

Pitfalls and practice of IEC 61000-4-6 conducted immunity testing

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Introduction

IEC 61000-4-6 is widely used for compliance testing of RF immunity of apparatus for the EMC and R&TTE Directives. It applies an RF stress over the frequency range 150kHz–80MHz to the cables connected to the equipment under test (EUT) to determine its immunity to this stress.

The principle of the test is to excite both electric and magnetic disturbance fields within the EUT by applying the stress in common mode with respect to the ground reference plane (GRP) to certain selected cables entering it (Figure 1). The stress is applied through a defined source impedance of 150Ω , which is also taken to be the impedance of other cables connected to the EUT. Therefore we must use networks to stabilise this impedance or to decouple it, so as to ensure that unwanted variations have little effect on the test; and also make sure that the layout of the test is controlled so that variations due to stray coupling are minimised. Clause 7 of the standard covers these issues.

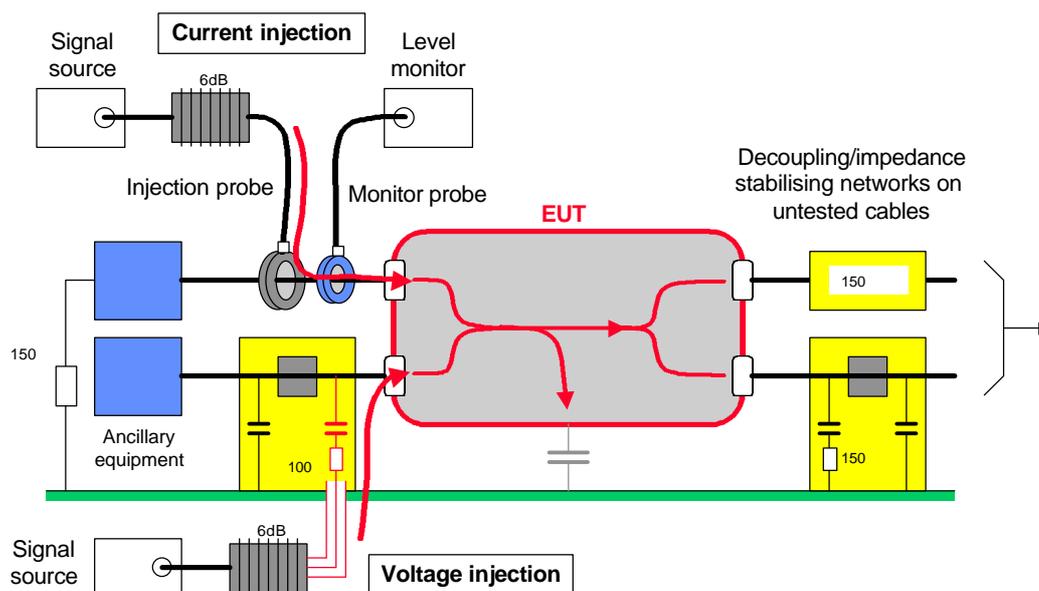


Figure 1 Principle of conducted immunity testing (according to the first edition)

The second edition

IEC 61000-4-6 has recently been republished in its second edition [4], although at the time of writing this has not yet been published in Europe as an EN. There are numerous changes from the first edition, ranging from merely editorial to fundamental changes in the method, and anyone who is familiar only with the first edition will need to revisit the standard to upgrade themselves. One of the most important changes is the move from multiple 150Ω terminations to only a single one. Conceptually, we can imagine the tests applying to a range of different products (Figure 2):

- (a) simple mains-powered apparatus with no other signal or power connections, e.g. household appliances: RF returns only through stray capacitance to the ground plane (remember that the RF is applied in common mode to L, N and E together with respect to the ground plane)
- (b) mains or DC powered apparatus with one other signal or power port, e.g. power supplies, some instrumentation: RF returns through stray capacitance and through the untested but terminated port
- (c) apparatus with more than two ports for power and signal, e.g. most IT equipment: RF returns through stray capacitance and all untested but terminated ports

