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Testing for immunity to simultaneous disturbances and similar issues for risk managing EMC

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***Abstract* – Where electronic equipment must function so as to maintain very low risk levels for safety, financial, or other reasons, it is not sufficient to *only* test it for immunity to electromagnetic (EM) disturbances, whatever the test levels used.**

However, where EM immunity tests are used as a part of such equipment's verification or validation, for their results to be meaningful for the achievement of low risks, it is necessary to increase the test levels significantly above the levels of EM disturbances that could occur in the operational environment(s).

This paper describes a number of reasons for increasing immunity test levels, gives some guidance on by how much, and discusses the problems that this approach can encounter.

I. Introduction

IEC 61508 [1] or any functional safety standard based upon it, requires equipment within its scope to be verified and validated as achieving various low levels of risk [2], [3]. Where such equipment employs electronic technologies (including software) it is usual to test it for EM immunity, using higher levels of EM disturbances than could occur in the equipment's environment. However, [2] [3] show that immunity testing cannot, on its own, prove the equipment's risk levels are low enough to comply with [1] even at SIL 1 [4].

The same conclusion applies to non-safety-related applications, where the correct functioning of equipment is critical for the achievement of low risks.

(In this paper, "equipment" is used to mean electronic devices, modules, units, products, systems, installations, etc.)

Figures 1 and 2 relate safety risk levels to confidence and are taken from [4], which adapted them from IEC 61508 [1].

Safety Integrity Level (SIL)	Average probability of a dangerous failure, "on demand" or "in a year*"	Equivalent mean time to dangerous failure, in years*	Equivalent confidence factor required for each "demand" on the safety function
4	$\geq 10^{-5}$ to $<10^{-4}$	$>10^{4}$ to $\leq 10^{5}$	99.99 to 99.999%
3	$\geq 10^{-4}$ to $<10^{-3}$	$>10^{3}$ to $\leq 10^{4}$	99.9 to 99.99%
2	$\geq 10^{-3}$ to $<10^{-2}$	$>10^{2}$ to $\leq 10^{3}$	99% to 99.9%
1	$\geq 10^{-2}$ to $<10^{-1}$	>10 to $\leq 10^{2}$	90 to 99%

*** Approximating 1 year = 10,000 hrs of operation**

"Failure" includes any error, malfunction or fault that causes a hazard

Figure 1 Confidence for "on demand" safety functions

Safety Integrity Level (SIL)	Average probability of a dangerous failure per hour	Equivalent mean time to dangerous failure, in hours	Equivalent confidence factor required for every 10,000 hours of continuous operation
4	$\geq 10^{-9}$ to $<10^{-8}$	$>10^{8}$ to $\leq 10^{9}$	99.99 to 99.999%
3	$\geq 10^{-8}$ to $<10^{-7}$	$>10^{7}$ to $\leq 10^{8}$	99.9 to 99.99%
2	$\geq 10^{-7}$ to $<10^{-6}$	$>10^{6}$ to $\leq 10^{7}$	99% to 99.9%
1	$\geq 10^{-6}$ to $<10^{-5}$	$>10^{4}$ to $\leq 10^{5}$	90 to 99%

"Failure" includes any error, malfunction or fault that causes a hazard

Figure 2 Confidence for "continuous" safety functions

However, EM immunity tests *can* be helpful as *part* of the verification/validation of equipment in low-risk applications, provided the tests achieve a level of confidence in the design that is appropriate to the risk levels, and this is the subject of this paper.

EMI is identified as a systematic failure in Part 2 of [1], which states that statistical approaches based on average probabilities and mean times to failure are inappropriate. Instead, it requires systematic failures to be controlled by the use of proven design techniques to achieve the levels of design confidence associated with the SILs in Figures 1 and 2.

Ron Brewer says [5]: "…there is no way by testing to duplicate all the possible combinations of frequencies, amplitudes, modulation waveforms, spatial distributions, and relative timing of the many simultaneous interfering signals that an operating system may encounter. As a result, it's going to fail."

[5] recommends testing all possible EM disturbances at higher levels than can occur in the environment, while recognizing (as does [2]) that such testing cannot *on its own* prove that failure due to EMI cannot occur.

The following sections discuss some reasons why test levels should be increased, and gives guidance on how much. Finally, it discusses some of the problems that this approach can encounter and the alternatives that are available.

