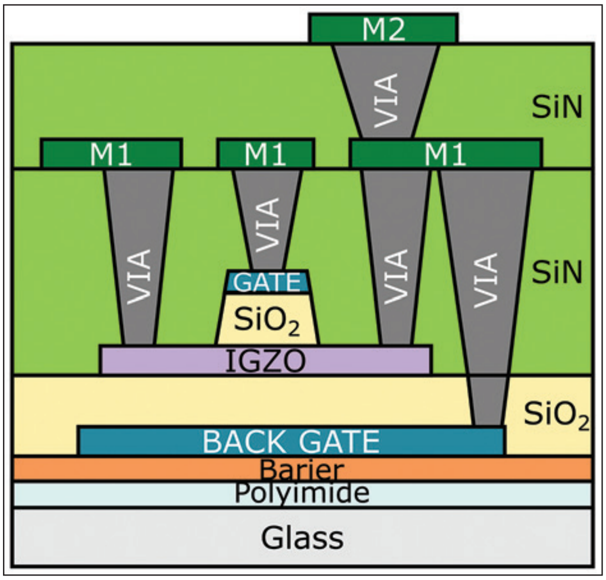

Figure 1: Example cross-section of an IGZO TFT with a dual-gate fabricated on a glass substrate. The top and bottom gates can be connected by vias through the first metal layer (M1). Silicon dioxide (SiO_2) is used to insulate the gates from the active IGZO layer, to achieve the field-effect transistor. After fabrication, the glass can be detached from the polyimide layer resulting in a flexible circuit.

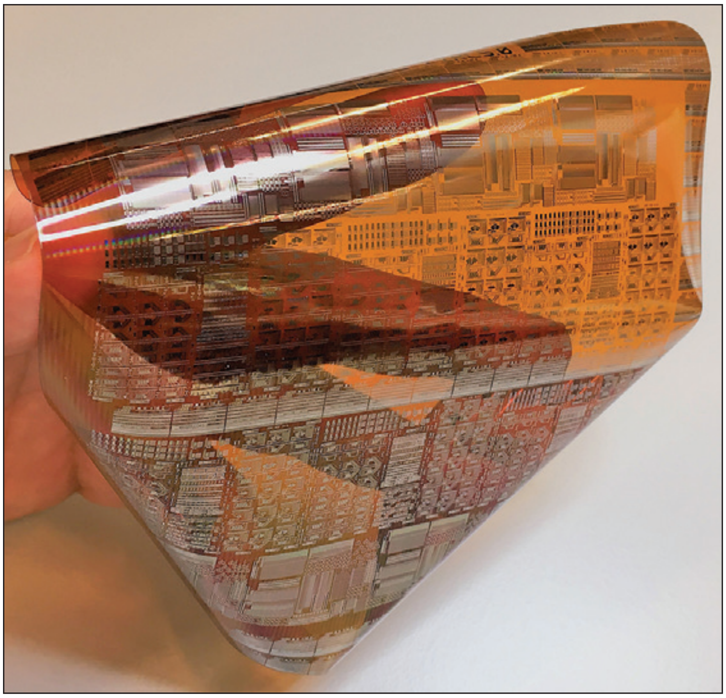

Figure 2: IGZO test circuits fabricated on a semi-transparent flexible substrate.

Luckily, the negative threshold issue that was observed in the early IGZO TFT technology improved significantly. Therefore, the significant leakage at the zero-volt bias that would be present in IGZO TFT ESD protection circuits can be solved from the technology side.

Nevertheless, given the limited IGZO TFT conductivity, to achieve a product-worthy ESD protection level, the ESD circuits will have to be in the millimeter or even centimeter size range [5][2]. Given the IGZO TFT technology is optimized for large areas, spending these kinds of areas for ESD protection should not be a showstopper.

Unlike the silicon integrated circuit technology, there is a very limited choice of devices in IGZO, which also limits the possible solutions of ESD protection circuits. Passive devices could help with that. Inductors, capacitors, and resistors could be used as ESD protection or to complement the active devices. A spark gap could be a compact ESD protection option too.