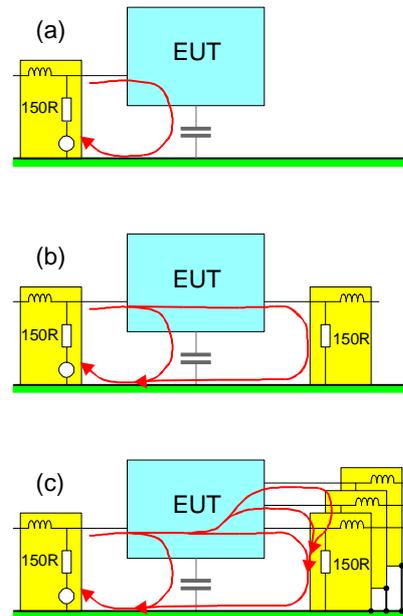


Figure 2 Terminating different types of EUT

The issue here is whether in the third case above, more than one untested port needs to be terminated. The first edition Figure 9 shows that "all non-excited Coupling-Decoupling Network (CDN) ports shall be terminated by 50Ω loads", implying a 150Ω termination for *each* cable, so that potentially the RF return path could have a low impedance if several terminated CDNs are used. In the second edition, this has been changed to insist that "in any one test, only two 150Ω networks are required ... one CDN shall be connected to the port to be tested and one CDN with 50Ω termination shall be connected to another port. Decoupling networks shall be installed on all other ports to which cables are attached. In this manner there is only one loop terminated with 150Ω at each end." (new 7.1.2, 7.2).

This change will mostly affect small multi-port devices, since the untested but terminated port will now be the only one passing RF current out of the EUT. All other ports are decoupled but not terminated. The change will *increase* the capacitively-coupled voltage stress and *decrease* the magnetically coupled current influence. Decoupling networks just provide a high series impedance; they are usually clamp-on ferrite absorbers, but you have to be sure you are using an absorber which has a high impedance down to 150kHz . This is not an everyday item, even in an EMC test lab, although it is possible to build or otherwise procure one [2].

For a large EUT in a metallic enclosure the changed method of the second edition will make little difference since the capacitance to ground of the EUT will typically be sufficient to bypass current away from the non-excited ports.

Choice of transducers

The standard allows three methods for injecting the stress, and assumes that results from each will be equivalent, although it is now stated that the CDN method is preferred:

- CDN (including direct injection)
- EM-Clamp
- Current probe

This paper discusses the pros and cons, as well as the precautions to take for best practice, for each method. It refers throughout to the second edition for relevant paragraphs, although where this has made changes, the first edition is also quoted.

CDN



The Coupling-Decoupling Network (CDN) is designed to couple the disturbance signal directly to the EUT cable while at the same time preventing it from passing towards the AE (associated or auxiliary equipment). It must also provide a fixed common mode source impedance towards the EUT. The discrete components allow a more compact assembly than the other transducers to be discussed; in the assembly shown above the EUT and AE connections are at the top and bottom respectively of the picture and the rf injection is to the BNC connector on the left.

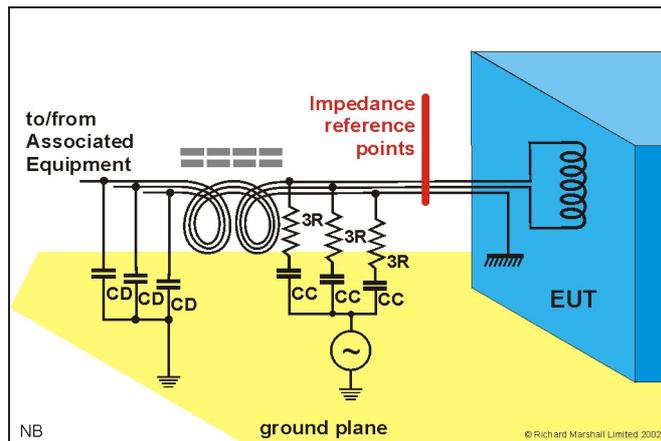


Figure 3 An “M3” Coupling-Decoupling Network schematic

Figure 3 shows the schematic of a CDN for a mains three-wire (M3) circuit. It comprises an assembly of a multi-turn common-mode choke for insertion in series with the EUT cable, together with shunt rf filter capacitors **CD** on the AE side and injection coupling components on the EUT side. In general, if there are n wires then each is coupled to the tester via an equal resistor of value $n \cdot R$ ohms with an appropriate blocking capacitor **CC** in series. R is 100Ω in the standard specification.