II. Simultaneous EM disturbances

Testing with individual immunity tests at higher levels than can possibly occur in real life helps deal with the simultaneous EM disturbances that will occur in real life, for example:

- Two or more radio channels at significant levels.
  It is becoming very difficult, if not impossible, to reliably control the proximity of RF transmitters. As well as walkie-talkies, cellphones, GSM-enabled laptops and e-book readers, many applications are adding RFID (up to 5W) and Machine-to-Machine (M2M) using GSM modules within equipment, controlled remotely, making it possible that no-one on a site might know when they will transmit.
- A radio channel plus transient burst, surge or ESD.
- Two independent transients, or a transient plus a surge, either overlapping in time or with a critical time spacing. Analysis might show that these can occur more often than is acceptable for the risk level.
- Conducted transients entering two or more ports simultaneously, e.g. mains power and Ethernet (or other ports with long cables) during nearby lightning strikes.

Michel Mardiguian showed in [6] that equipment that passed individual immunity tests at the maximum specified levels would not pass when two tests were applied at the same time with both at maximum levels. For example, with the maximum RF field applied, EFT/B could only be applied with very low levels.

This is very important where EMI can cause errors and malfunctions that could cause risks to exceed acceptable levels. But what causes this effect? And how can we deal with it?

Simultaneous disturbances affecting a single circuit node

Figure 3 shows that a typical logic 0 digital signal voltage waveform is "polluted" with systematic noise (self-generated, intra-system). This is caused by operation of the circuit itself, plus noise generated by other electrical/electronic activities in the equipment, such as switched-mode power converters.

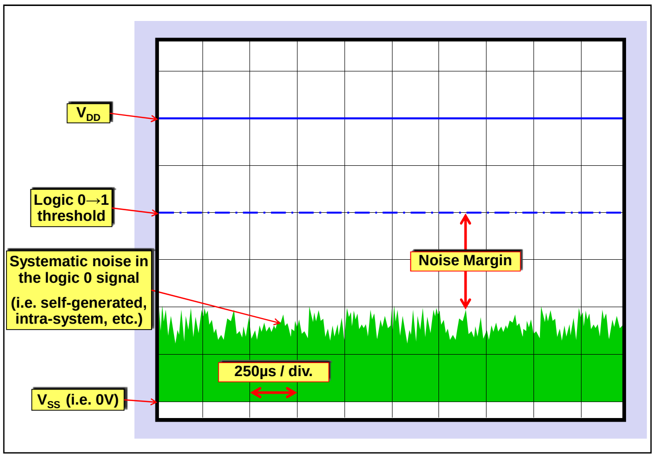

Figure 3 Typical digital system node at logic 0

Digital designers ensure systematic noise is below the logic threshold by an amount called the "noise margin", so that ambient noise (i.e. inter-system noise) does not add to it by enough to cause the logic 0 signal to exceed the logic threshold and appear to be a logic 1 signal – a "bit flip".

Figure 4 shows the same signal as Figure 3, but this time whilst the equipment is being immunity tested with continuous radiated or conducted RF (e.g. to IEC 61000-4-3 or -6). This sketch is just to help illustrate basic principles; in reality the systematic noise would be present on top of the sine wave noise from the immunity test.

Where designers have to meet cost targets, most circuits will just about meet the RF immunity specifications in the relevant EMC standards. So the ambient noise, added to the systematic noise will be just a little below the logic threshold. We could say that the noise in the logic signal during this immunity test just about "uses up the noise margin".

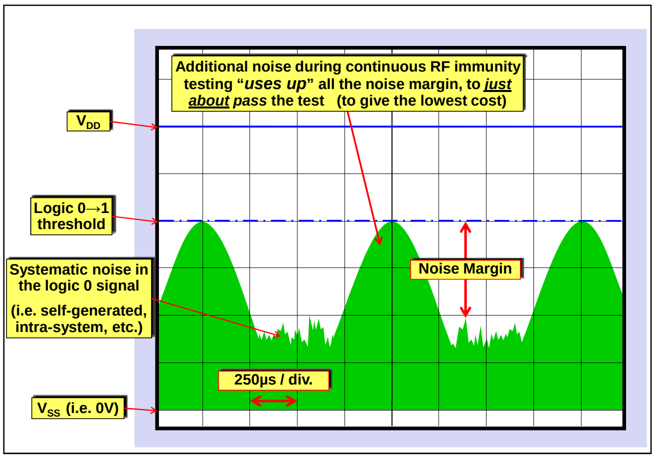

Figure 4 Logic 0 during continuous immunity test

Figure 5 shows the same signal as Figure 3, this time with the equipment being tested with EFT/B (e.g. to IEC 61000-4-4).

