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Specifying Lifecycle Electromagnetic and Physical Environments to Help Design and Test for EMC for Functional Safety

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Specifying Lifecycle Electromagnetic and Physical Environments – to Help Design and Test for EMC for Functional Safety

Note 15 Dec 06: this is all inter-system assessment, need to add something on intra-system

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Abstract

Certain kinds of equipment must maintain sufficiently low risks to users and third parties over their entire lifecycles, despite at least one fault, and despite foreseeable misuse.

Where electromagnetic interference (EMI) could foreseeably have an effect on such equipment, it will need to maintain an adequate level of electromagnetic (EM) immunity over its lifecycle. This is the concern of 'EMC for Functional Safety'.

The EM environment that such equipment could experience over its whole lifecycle can be very different from that tested by standard immunity tests used for EMC compliance. IEMI – Intentional EMI – could also be an issue.

The physical and climatic environments, plus the wear and tear and misuse that such equipment is subjected to over its lifecycle can cause circuit EM behavior to alter, and can degrade the performance of EM mitigation measures.

This paper outlines an approach to specifying the "lifecycle environment" for such equipment, as an aid to safe design and appropriate verification testing.

Although this paper focuses on safety concerns, the lifecycle EM and physical environment issues discussed here are also important for high-reliability, mission-critical and legal metrology equipment, to help control financial or security risks.

Designing and testing to achieve adequate EMC for functional Safety will be covered in future papers.

Introduction

Equipment which could have an impact on functional safety, or is 'safety-related' or 'safety critical', should maintain sufficiently low risks to users and third parties over its entire lifecycle. It is usually required to be safe despite the occurrence of at least one fault, and also despite foreseeable misuse. IEMI may be a real concern in some applications.

In such equipment, where foreseeable real-life EMI could affect hardware or software during its operational lifetime in a way that might increase safety risks – the equipment concerned will require a sufficient level of EM immunity performance to be maintained over its entire lifecycle.

This is an aspect of what is sometimes called EMC for Functional Safety – a very different technical discipline from compliance with EMC regulatory regimes that include immunity, such as the EMC Directive. These differences were discussed in [1] [2] [3] [4] [5] [6] and [7].

Equipment may need to maintain certain minimum levels of EM immunity despite at least one fault, such as the wear-out of a surge protection device by the surges it is exposed to over time. Another example is a broken filter ground connection, which could be caused by poor assembly; shock, vibration or corrosion over the lifecycle; or willful damage.

It is not generally appreciated that the EM performance measured by the normal immunity tests can have very poor correlation with an equipment's behavior in real life, see [1] [2] [3] [8] and [9]. For example, in real life it is common for two or more EM disturbances to occur simultaneously (e.g. radiated disturbances at more than one frequency; an electrostatic discharge or fast transient burst whilst a continuous radiated disturbance is present). But all standard EMC immunity tests apply one disturbance at a time, and [10] shows they can lead to a very optimistic view of equipment's real-life immunity.

It is well known in the EMC community that the physical environment can degrade equipment immunity performance over a lifecycle, for example by corrosion, shock and vibration, bending forces, temperature extremes or cycling, wear and tear and many other lifecycle physical influences. Some of these issues are discussed in [11] [12] [13] [14] and the last paragraph of [15].

Despite this, immunity is verified by applying standard test methods (e.g. the IEC 61000-4 series or MIL-STD-461) to samples of *new* equipment in a *benign* physical environment. The effects of lifecycle physical environments on immunity are rarely tested.

Equipment designers need to know enough about their equipment's 'environment' (EM, physical, climatic, wear and tear, etc. over the lifecycle) and foreseeable faults and misuse, to select appropriately rated components, and to design circuits, software, filtering, shielding and overvoltage protection. They need this information to be able to achieve the reliability required for operational functions that could have an impact on safety over the entire lifecycle.

For example, engineers need enough information to be able to design…

- EM mitigation techniques to cope with the foreseeable range of EM disturbances over the equipment's lifecycle, including low-probability events (how low depends on the safety requirements of the application) and simultaneous EM disturbances.
- Feedback circuits – so that they do not become unstable due to temperature variations affecting component parameters (e.g. gain-bandwidth product, phase margin, etc.).
- Filters – so that vibration and corrosion will not cause their ground bonds to degrade; and that variations in supply voltage, load current and temperature do not degrade their attenuation too much [12].
- Shield joints and gaskets – so they will continue to perform as required despite twisting of the frame due to mounting on non-flat surfaces; and will withstand wear and tear, corrosion, mould growth or other lifecycle influences [28].
- Surge protection that will withstand the foreseeable overvoltages and overcurrents for the lifecycle of the equipment, or at least for the period between maintenance activities. …etc.