WHAT ABOUT TESTING ESD PERFORMANCE OF LARGE AREA WEARABLE DEVICES?

IGZO TFT technology is a good candidate for future wearable and flexible electronic devices. If it is used in a wireless or non-contact way, consumer-side ESD protection should not be a great concern. However, if it will be used as a wearable with electrically exposed pads, it will certainly require ESD protection designs and ESD testing. In this case, the ESD testers might need to be adapted. Take the Human Body Model (HBM) ESD tester, for example. Most HBM ESD testers today target small, packaged devices in millimeter or centimeter sizes. HBM ESD testing of an IGZO TFT product might imply pins to be more than 10 cm apart. That might be challenging indeed,

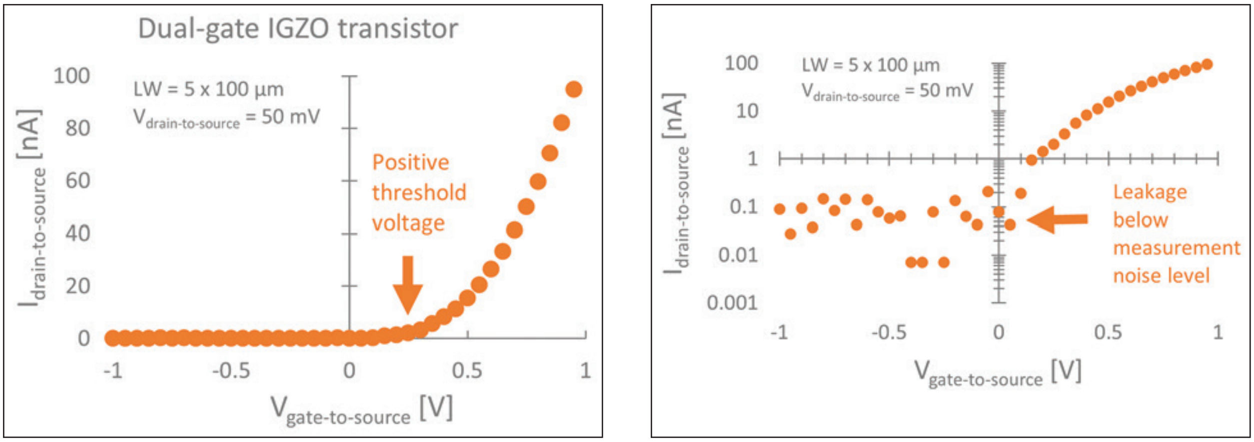

Figure 3: Drain-to-source current as function of the gate-to-source voltage measured on a dual-gate IGZO transistor shows a positive threshold voltage (top) and leakage currents below the measurement setup noise level (bottom). These data have been measured on a 5 µm by 100 µm TFT with a drain-to-source bias voltage of 50 mV.

but perhaps some ingenious test fixtures or packaging could overcome this. Bending the flexible wearable device for ESD testing purposes could be an example.

The Transmission Line Pulse (TLP) ESD tester could be an alternative to HBM testing. Since the TLP tester is of a more academic nature than the HBM tester, it could perhaps offer more flexibility in connecting to the large IGZO circuit. Even though the TLP is a 50-Ohm tester while HBM has a typical series resistance of 1500 Ohm, we have observed comparable ESD testing results with both testers [6]. Since there is no universal conversion rule, care needs to be taken when interpreting TLP measurement results as HBM protection values.

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PRODUCT MANUALS IN FOCUS

By Erin Earley

Best Practices for Manuals within Your Product Safety Strategy

In one of our last "On Your Mark" columns, we explored the different elements of a product safety and liability prevention strategy – from risk assessment to safety labels. While on-product labels, and the symbols, standards and best practices related to them, are the focus of our columns, they don't operate all on their own. They need to be developed alongside all of the other safety and risk reduction documents and measures being taken. That includes product manuals. For specific insight on manuals, we turned to Dr. Patricia Robinson, the author of "Writing and Designing Manuals and Warnings" with over 35 years of experience in product safety consulting and training, specializing in warnings and instructions. Read our interview with Dr. Robinson for context on manuals, including the latest standards and best practices for incorporation with your product safety strategy.