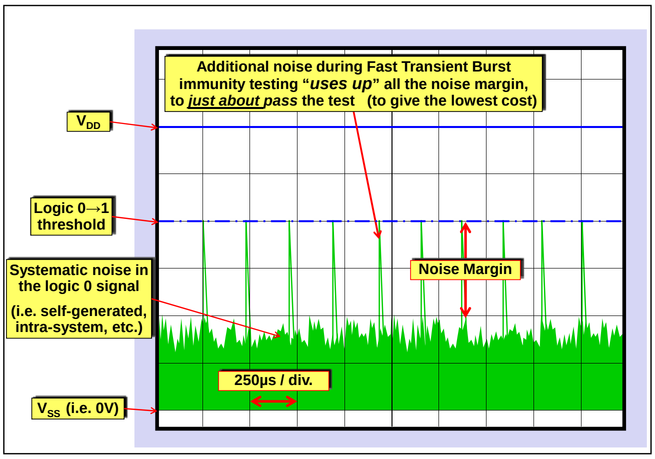

Figure 5 Logic 0 signal during EFT/B test

For the same reasons as for the continuous RF immunity tests discussed above, we could say that the EFT/B noise in the logic 0 signal just about "uses up the entire noise margin".

Figure 6 shows the equipment subjected to the continuous RF *and* EFT/B disturbances (Figures 4 and 5), at the same time.

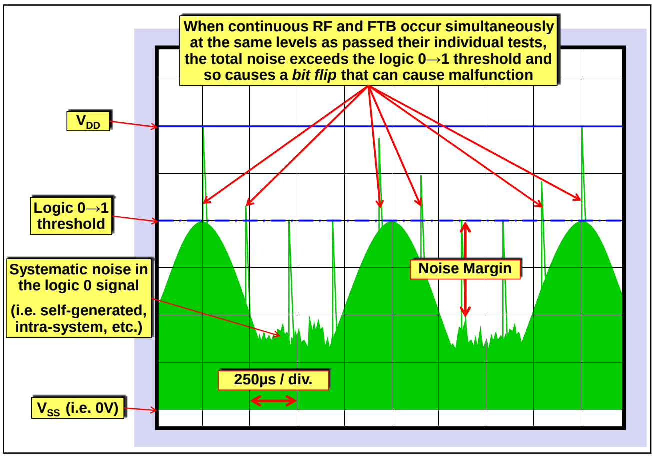

Figure 6 Logic 0 during RF *and* EFT/B testing

We can see that the addition of the EFT/B noise to the continuous RF noise and the systematic noise causes the logic 0 to cross the logic 1 threshold and so, if sampled during the occurrence of some of the transient noise spikes, the logic 0 signal will be mistaken for a 1 and an error will occur.

Logic 1 signals can be mistaken for logic 0 in the same way, as shown in Figure 7.

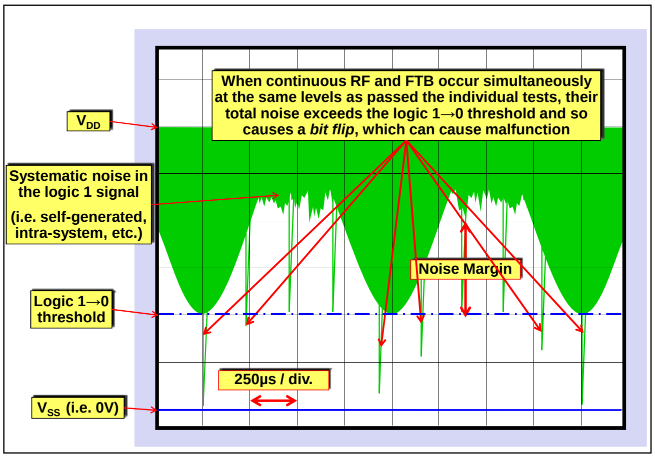

Figure 7 Logic 1 signal during RF *and* EFT/B testing

There are many different ways in which simultaneous EM disturbances can interact to affect the correct operation of equipment, but the above discussion seems to account for the results of simultaneously applying two different immunity tests in [6].

The above discussion shows that when testing immunity with individual EM disturbances in the usual way, to allow for the fact that noise levels in a circuit node can build up due to two or more sources of EMI, the test levels should be set to be equivalent to the foreseeable *combined* noise level in the equipment's operational EM environment over its lifetime.