Advantages

- Its prime advantages are near-perfect decoupling of the AE and low uncertainty of the applied stress.
- Minimal power is required and there is minimal radiation or environmental influence.
- Additionally it defines a 150Ω common-mode cable impedance, formed from the 50Ω generator impedance in series with 100Ω resulting from the injection resistors in parallel. This impedance damps cable resonance to increase the repeatability of the test and approximates to real-life, giving a very credible test.

Disadvantages

- It is invasive, that is it requires an electrical connection to the cable shield if there is one, or to each core of an unshielded cable. Accordingly different networks are required for different cables, increasing the capital investment required for general test house use.
- This disadvantage has been partially overcome by versatile CDNs [6] in which a variety of CDN configurations can be achieved by patching links within the AE and EUT connectors. The CDN pictured here may properly be used with coaxial and shielded cables of 1 to 6 cores, and with unshielded cables of 1,2,3 and 6 cores.
- Serious errors may result if an ordinary CDN is used with fewer than its intended number of wires, such as for instance using an M3 CDN for a mains port with only live and neutral. The reasons for this are set out below under “CDN Cautions”.

CDN Cautions

The standard for the CDN only specifies its common-mode impedance. The coupling between the individual conductors is not specified. This leaves the choice and arrangement of the ferrite cores and the construction of the winding entirely to the test equipment manufacturer. Consequently a variety of solutions are in use that meet the common-mode requirements but have varying differential-mode characteristics.

Leakage inductance and transmission-line resonance within the choke are both important but unspecified sources of error since both effects allow the individual wires through the CDN to exhibit individual impedances – that is they may carry different rf voltages if the circuit conditions allow. This may be understood from Figure 3, where the EUT has an isolated transformer winding connected to two wires of its mains cable, whilst its chassis – and hence most of its circuitry and any other cables – is connected to the third. The impedance seen looking into the EUT from the CDN at the reference points is quite high for the upper two wires, being dominated by the effect of the stray capacitance of the transformer winding to its surroundings. The impedance of the lower (ground) wire may be very low, being dependent upon the capacitance from the EUT to the ground plane below, and on any other cables connected to the EUT (but not shown on this simplified drawing). If the CDN's isolating inductor comprised three un-coupled chokes then because of the source resistors $3R$ the immunity test voltage injected into the EUT would clearly be much higher on the upper two wires than on the lower one. Unless the multi-wire choke acts as an effective transformer to equalise the voltages on these three wires there will be transducer errors – but if the choke were perfect in this respect then much less intrusive CDNs could have been specified in the immunity standard which used only transformer action and a primary circuit with a single injection resistor.

The magnitude of this effect with commercially available CDNs can be measured with the test set-up of Figure 4, in which the desired selection of the CDN EUT wires – 1 of 3, 2 of 3 or all 3 of 3 – are connected to the input of a spectrum analyser, and the CDN is driven from the output of the tracking generator. If the transformer action of the common-mode choke were perfect then we would expect the same voltage measurement in each case.