They also need this information to create a test plan for both EMC and HALT (Highly Accelerated Life Testing) that will prove the design; and to design the routine EMC testing and physical stress screening required in volume manufacture.

The Institution of Electrical Engineers (IEE, London, UK) has developed guidance [7] and a training course [16] on EMC for Functional Safety, and this paper is based on the parts of their training course created by the author.

The approach described here is also relevant where equipment must achieve high-reliability (e.g. server farms), is part of national infrastructure (e.g. power generation, distribution), is mission-critical, or concerned with security or legal metrology (e.g. speed cameras, automatic tolling, etc.).

The lifecycle

A lifecycle consists of the following stages:

- Research, design and development
- Manufacture, storage and transport (shipping)
- Installation and commissioning
- Operation
- Maintenance, repair and refurbishment
- Modification and upgrading
- Decommissioning and disposal

Depending on the application, some of the above may have no implications for EMC for Functional Safety.

Assessing the EM environment over the lifecycle

The EM environments assumed by generic and product-family EMC Directive immunity standards are not appropriate where functional safety is a concern, because they are based on what is considered commercially acceptable for 'normal' reliability for equipment that does not perform any safety functions. They assume a 'compatibility level' that may only cover 80% of the possible EM events experienced by an equipment, for the few types of EM disturbances they cover, see [1] [2] and [3] and Figure 1.

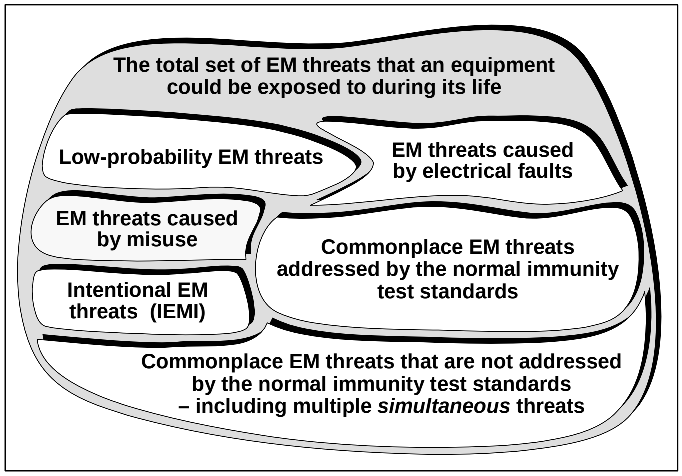

Figure 1 Issues to be considered in the assessment of a lifecycle EM environment

Not much has been written about how to assess an EM environment for the lifecycle of an item of equipment, especially where low-probability EM disturbances are concerned. [17] provides some useful information but is aimed at helping comply with the EMC Directive so may need to be extended in some areas (e.g. IEMI) to be useful for functional safety.

Assessing a lifecycle EM environment is all about determining what 'EM threats' are present that might interfere with equipment. It requires appropriate expertise and experience, EM survey equipment, a personal library on EM environments and standards, and Internet access.

EM environments can be very different even within a single building. For example a video camera for a hospital will experience very different, sometimes very powerful EM threats if used in an operating theatre; near X-Ray, CAT Scan or MRI equipment; in a physiotherapy department, life-support ward, or public area.

For custom designed equipment, it is always best to agree the specifications for the operational EM environment with the customer in a written contract. Then, if the customer alters the EM environment and a safety incident occurs with the custom equipment, the blame can be apportioned.

An overall procedure for assessing a lifecycle EM environment includes the following…

- A check list of initial questions
- Consideration of future technology trends
- Consideration of future changes in the environment

- Consideration of the foreseeable EM threats caused by electrical faults, misuse, and IEMI [18] [19]
- Comparison of the foreseeable EM threats with the equipment's technologies to decide where in-depth investigation of the EM environment is required (depends on the criticality of the safety application)
- In-depth investigation of aspects of the environment
- Writing a quantified engineering specification for the lifecycle EM environment

An EM environment assessment begins with initial questions about the foreseeable location(s) of the equipment concerned and the quality of its AC or DC power supplies. There are also a number of simple questions about the types of equipment or industrial processes (e.g. arc welding) that will be used nearby, including nearby buildings. A special concern is other equipment interconnected by cables to the equipment in question, for example by shared AC or DC power supplies, data, signal or control cables.