For example, if the intended operational EM environment can suffer from just *one* strong radio channel plus ESD, EFT/B and surges, then we have two choices of test method:

a) Test with continuous RF plus simultaneous ESD, EFT/B and surge in turn, which would be much too costly and time-consuming (at least until combined test methods are IEC-standardized, perhaps according to work being done in MT15 [7]).

b) Test with each type of disturbance one-at-a-time, at twice the test level, so that each uses up half of the noise margin. Then – when they both occur together in real life (as they will) – the noise margin should "just about not be exceeded".

Similar arguments to the above also apply to testing analog systems, when the signal-to-noise ratio at each circuit node must remain less than a specified level, for correct operation.

Assessment of the application's EM environment might reveal that equipment needs to cope with three or more simultaneous EM disturbances at significant levels, for example:

- Three or more radio channels
- Two or more radio channels plus a transient burst, surge, or ESD event
- One or more radio channels plus two or more independent transients or surges that either overlap or have a time-spacing that is critical for circuit operation

In such EM environments, individual immunity test levels may need to be set even higher than double the maximum levels expected for each individual type of disturbance.

An example of three or more simultaneous EM disturbances, is where equipment could be exposed to significant levels from two or more cellphone, Wi-Fi, M2M or RFID transmitters.

For example, if the proximity of RF transmitters was reliably-enough constrained in the final application, so that they could not be closer than would generate 30V/m at the equipment, there is no limit on how many such transmitters could be operated at the boundary of their "exclusion zone".

If we assumed the maximum possible number was four, we would (crudely) test with at least 120V/m over the relevant frequency range. More sophisticated analyses based on the digital modulation characteristics and channel occupancies of the transmitters might reduce this test level.

Simultaneous disturbances to different circuit nodes

In a given circuit design, certain circuit nodes could be more sensitive to some types of disturbances than others.

For example, an analog signal amplifier could be especially sensitive to certain continuous disturbance frequencies, whilst a digital processor could be especially sensitive to certain ESD impulses, and a power converter could be especially sensitive to certain types of transients or surges.

Some types of EM disturbances will – in real life – almost always stimulate many ports at the same time. This could cause two or more simultaneous circuit upsets that could possibly cause a dangerous error or malfunction. But because these disturbances are immunity-tested one conducted port at a time, these immunity issues tests might not be discovered.

For example, continuous conducted RF tests that simulate exposure to RF transmitters (generally below 80MHz) test one port at a time, but in real life this type of disturbance will apply simultaneously to all ports that have long-enough cables installed, often with a small delay (phase angle) between each.

Another example is when a nearby lightning strike simultaneously induces surges in two or more ports connected to long cables (e.g. mains power and Ethernet).

It is feasible to test the immunity of two or more ports at the same time [8]. Alternatively, when testing ports one-at-a-time in accordance with the normal test methods, we should record what parts of the equipment suffer errors, malfunctions or failures, whether they affect the functions that are important for helping control risks or not.

Then after completion of the test program, the results should be analyzed to see if simultaneous EM disturbances occurring at two or more equipment ports could affect the functions important for risk management in an undesirable way.

III. Expanded Uncertainty and Risk Level

Where immunity testing is being used as a significant part of the validation of a design, the levels at which the tests are performed should provide a level of test confidence that is comparable with (ideally, better than) the design confidence required.

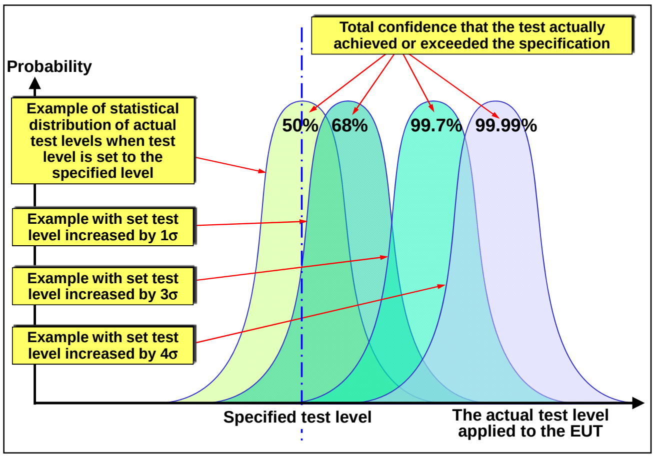

Figure 8 Expanded Uncertainty in immunity testing

Figure 8 is taken from [2] and [9], and shows that if you set the test level to the specified level, the confidence that the test actually met or exceeded the specified level, is only 50%.