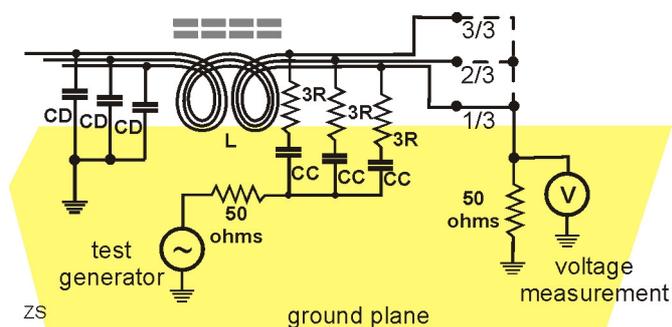


Figure 4 Test of a CDN with an unbalanced load

Figures 5 and 6 show how the output varies with frequency for two different implementations of the standard M3 3-wire CDN. In each chart the “0dB” ordinate represents the theoretical loss of a 100Ω resistor between a 50Ω source and a 50Ω load. The dotted “3 of 3” plots represent the uniform loading of the wires as envisaged in the standard and show less than 1dB of additional loss which would be partially calibrated out by the normal calibration set up with a 150Ω load. The “1 of 3” lines in each case correspond to only one wire being connected to

the analyser. That plotted in Figure 5 exhibits a fall of 5 to 6dB over a wide range of frequencies around 15 and 50MHz, whilst that in Figure 6 shows a 9dB fall in coupling in a narrow frequency range at about 67MHz.

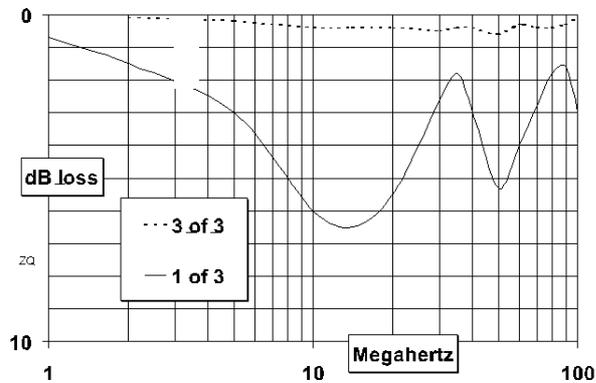


Figure 5 Loss through M3 CDN “B”

In CDN “B” the wires occupied separate sections of the core perimeter. The resulting large leakage inductance resonates with stray capacitances but is damped by the core losses producing the broad resonance bands that may be seen in Figure 5.

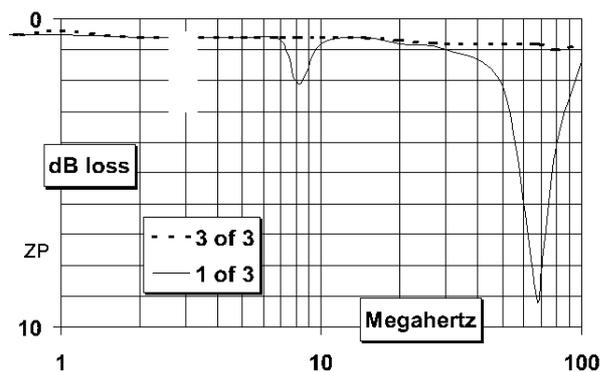


Figure 6 Loss through M3 CDN “A” with unbalanced load

In contrast, CDN “A” embodied a choke constructed with its three wires twisted together before winding. This minimises leakage inductance – but there is still a narrow-band resonance at 67MHz at which the wire being measured is almost totally disconnected from the other two wires. It can only “see” its own $3R$ injection resistor. At this frequency the length of the wires that form the CDN choke is an electrical quarter-wave. The wires are short-circuited to rf at the AE end by the capacitors **CD** (see Figures 3 or 4). This short-circuit is transformed by the quarter-wavelength into a very high mutual impedance at the EUT end. This is purely a differential-mode effect in which the ferrite choke core plays no magnetic part. The “Q” factor of the resonance is high since the only losses involved are those of the dielectrics surrounding the wire and within the capacitors **CD**.

As stated above both these CDNs work well when the EUT circuits offer the same impedance to each wire but give unquantifiable errors in other cases. We have taken as an example the case of the 3-wire mains lead, but other important cases are process control cables with varied circuits within the same cable, and 4-pair data circuits such as “Cat.5 UTP” where some pairs

are used for balanced data and the remaining wires are either used for unbalanced power or not used at all.

There are only two CDN design solutions to this problem; the length of wire in the choke must be short enough to push the resonance above the maximum frequency of test, or the resonance must be damped by introducing extra resistive impedance at the AE end.