Erin Earley, head of communications at Clarion Safety Systems, shares her company's passion for safer products and workplaces. She's written extensively about best practices for product safety labels and facility safety signs. Clarion is a member of the ANSI Z535 Committee for Safety Signs and Colors, the U.S. ANSI TAG to ISO/TC 145, and the U.S. ANSI TAG to ISO 45001. Erin can be reached at eearley@clarionsafety.com.

When it comes to requirements for product manuals in the U.S., while we don't have regulations that carry force, we do have the consensus standard, ANSI Z535.6: Product Safety Information in Product Manuals, Instructions and Other Collateral Materials. What are some of its core concepts and best practices for manufacturers to be aware of?

ANSI Z535.6 provides guidance to manufacturers in how to format safety messages in manuals and other "collateral materials" in a way that is consistent with ANSI Z535.4, the standard that addresses on-product labels. The intent is to make it possible for all the parts of the product "package" to work together to convey essential safety information to users. The focus of ANSI Z535.6 is on format. The standard doesn't tell you what safety messages to include or what any individual safety message should say, but it does provide a variety of options for how to format those messages.

Two key parts of ANSI Z535.6 are recommendations for handling grouped safety messages (the safety pages typically found at the front of a manual) and the use of embedded safety messages.

1. **Grouped safety messages:** manufacturers often include a great many warnings and safety messages at the beginning of a manual. It's easy for the user to simply flip past these pages. To avoid that, make this section visually inviting by grouping warnings in logical categories with a heading identifying the content (such as, "Electrical Hazards") and make it relevant by focusing on hazards specific to the product rather than filling pages with messages describing generic good work practices (such as "Keep the floor clear of debris.")
2. **Embedded safety messages** are built right into procedures. They may include some special formatting, such as bold type or the safety-alert symbol, but they are not set apart from the instructions. We used to think that safety messages in a manual should be formatted like on-product labels to make them conspicuous, but research has shown that when warnings interrupt the flow of text too much, people tend to just skip over them. Working the safety message right into the procedure is more effective.

Most manufacturers engage in continuous improvement of their products, meaning that manuals frequently become out of date. Two strategies can help to make sure your users have access to current information.

Pivoting to a global perspective, do you have similar guidance related to the international consensus standard, ISO 20607: Safety of Machinery – Instruction Handbook – General Drafting Principles?

This standard offers clear and specific guidance for developing manuals, in line with the principle that instructions for use are an essential component of machine design—not an add-on. The sections cover many aspects of manual creation including identifying your target audience, planning content and structure, and principles for writing instructions. While it's all helpful, the guidance on language and style (in the standard and in the annexes) may be particularly useful. Such principles as phrasing instructions positively, using consistent terms, using simple language, and presenting instructions in numbered steps are all vital to making manuals user-friendly. Most people don't like to read manuals, so making them easy to read is essential. The annexes provide recommendations for formatting and examples of well-written instructions. Machine manufacturers know their machines very well and can usually identify needed content. But many manufacturers don't know as much about how best to present that content; this standard offers a concise guide that's in line with the principles of effective communication.

In your experience, what are some of the main pain points that manufacturers have in developing quality manuals that are in line with the best practice ANSI and ISO standards?

Three aspects of developing high-quality manuals consistently cause manufacturers difficulty:

- **Cost:** Producing a high-quality manual costs money, just like producing a high-quality machine. If the manual then must be translated into multiple languages, it costs even more. It's tempting to skimp on quality, by doing such things as reducing white space or using a smaller font size, so there are fewer pages, or using reduced-size CAD drawings rather than illustrations designed specifically for the manual. But that sort of cost cutting may be counter-productive: if a manual never gets read because it looks too difficult, whatever it cost to produce is money lost. Paying a little more to make a manual that's readable and has high-quality illustrations that can carry some of the communication load (resulting in less text!) can save both on translation costs and reduced service calls.
- **Audience analysis**: Knowing who your users are and how much they do (or don't) already know is crucial to developing a manual that works for them. It pays to spend some time with the marketing department to find out if your user group has changed over time. Doing some informal usability testing of the manual with people who fall into your expected user group can pay major dividends in helping create a manual that actually gets used.
- **Keeping the manual up to date with model changes:** Most manufacturers engage in continuous improvement of their products, meaning that manuals frequently become out of date. Two strategies can help to make sure your users have access to current information. First, posting current manuals in .pdf form on the company website means anyone with an internet connection can see the latest information. Secondly, designing your manuals in modular form, with more-or-less standalone components means that when something changes, you can update just that specific module and assemble an up-to-date manual quickly without having to rewrite everything.

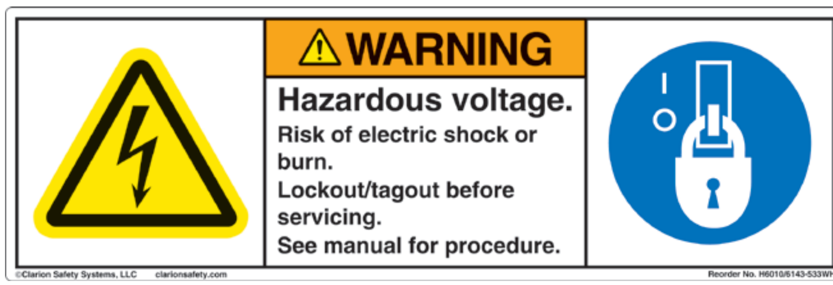
Let's hone in on how on-product labels work together with manuals. Labels need to be concise (while still including the pertinent safety, warning, or informational information), while the product manual can be more explicit. In that way, the product manual can be used as a more comprehensive extension of the on-product labels. What best practices should manufacturers be aware

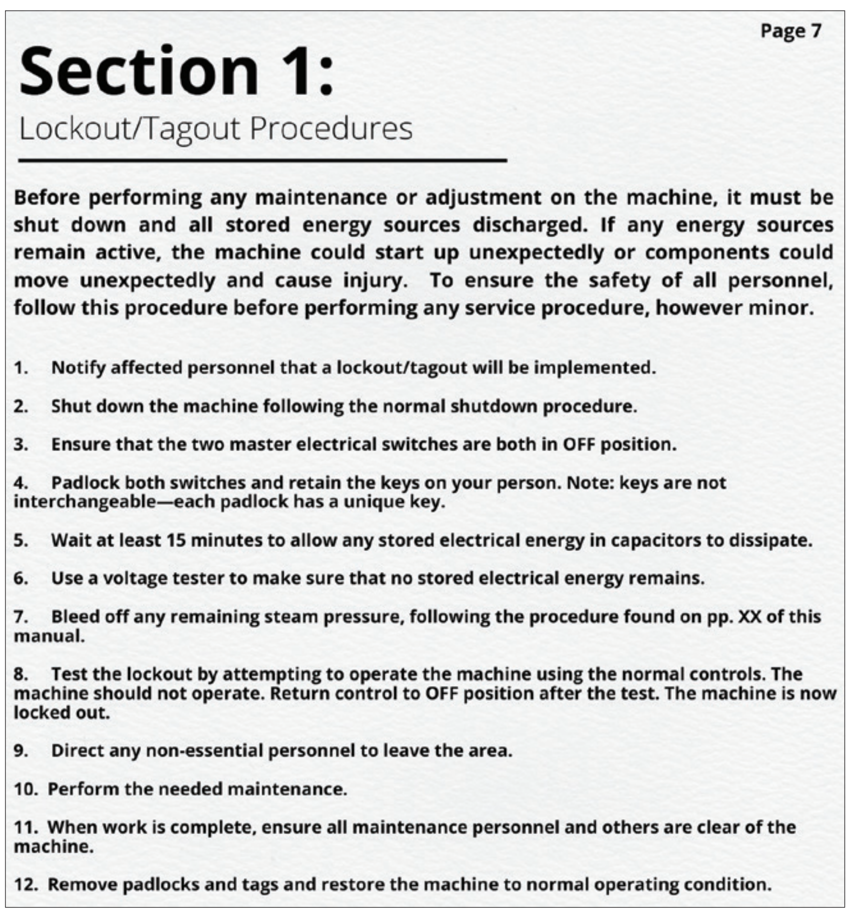
of when it comes to deciding what information to include in the label, what information to include in the manual, and how to make sure that information is given in a cohesive way to the user?