But – assuming a Gaussian distribution for the measurement uncertainty – increasing the set level by one standard deviation (σ) increases the confidence to 68%.

This process of "expanded uncertainty" is well-known to all EMC test engineers [10], and makes it possible for us to adjust our immunity tests according to the reliability we need for our equipment.

- For test confidence of 90-99% (SIL 1 in Figures 1 and 2), increase the test level by at least 2σ
- For 99-99.9% confidence increase test level by ≥ 3σ
- For 99.9-99.99% confidence increase test level by 4σ
- For 99.99-99.999%, increase test level by 5σ

For example: assuming a standard deviation (σ) of 2dB means that to achieve an EM immunity test confidence of 99.9-99.99% the test level should be increased by 8dB.

Where the measurement uncertainty has a different shape of probability distribution (i.e. non-Gaussian) the relationship between the test level and the expanded uncertainty will be different from the above example.

IV. Ageing

Another reason why testing at higher levels can help achieve more reliable equipment is because of the degradation of EMC characteristics during the entire lifecycle that is covered by [1], due to various aspects of ageing.

Ageing of electronic components

Boyer *et al* [11] say: "Although electronic components must pass a set of EMC tests to (help) ensure safe operations, the evolution of [immunity performance] over time is not characterized and cannot be accurately forecast."

However, [12] shows the EM susceptibility of some tested ICs using a particular type of 0.25µm MOS technology degraded by between 3dB and 12dB after simulating a few years of operation.

There are also ageing effects on passive components and printed circuit boards, connectors, etc.

This issue can be dealt with by applying appropriate immunity tests to equipment *after* it has been put through highly-accelerated lifecycle simulation designed by experts in that field.

Alternatively, test levels could be increased by (from [12]) 10dB or more. This is very much cruder, but at least tries to deal with this known issue, so is much better than ignoring it.

Simulating the anticipated equipment lifecycle without causing artifacts to arise by accelerating the simulation too much, could mean that it takes a few weeks. However, simulating the operational lifecycle is considered good engineering practice anyway where equipment has to perform reliably. Many manufacturers of such equipment already do it, but don't retest the EMC of the artificially-aged samples, as they should if they want to know how ageing affects EMC.

Even when testing a sample of equipment for EM immunity after its simulated lifecycle, it makes good cost-effective engineering sense to increase the immunity test levels beforehand by 10dB or so, to help find ageing problems earlier in the project. This is because design changes are very much less costly, and cause much less delay, when problems are identified and fixed earlier in a project.

Ageing of EM mitigation

The effectiveness of shielding degrades over time due to oxidation, galvanic corrosion and wear. Also, filtering and surge suppression performance usually degrade too.

As before, we can deal with this by retesting the EM immunity of equipment after they have been put through highly-accelerated lifecycle simulation. For filters and surge suppressers this should include simulation of electrical power quality and lightning exposure.

It is tempting to instead test equipment with its EM mitigation removed, but this is not a good idea because slots and gaps in shields, and resonances in filters are capable of creating negative attenuation (i.e. gain) at certain frequencies. This means that – at those frequencies – testing with the shielding and/or filtering removed can be easier to pass than if the mitigation was in place!

As before – even if intending to test an EUT after its lifecycle has been simulated, it makes good cost-effective sense to increase the test levels applied to the new EUT to help find ageing problems earlier in the project.

Shielding and filtering that has been "well-designed" (proven by competent design analysis and assessment) can be expected to degrade by, say, XdB, over its lifecycle.

Where such reliable design is not practical (e.g. because the possible range of physical, climatic, cleaning, etc., environments cannot reasonably be predicted), a regular maintenance program that checks the performance of the EM mitigation should ensure that it is refurbished before degrading by more than XdB.

In both these cases, the immunity test levels should be increased by the XdB above.

It is tempting to think that the increased test levels appropriate for degraded filtering should only be applied to conducted tests, and those for degraded shielding should only be applied to radiated tests and ESD. But RF disturbances are, like all AC electrical phenomena, propagating EM fields and require a synergy between filtering and shielding for their effective suppression. So, all EM immunity tests that employ at least part of the RF spectrum, should be increased by XdB.

Poorly-designed shielding has been seen to degrade by 10dB or more over periods of weeks, sometimes days (even hours in one case!), so even where there is an EM mitigation maintenance program in place it does not remove the need for competent design of EM mitigation and maintenance intervals.