Another special concern is the proximity to any equipment that uses radio frequencies (RF). Any radio, TV or radar transmitters could be significant threats, as could diathermic processors such as those used in medicine and cosmetic surgery (e.g. electrosurgery, depilators, wart removal) and those covered by CISPR 11 and used to treat materials (e.g. plastic welders, microwave dryers, induction heating of metal, etc.).

Military and civilian avionics designers are used to dealing with significant RF threats from broadcast transmitters and radar systems, but these threats can just as easily affect other types of equipment if they are close enough to the transmitting antennas [20].

Personal mobile radio transmitters (e.g. cellphones, walkie-talkies, etc.) have low transmitted powers, but if held just inches away their radiated field strengths can be very high, so they can be significant threats to other electronics equipment, such as computers.

Foreseeable electrical faults and other low-occurrence disturbances should also be assessed, including ground-fault currents and their 'ground-lift' effects; transient overvoltages and noise bursts due to the opening of fuses or circuit-breakers; proximity of arcs and sparks; lightning; etc.

Ground faults occur often enough (e.g. due to insulation failure) for safety standards to make it mandatory to use overcurrent protection devices (such as fuses, circuit breakers, etc.). The EM disturbances associated with a ground fault include a sudden large increase in the magnetic field at the powerline frequency (and its harmonic distortion frequencies), plus a 'ground lift' at the powerline frequency (and its harmonic distortion frequencies) due to the fault currents traveling in certain protective ground conductors.

These two EM disturbances last for as long as it takes the overcurrent device to open and 'clear' the fault, which can be several seconds. The ground fault ends with a burst of very broadband noise emissions as the fuse element or contacts open. This burst can last for several seconds when high currents are being interrupted or if the fuse or breaker rating is inadequate. These EM threats occur at the same time as any continuous EM threats in the environment, such as proximity to radio transmitters or diathermy equipment, see [10].

Past years have seen sudden increases in the EM threats at 27MHz (Citizens Band), VHF and UHF (vehicle mobile e.g. taxis, and walkie-talkies). More recently, increases in EM threats have occurred around 900MHz, 1.8GHz (Europe) and 1.9GHz (USA) due to cellphones and GPRS datacomm's; and below 100MHz due to variable-speed motor controls and other switched-mode power converters. These have all caused significant EMI upsets, and some are still causing problems. An increase in EM threats is now occurring at frequencies above 1GHz, and not just at the 2.45 and 5GHz frequencies used by IEEE 802.11. It is important to try to foresee future technology trends, to reduce the risk of unpleasant surprises.

Possible future developments near the location of the equipment concerned should also be considered. For example, is it foreseeable that high-power RF equipment (transmitters, diathermy, etc.) might be employed nearby, or that a mobile radio communication system might be installed?

IEMI might be a possibility, from disgruntled employees, competitors, criminals, political activists, terrorists or by people who just like to cause a nuisance.

Following on from the initial assessment, the possible EM threat phenomena and their levels are identified and quantified using appropriate standards, other resources and experience, including whatever emissions test data is available for nearby equipment, or equipment on the same power network.

Simple calculations and computer simulations are often used at this stage to get at least order-of-magnitude estimations of all foreseeable EM threats. It is important to understand that EM test standards measure emissions data in the far-field. But if the emitting equipment will be located close enough for its near-field emissions to be significant, its radiated threat cannot be calculated from its far-field test results.

The foreseeable EM threats are then compared with the equipment's proposed technologies, construction techniques, and operational modes. This process usually allows some threats to quickly be assessed as negligible, taking into account the safety requirements of the final application.

The remaining threats should be investigated in more depth to see if they really are credible as a cause of increased safety risks, in which case they will require appropriate design measures and verification (by appropriately designed tests).

In-depth investigations often involve instrumented site surveys. These are a very powerful tool but are most suitable for continuous or common threats, such as a nearby broadcast transmitter, road or railway line; or where foreseeable threats can be repeated at will (e.g. proximity of personal or mobile transmitters, microwave cookers, ground faults, fuse-opening, operation of HV circuit breakers, switching of reactive loads, etc). In some highly critical cases it may even be desirable to initiate cloud-to-ground lightning using rocket or laser lightning initiation methods, and measure the effects of the resulting strikes at the equipment's intended location.

Site surveys should try to capture the worst-case threats, as well as trying to get an idea of their statistical variations. Spectrum analyzers with a range of suitable antennas are often used to fully measure threats in terms of their frequencies, amplitudes, modulations, and statistical variations. With some sites, surveys may need to continue for some time to capture the full range of activities. Automated site survey instruments are available for wide a variety of RF and power quality phenomena, and are often used in these situations.