A reduced length of wire is possible for some varieties of low-power CDNs but since IEC 61000-4-6 edition 2 Annex B extends the common mode impedance specification from 80MHz to 230MHz the scope for this method is now limited.

Damped-resonance CDNs are available [3] for the particularly difficult high-current applications where the choke must be a physically large component. Damping is achieved by resistors that are transformer coupled to the *individual* choke wires as may be seen in Figure 7.

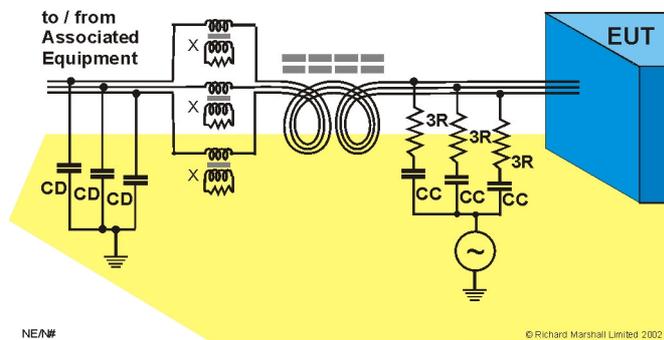
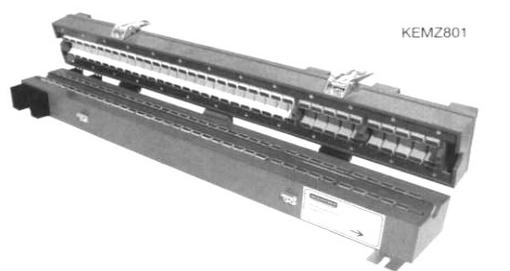


Figure 7 Resistors X provide damping of transmission-line resonance in a CDN

Note that the damping components **X** are applied at the AE end of the transmission line choke adjacent to the rf short-circuits provided at **CD**. At this point rf current is highest and the damping resistors will have greatest influence. Because the coupling between the wires of the main choke is now much more effective, this solution does allow a single CDN to serve almost any conceivable ac or dc single phase or three phase application up to 100 amps with or without associated voltage or control circuits, overcoming for power applications all the disadvantages of CDNs listed earlier.

EM-Clamp



The EM-clamp is a clamping device that subjects the cable under test to both capacitive and inductive coupling of the RF stress. It was invented largely for this test by Bersier and Ryser at the Swiss PTT.

Advantages

- Its principal advantage is that it is entirely non-invasive. No connection need be made to the cable under test.
- Its second main advantage is that it allows adequate decoupling of the AE at high frequencies. The design is arranged so that the capacitive and inductive coupling paths reinforce one another at the EUT end, and cancel at the AE end. This gives the clamp about 10-15dB of directivity above 10MHz.
- Thirdly, it is reasonably power-efficient, although not as good as a CDN; for the same stress, about 6dB more power is needed.

Disadvantages

- Because it uses a series of ferrite sleeves to provide the inductive coupling, it is quite long, and to provide good capacitive coupling it has a relatively narrow inside diameter. This makes it bulky to use and restricts its application for short or large-diameter cables.
- Below 10MHz its directivity is negligible and therefore the AE low frequency common mode impedance is not decoupled.
- It does not provide an accurate source impedance of 150Ω across the frequency range.

Current injection probe



The current injection probe (or Bulk Current Injection, BCI, probe) was not part of the original method but was added before the standard was published at the insistence of several laboratories who were already using it for military standard tests. It acts as a current transformer whose secondary is the cable under test; it provides inductive injection only.

Advantages

- Its main advantage, and the reason it is widely used by many labs, is that it is both convenient and non-invasive. Because it is compact and can be made with quite a wide aperture, it can be used on virtually any cable, even short runs with limited access. This makes it the transducer of choice for in-situ tests.