Companies can run into trouble when either they have no consistent process for creating on-product labels and warnings in manuals or when the process is consistent, but the functions are separated. For example, in some companies, the legal department is responsible for creating on-product label content, but technical writers and/or engineers write the manual. When the right hand doesn't know what the left hand is doing, communication will be compromised.

The best approach is three-fold:

1. Establish a product safety team with representation from all relevant parts of the company – legal, technical writing, marketing, engineering, and service – and give that team the authority to make decisions.
2. Develop and implement a comprehensive, rational, and well-documented hazard analysis process. The goal of a hazard analysis is to identify all the ways someone could get hurt or damage could occur, whether the machine is operating properly or not. Once those hazards are identified, categorize them by the severity of potential injury/damage and by the likelihood of occurrence. Use the results to determine what needs an on-product label (most immediate, likely, and severe hazards) and what can be addressed solely in the manual.
3. Coordinate the labels and the manual to ensure that the information presented in the manual is consistent with the label. For example, the signal word used should be the same. If the label says "WARNING", but the manual says "DANGER", that inconsistency could pose a problem if the hazard really was a DANGER-level hazard.





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Section 1:

Lockout/Tagout Procedures

Before performing any maintenance or adjustment on the machine, it must be shut down and all stored energy sources discharged. If any energy sources remain active, the machine could start up unexpectedly or components could move unexpectedly and cause injury. To ensure the safety of all personnel, follow this procedure before performing any service procedure, however minor.

1. Notify affected personnel that a lockout/tagout will be implemented.
2. Shut down the machine following the normal shutdown procedure.
3. Ensure that the two master electrical switches are both in OFF position.
4. Padlock both switches and retain the keys on your person. Note: keys are not interchangeable—each padlock has a unique key.
5. Wait at least 15 minutes to allow any stored electrical energy in capacitors to dissipate.
6. Use a voltage tester to make sure that no stored electrical energy remains.
7. Bleed off any remaining steam pressure, following the procedure found on pp. XX of this manual.
8. Test the lockout by attempting to operate the machine using the normal controls. The machine should not operate. Return control to OFF position after the test. The machine is now locked out.
9. Direct any non-essential personnel to leave the area.
10. Perform the needed maintenance.
11. When work is complete, ensure all maintenance personnel and others are clear of the machine.
12. Remove padlocks and tags and restore the machine to normal operating condition.

An example of how an on-product label can be coupled with expanded information in the product manual.

PRODUCT Showcase

Advertiser Index

Upcoming Events

April 3-6
A2LA Tech Forum 2022

April 5-7
DesignCon 2022

April 5-7
Fundamentals of Random Vibration and Shock Testing

April 11-14
EMC: Designing for Compliance

April 18-22
EMC Week

April 19
EMC Mini

April 28-29
Fundamental Principles of Electromagnetic Compatibility and Signal Integrity

May 8-11
Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC)

May 10-13
Applying Practical EMI Design and Troubleshooting Techniques

Advanced PCB Design for EMC & SI

Mechanical Design for EMC

May 10
Chicago IEEE EMC Mini Symposium

May 12
EMC Fest 2022

May 16-19
IEEE International Instrumentation and Measurement Technology Conference (I2MTC)

May 18-19
EMC & Compliance International Workshop

June 13-16
MIL-STD-810 Training

June 19-24
International Microwave Symposium

June 27-29
Sensors Expo & Conference

Due to COVID-19 concerns, events may be postponed. Please check the event website for current information.