As well as frequency and level, it is also important to determine the modulation types and frequency ranges, for each radiated or conducted RF frequency threat. Simply knowing the purpose of the RF signal (e.g. broadcast FM radio) is often enough to be able to specify its modulation scheme and range of possible modulation frequencies.

Where short-lived EM phenomena occur, for example from vehicles traveling at speed, the sweep times of spectrum analyzers make it very difficult to capture the full spectrum of their possible emissions. [21] describes a measuring technique that can overcome this problem.

During a site survey, mobile radio communications devices that will be used on the site (personal and vehicle mobile, voice and data) can be brought close to the measuring antennas to simulate their foreseeable closest proximity to the equipment concerned. Where this distance is closer than the calibration distance for the antenna, and especially when it is within the antenna's near-field region, care is required not to make erroneous measurements. Data obtained in this way can help specify the real-life EM environment for the increasingly difficult problem of portable wireless devices.

A problem with site surveys is that it can be difficult to obtain reliable data on uncontrolled transient and other low-probability disturbances, because they can require a large number of measuring stations, and/or a very long measuring period. So for low-probability EM threats the usual approach is to do some research instead.

Research into EM environments usually begins with standards. The IEC 61000-2-x series generally addresses the household, commercial or industrial environments, but electronic equipment can find itself in other environments such as outdoors, marine, land mobile, air mobile, space, etc., and there are standards and other documents that provide information on the EM threats in such situations.

The telecomm's industry places great emphasis on reliability, especially for 'central office' (telephone exchange) equipment. Also, some telecomm's equipment is located outdoors and very exposed to lightning. So telecomm's EMC standards can contain useful information, for example [22], [23].

[11] and [24] are very useful for high-power EM environments, such as near radio transmitters or radar systems. Military authorities have field strength maps covering most of the world, but it may be hard to obtain them unless you are a member of that country's military or an allied nation. The national authorities in charge of civil aviation keep records of the radars in use (frequencies, power levels, and pulse characteristics) in their countries and should also be a good source of information on mobile radars (e.g. on ships). They may also be able to help with field strength maps.

Automotive and roadside EM environments have characteristic EM features. The UK's Motor Industry Research Association [25] surveys the EM environment of the UK's roads every few years and publishes a report. Some EMC consultancies specialize in railway EMC and should be able to provide data on railway and traction EM environments.

Lightning protection standards, lightning incidence ('isokeraunic') maps and knowledge of a site's lightning protection system help determine the threats from lightning and their statistical probabilities, see Chapter 9 of [26]. There is a natural tendency to focus on the highest peak voltages and currents during transient/surge events, but [27] shows it is possible for lightning events to have relatively low voltages and currents but continue for long enough to burn out simple designs of overvoltage protection – which then fail to protect their equipment.

'Ground lift' voltages from remote ground faults, and 'power cross' caused by mechanical damage to bundles of cables that include signals and mains power, are often just a few tens or hundred volts, but can damage equipment because simple types of overvoltage protection might fail to trigger, or be burnt out by the long duration currents. So the likelihood of such events needs to be considered too.

Information on IEMI is now starting to appear in standards such as IEC 61000-1-5, and in papers such as [18].

The Records of the IEEE International EMC Symposia are very good sources of information on real-world EM environments, and are all available on CD-ROM to facilitate searching. Other regular international Symposia at which papers on EM environments are often published include Zurich, Rome, EMC-Europe and Wroclaw.

[17] includes some simple and very crude calculations that can help assess EM phenomena. Computer simulation of aspects of the EM environment is increasingly possible, e.g. for the fields created by HV power lines or by nearby transmitting antennas. Some consulting companies offer bureau services in this area.

Once all the EM environment information has been acquired, a specification can be written for the equipment's EM environment. This should be used by engineers to help design the equipment's circuits, software and EMI mitigation measures, and to be used to help plan the design verification (EMC testing) and serial-manufacture testing regimes.

Where multiple EM threats can occur simultaneously (e.g. two or more RF frequencies, one RF frequency plus an ESD or mains transient, etc.) it is most important that the specification makes this clear [10].

Assessing the lifecycle physical environment

Designing and testing equipment to achieve adequate EM immunity to its anticipated EM environment over its lifecycle, requires knowledge of the *physical* environment the equipment will have to withstand over its operational life.