Disadvantages

- Balancing this practical advantage are several technical failings. There is absolutely no decoupling of the AE, since the current induced on the cable must flow both into the EUT and the AE. Therefore the AE is being tested just as much as the EUT.
- The applied stress is very dependent on cable layout and AE impedance. The current flowing into the EUT is determined by the impedance of the cable, which acts as a transmission line at high frequencies and so may have standing waves due to mismatches, and by the impedance to the reference plane of the AE. So this offers the highest uncertainty and least repeatability of all the methods.
- The probe is lossy and has a high power requirement. The higher its internal turns ratio the more power is needed, but low turns ratios affect the coupling of the probe to the cable and are effectively forbidden by the standard.

Equivalence of results

The standard does not categorically specify which transducer method to use. Its Figure 1, "Rules for selecting the injection method", asks the first question "Are CDNs suitable?", to which if the answer is yes they should be used. Criteria for suitability are not defined. Clause 6.2 of the second edition says that CDNs are to be preferred but are not mandatory. In the European pre-standard ENV 50141 they were mandatory for all AC and DC power supply cables, but only a recommendation appears in IEC 61000-4-6 (in clause 6.2.1.1).

It must therefore be assumed that if one laboratory decides that for a particular port a CDN is suitable, and uses it, while another does not and uses an EM-clamp, and a third elects for the current injection probe, then the results of all three laboratories are deemed equivalent.

Reference [1] investigated this equivalence and concluded

- If the Z_{AE} (see later) is maintained accurately at 150Ω then all three transducers can give very similar results; the two clamp methods differ from the CDN reference level by less than 2dB over the range up to 10MHz, unless the current probe turns ratio is as low as 1:1.
- Any departure from 150Ω of Z_{AE} causes a deviation in the injected stress corresponding to the ratio of the total impedances for each of the clamp methods, but no change for the CDN. The deviation is equivalent for the EM-clamp and current injection probe at low frequencies, but reduces markedly for the EM-clamp at high frequencies.

Aspects of best practice

This section discusses precautions which must be taken in the test method for each of the above transducers in order to get the best repeatability.

In all cases, you must respect the rule that says the transducer-to-EUT cable length should be 10 – 30cm. Anything longer contravenes the standard. It will become resonant towards the top end of the frequency range, and at a quarter wavelength the common-mode impedance

presented by the EUT will be transformed into its opposite: a high impedance will appear as a low impedance at the transducer, and vice versa. This introduces problems for EUTs which have cable entries more than 30cm above the ground reference plane.

These problems have been addressed in A1 to the second edition [5]. This adds an informative Annex F, "Test set-up for large EUTs". The modified set-up uses either an elevated horizontal ground reference plane to which the CDNs are bonded, and which allows the CDN-EUT cable length to be maintained at less than 30cm; or a vertical ground reference plane, again used for bonding of the CDNs. The vertical GRP, for instance a screened room wall, is likely to be the more attractive to test labs, since it can be used for all types of EUT regardless of the actual height of their cable entries. It will also give more repeatable results than an elevated horizontal plane, which is likely to suffer from resonances caused by its own capacitance and an inductive connection to the main ground reference plane.

In all cases the dc or low-frequency current path through the transducer should be controlled to prevent saturation of the ferrite. This requires that for all circuits the flow and return conductors must go through a single transducer. For example, even if a high-power dc supply uses separate cables for its positive and negative wires these should both pass through a *single* M2 CDN.

CDN

Selection

Use the right one for the cable: don't use M3 for M2, M5 for M3 etc unless the CDN supplier specifically recommends this. For details see "CDN Cautions" above.

Grounding

Ground it properly. The disturbance voltage must be applied with respect to the GRP but the voltage feed from the generator is actually connected via the BNC socket on the CDN case. Therefore there must be minimal impedance between the case and the GRP, since this impedance appears directly in series with the applied stress. A metal-to-metal contact is best; any grounding strap must be short and wide since its inductance must be negligible all the way up to 80MHz (or 230MHz). Green-and-yellow wires, always the bane of EMC engineering, are outlawed.

EM-clamp

AE CM impedance

With the EM-clamp, it is necessary to constrain the AE CM impedance (Z_{AE}) to 150Ω at low frequencies. At these frequencies (generally below 10MHz) the EM-clamp acts mostly like the current injection probe, in that it applies current more than voltage to the cable under test, so that the impedance of the total loop is important.