V. EFFECTS OF TEMPERATURE, VOLTAGE AND LOADING

[13] shows that when the ambient temperature and/or power supply voltage and/or load current exceed certain values, power supply filter attenuation can fall by up to 20dB when compared with the results of CISPR emissions tests.

It is important to note that the variations in ambient temperature, power supply voltage and load current that were tested in [13] remained within the filter's normal operating specifications at all times. Also, different filter designs might do better or worse than the ones used in [13].

[13] tested conducted emissions, but similar degradation in filter attenuation would probably have been found if conducted immunity tests, so the results of [13] are important where filtering is used.

Because the attenuation provided by filters can vary in this way, it is clearly advisable to test equipment for conducted EM immunity on their power supplies (continuous and transient) at the maximum ambient temperature, with the maximum mains voltage and with them carrying the maximum load current.

It is usually rather impractical to have the EUT in an environmental chamber whilst performing radiated EM immunity tests according to IEC 61000-4-3 and the like. But conducted immunity tests are often practical to do during environmental testing, and other methods (e.g. close-field probing) might be used to determine the change in radiated characteristics.

Perhaps filter simulators can be programmed to predict filter performance under "worst-case" combinations of ambient temperature and/or power supply voltage and/or load current?

Perhaps filter suppliers can be persuaded to supply filter data that covers the worst-case combinations of ambient temperature and/or power supply voltage and/or load current?

If reliable filter data under such conditions is not available, and conducted immunity testing is not done whilst creating the worst-case physical environment (highest ambient, highest mains voltage, etc.), then we are left with performing conducted immunity tests under normal laboratory conditions.

In this case – based on [13] (or other relevant information) – immunity tests should be carried out at least at a 20dB higher level to help ensure that the desired level of immunity is met during the worst-case environmental conditions.

VI. PROBLEMS WITH INCREASING TEST LEVELS

Where the issues discussed above would require increases in test levels, because they are independent of each other, it seems to the author that their increases should be added together linearly.

So if, for example, five different issues individually required the test level to double, and they all applied simultaneously, the test level that took them all into account would be 5 times higher than the level specified by the usual immunity test standard.

When such an increase is applied to a continuous RF immunity test, for an EM environment in which the greatest such disturbance is limited to 30V/m over the anticipated lifecycle (by the use of reliable methods to prevent too-close proximity of RF transmitters), the test level would be raised to 150V/m.

We know from [14] that some computers and computer networks might not function reliably at such levels – but we also know that certain automotive and aerospace electronics normally pass tests at such levels, sometimes much higher.

But increasing the levels of ESD, EFT/B and surge tests (normally, say, 8kV, 1kV and 2kV respectively) to allow for the possibility of simultaneous continuous RF disturbances, can soon reach test voltage peaks that could cause non-linear effects (flashovers and component damage) in the EUT, that would never occur in real life, so such tests would not help to increase confidence in the design.

It might be considered reasonable to increase them by, say, four times (32kV, 4kV and 8kV respectively) because such high levels have sometimes been reported or may be theoretically possible, and coping with them might help prove equipment suitable for some applications. Indeed, in some situations (high exposure to lightning, satellites and space vehicles, etc.) these surge and ESD levels might be considered too low.

However, where non-linear effects can be caused by increasing test levels beyond what could *possibly* occur in real life, sufficient confidence must instead be achieved by design analysis and assessment, and/or by performing tests with two or more EM disturbances applied simultaneously, as in [6].

Test methods for dual (or more) simultaneous disturbance tests, which do not increase test times or costs by too much, are starting to be discussed [7].

A more cost-effective goal would be the development of appropriate design analysis/assessment techniques [15] that make it possible verify/validate that foreseeable EMI will not cause risks to exceed certain levels, whilst also reducing overall costs and timescales.

VII. Conclusions

There are several reasons why test levels should be increased (or alternative approaches taken) to improve confidence in electronic design, where equipment (devices, modules, units, systems, installations, etc.) need to function with high reliability to help achieve low risk levels in certain applications.

Even taking these into account, it is still generally the case that no affordable amount of testing [3], at any test level [2], can prove equipment is reliable enough to achieve functional safety according to the basic standard IEC 61508 [1] or any generic, product or product-family standards based upon it. Verification/validation techniques additional to immunity testing are needed for such applications (see [16] and [17]).

This conclusion applies to many other applications where the correct functioning of electronic equipment is critical for control of risks.

However, where immunity testing is used, it should take the issues described above into account, to achieve a level of test confidence appropriate to the levels of risk required for the application.

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