The lifecycle EM environment affects *what* performance is required from the EMI mitigation measures – whereas the lifecycle physical environment affects *how* those measures should be implemented in practice.

For example, it is necessary to know the vibration environment to decide whether vibration-proof fixings are required for a filter, so that its RF attenuation is more likely to be maintained over the equipment's life. Knowledge of the climate and possibilities for condensation, liquid splashes and spills etc, is necessary to be able to choose cost-effective conductive gasket materials and metal plating, so that corrosion does not reduce shielding effectiveness over the years [28].

EMI suppression techniques that will last the lifetime of an office printer may not be physically robust enough for an automotive product; whereas applying the auto product's EMI suppression techniques to a printer might add too much cost without appreciably improving functional safety.

So the *physical* environment of equipment needs to be specified, over its *whole* lifecycle – so that reliable EMC mitigation measures can be designed at a reasonable cost.

The physical environment to be assessed should include…

- Bending and twisting forces, such as caused by non-flat mounting, or stacking other equipment on top, etc. (which can cause joints to open up, degrading shielding effectiveness.)
- Shock, vibration, etc.
- Climatic parameters such as temperature extremes and cycling, air pressure extremes and cycling, humidity extremes, likelihood of condensation, etc.
- Pollution, such as conductive or dielectric dusts; liquid splashes and spills such as: fuels, beverages, inks, coolants, lubricants, human sweat, human and animal body fluids, etc.
- Wear and tear; misalignment; etc., over the whole lifecycle, including the effects of repetitive operations, maintenance and cleaning regimes.

  Where electrical bonding is required, the build-up of grease, dirt, sealants, etc.; wearing away of plated surfaces by abrasive cleaning; painting and other 'improvements', have in the past increased contact resistances and degraded EM performance. These issues could also cause problems for new equipment unless it is designed accordingly.
- Exposure to solar and other radiation.

A number of good examples showing how the physical environment, and well-meaning human activities such as cleaning and painting, can significantly degrade EM performance, are given in the appendices to [11].

Physical and climatic environments have generally been better characterized than EM environments. IEC 60721 is a series of standards that classify dynamic, climatic and environmental conditions to help the designer apply the IEC 60068-2 tests. IEC 60721 covers a range of conditions, including:

- Transport, storage, installation and use
- Extreme (short-term) conditions during transport, storage, installation, and use
- Solar radiation, temperature and humidity.
- Stationary use at weather-protected locations.
- Portable and non-stationary use.

It is impossible to specify mandatory requirements for worldwide use, but the IEC 60721 series establishes principles and methodologies to determine alternative tests. Issues such as 'safety margin', 'acceleration factors', etc. are left to the designer's judgment.

There are also well-established military standards covering a wide range of physical and climatic environments, and some very well-established institutions devoted to reliability who may be able to provide additional data. Civilian equipment might use military standards and sources to fill in any gaps in the coverage of the IEC standards. Where information is not available from published sources: calculations, computer simulations, instrumented site surveys and research amongst books, articles and papers should fill the knowledge gaps.

[29] says that it is not uncommon for people to make incorrect assumptions about the physical environment, and references Neumann's collection of computer-related risks which contain numerous examples of environmental variables that have fallen above or below their anticipated ranges during 'normal' operation [30].

Foreseeable misuse

This includes foreseeable use and misuse (such as leaving a shielded door open), operator error and willful damage (e.g. vandalism). Some wear and tear issues are also covered. [11] gives some examples of how these issues have degraded EM immunity and caused significant problems, but there are no standards covering this aspect of a lifecycle environment.

The only effective way to specify the issues so that engineers can design accordingly is to do 'brainstorming'. Established brainstorming methods exist, but the personnel used must extend well beyond the design department. Actual users, installers, field and in-house service personnel, independent safety and/or reliability experts (for their different perspectives), should all take part.

The enthusiasm of sales and marketing personnel can present some of the most serious foreseeable misuse problems, when they sell an existing equipment design into an environment that was not considered during its original design. An assessment of the EM and physical exposures over the lifecycle is required for each new market area, possibly leading to a need for new specifications, design changes, reverification, etc., before the equipment can be supplied into the new area.

Conclusions

Designing and testing an equipment to achieve an adequate level of EMC immunity for functional safety purposes, requires a specification for the EM, physical and climatic environments; wear and tear; misuse, etc., and faults that it could foreseeably experience over its lifecycle.

This paper outlined the main issues and briefly described how to collect the data required to create a "lifecycle environment" specification.

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