However, the directivity of the clamp above 10MHz means that this requirement largely vanishes and the Z_{AE} may be uncontrolled. This is actually a happy result, because the principal difficulty in controlling Z_{AE} is at high frequencies, where stray capacitance of the AE to the ground plane, and resonances in unavoidably long cables to and from the AE, cause the most

problems (but see [2]). Provided that the LF impedance is maintained at 150Ω , which can most easily be done if the AE is mains-powered with a mains CDN on its input and all ports other than the cable under test left floating, then the HF impedance can be left to look after itself.

Grounding

Like the CDN, the EM-clamp applies a form of voltage injection with respect to the ground reference plane. Therefore it is again necessary to ground it properly, with a short, direct strap and preferably with the ground plate making direct contact. It cannot be used correctly if it is not placed on and connected to the GRP. This differentiates it from other forms of clamp, such as pure decoupling clamps, common mode absorbing devices, or the MDS-21 absorbing clamp used for some emissions tests. These devices use only ferrite, to increase the common mode series RF impedance of the cable, without reference to ground.

Current injection probe

AE CM impedance

With the current probe, it is necessary to constrain the AE CM impedance to 150Ω at *all* frequencies. This, of course, is fundamentally difficult to achieve, and even more to confirm. The actual CM impedance at the AE port is out of the hands of the test laboratory; only the impedance of the AE itself to the GRP can be controlled, most easily using a CDN on its power supply, but at high frequencies this is compromised by its stray capacitance to the GRP. Add to this the effect of longer cables between the AE and the probe, and it can be seen that at high frequencies (typically 26MHz and above) predictability and repeatability of the stress induced by the current probe is very unlikely.

It follows from this that you should only apply the probe to short cables, preferably shorter than 60cm, and certainly less than 1m. For cables longer than this, use the EM-clamp. Some laboratories believe that a very long cable (> 5m) between the clamp and the AE will somehow "attenuate" the signal applied to the AE. This is nonsense; all that happens is an arbitrary and unnecessary reduction of the frequency at which cable resonance effects become significant, leading to even greater lack of repeatability.

Current monitoring

If you are using clamp application and the AE CM impedance cannot be constrained to 150Ω – which is, practically, the case for the majority of test set-ups – then clause 7.4 of the (new) standard puts further requirements in place. It states "it is necessary that the common mode impedance of the AE be less than or equal to the common mode impedance of the EUT port being tested. If not, measures shall be taken ... at the AE port to satisfy this condition." The applied current is then limited through the use of a secondary monitoring probe to what would occur in a true 150Ω system, that is, double that which occurs in calibration, which is a 300Ω system. The measures to be taken include, as an example, the use of a CDN-M1 or 150Ω resistor from the AE to ground.

It is unrealistic under real life conditions in test labs to verify the AE CM impedance across the frequency range for every test set-up. While a procedure for doing so can be envisaged, using a spectrum analyser, tracking generator, a small coupling jig and some data reduction software

[7], this would noticeably extend the time taken to complete what is already a potentially long-drawn-out test. It is also equally unrealistic to verify the EUT port CM impedance. So under real life constraints labs tend not to ensure that the common mode impedance of the AE is less than or equal to the common mode impedance of the EUT port. Although the current limiting method ensures against *over*-testing if the EUT port impedance drops to zero, it would only ensure against *under*-testing if the AE port impedance was in fact maintained at less than 150Ω . Thus laboratories are left largely without guidance in this crucial aspect of the test, and as a matter of practice it is easy for them to pay insufficient attention to controlling the AE CM impedance as the standard requires.

The threat is mainly that, if the AE is left floating, because for instance it is battery powered or passive and there is nowhere to connect a grounding resistor, the return path for the stress at low frequency is high impedance, being only provided by stray capacitance from the AE to the ground plane (Figure 8). Thus the EUT cannot avoid being under-tested at low frequencies since both types of clamp device inject mainly current rather than voltage at this end of the range. The lab will ignore this, since there is no requirement on them to control the minimum injected level, and the customer won't object if their equipment passes. At higher frequencies, the situation improves because the stray capacitive impedance of larger AEs is low enough for a real test to be made.

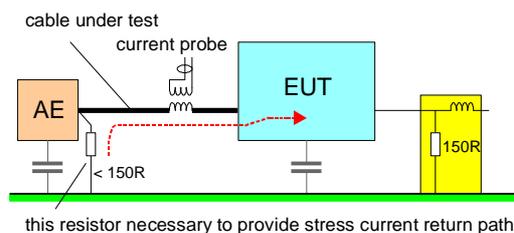


Figure 8 The problem of floating AEs

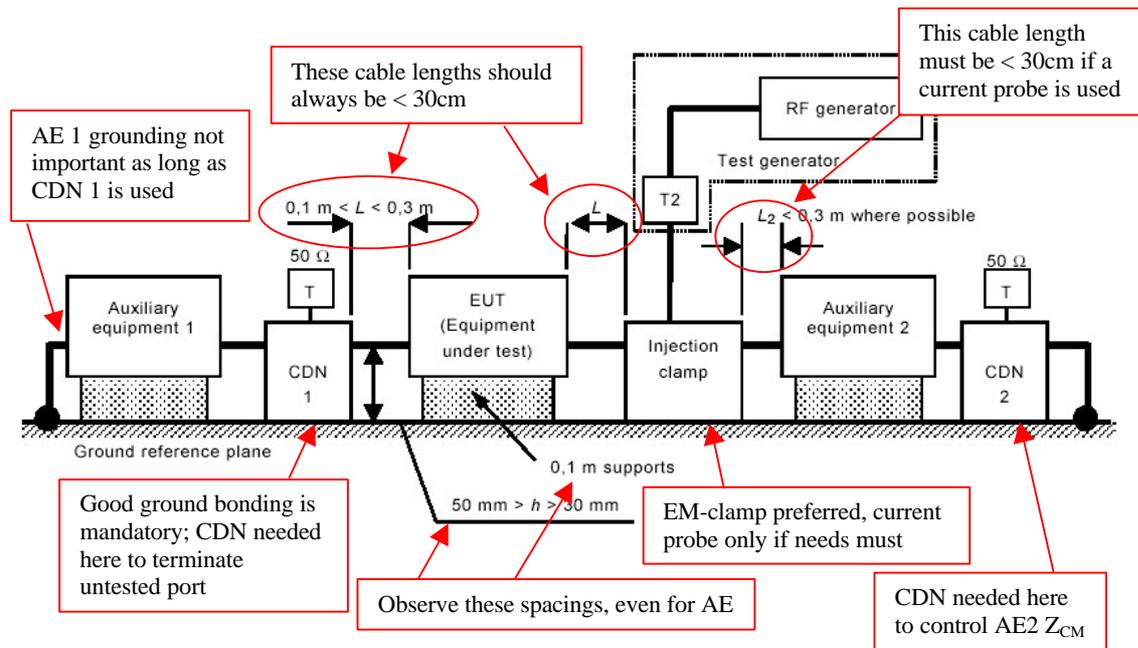
For a correctly implemented test, it is essential to find some way of ensuring an AE common mode impedance of at most 150Ω . Manufacturers' labs who regularly test only a few types of interface can create jigs for this purpose, but for a general test lab who may be faced with a wide variety of products from day to day, this is a major overhead. The article in the previous issue of EMC Compliance Journal [2] offers one solution to this problem for both the EM-clamp and the probe.

Conclusions

This paper has discussed several issues that arise from the application of IEC 61000-4-6. It is a very complex and difficult test to perform properly, especially if the EUT, AE and their cables do not conform to the simple set-ups envisaged by the standard. There is no universal guidance that can be applied for all cases, but an understanding both of the principles of the test and of the coupling transducers that it allows can guide a laboratory towards applying it in the most effective way for a given case.

Summary of best practice

The drawing below is a reproduction of fig 2b of the second edition of IEC 61000-4-6. The annotations should be self-explanatory.



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