AZD085 - A Standards Based approach to capacitive sensor EMC Problems

J.D. van Wyk, M. Visser, D.B. Rademeyer

I) INTRODUCTION

In its essence, capacitive sensing is a highly accurate analog measurement process, detecting changes in capacitance on the order of 10^{-15} to 10^{-12} Farads supported by extensive digital signal processing. If it was feasible to position sensing IC's extremely close to sensing electrodes, noise would not have been a problem. Alas, it is not so. In most real life capacitive sensing applications, a fair distance (few mm – cm's) exist between sensing electrode and IC. Given the extremely small capacitance changes measured, it is no surprise that noise can wreak havoc if allowed to couple in between electrode and IC. And as always, noise can cause digital data corruption via illegal bit detections or timing anomalies. But all is definitely not lost. By following a number of basic principles, making use of sensing solutions with high signal to noise ratios (1000:1 SNR is available in industry) and noise mitigation technology, it is possible to realize applications that will withstand all kinds of noisy abuse. This article will look at relevant EMC standards, noise threats, and what to do to achieve compliance for capacitive sensing applications.

II) RELEVANT STANDARDS

Often, the plethora of EMC standards and which ones exactly apply to a given product or design can be confusing for the uninitiated. Even for people active in EMC, clarity is not always forthcoming without a bit of effort.

EMC standards can be split into two groups, namely generic and product specific standards. The first gives general guidance on what is applicable, and how to test for specific compliance. However, for a given family of products, e.g. household appliances, specific product committees determine what is required for compliance. Mostly, product specific standards call upon / refer to the generic standard. Obviously, the number of product specific standards is quite large. Therefore, we will only review generic standards.

For EMC, two things matter. One, does the Device Under Test (DUT) cause other devices / systems to malfunction? Two, does the DUT itself malfunction due to a lack of immunity to unintentionally received electromagnetic energy? To establish the answer to question one, we do emissions testing to determine the amount of energy radiated into the space around the DUT, or conducted into the cables connecting the DUT to other devices and systems. These emissions needs to be less than the limit of the relevant EMC standard. Capacitive sensing IC's typically consume extremely little power, typically in the low µW range. Therefore, emissions by capacitive sensing applications are typically in the nW - µW range, and compliance is seldom a problem. (Our emissions testing have shown typical levels are at least -15dB below the **CISPR22** limit). So for brevity's sake, emissions will be not be discussed further.

But getting an answer to question two above is another beast altogether, with capacitive sensing circuits being so sensitive. Given the large number of interfering sources that may couple in, and high sensitivity, thorough immunity testing is advisable. Specifically, attention should be paid to those noise sources which result in capacitive currents flowing to earth, in other words common mode EMC tests. (This does not mean differential mode immunity can be ignored.) Typical noise sources include lightning, supply voltage fluctuations, 50Hz magnetic fields, arcing due to breaks in inductive circuits, radio transmitters, electrostatic discharges and switch mode power supplies.

In terms of energy, lightning strikes and related surges on power lines are the most destructive. The **IEC 61000-4-5** standard for **surge immunity** testing is most commonly referred to. Normally, surge immunity is addressed during design of the PSU front-end of an application and immunity of the capacitive sensing circuit per se is not tested.

Mains supply fluctuations should not affect a capacitive sensing application if a quality power supply is used. However, on occasion, cost may force use of a power supply with little fluctuation immunity. This may cause voltage rails variation for the sensing IC. In such cases, immunity testing according **IEC 61000-4-11** should be done.

A capacitive sensing application using a mains derived power supply, or in the vicinity of mains powered equipment, is likely to see some sort of 50Hz interference. Often, this is due to coupling of 50Hz magnetic fields into the product or cables feeding it. Use of intelligent DSP based 50Hz filters, as are available in some capacitive sensing IC's, may help ensure immunity. For formal **50Hz magnetic fields immunity** compliance, refer to **IEC 61000-4-8**.

Another noise source which should always be considered in capacitive sensing applications is **Electrical Fast Transient Bursts (EFT/B)**. These typically occur due to fast breaks in inductive circuits, and high voltage breakdown of air gaps, with the arc forming and decay happening in the ns range, implying frequencies in the tens to hundreds of MHz.. Testing according to **IEC 61000-4-4** is advisable, as EFT/B can be a real headache for capacitive sensing.

And then we have wireless, with radio waves from cellular telephones, Wi-Fi and other transmitters arguably posing the biggest threat to capacitive sensing applications. Coupling into the sensing system may be via a number of paths, always requiring some sort of inadvertent antenna structure. **Radiated Immunity** testing is described by **IEC 61000-4-3**, covering the frequency range from 80MHz upwards. However, additional testing beyond IEC 61000-4-3 is well advised. It may also happen that the radiation is just too strong to filter or compensate for. In such cases, available sensing IC's with integrated RF-detection becomes invaluable. Often, radiated interference with frequencies below 80MHz are coupled into long cables feeding a particular system, which has led to the establishment of **IEC 61000-4-6** that describes testing **for immunity against 150kHz to 80MHz conducted interference**. It should be noted that the interference here is a continuous wave, with AM, unlike that for immunity against surge of electrical EFT/B.

Lastly, we should not forget **Electrostatic Discharge (ESD)**. I remember the first time I discovered, as a little lad, that dragging your feet on a thick carpet and then touching a sibling with a pointed finger will give them a nice shock quite well. (The novelty wore off quickly, since you also have to shock yourself). But the phenomenon behind this will cause your capacitive sensing system to fail if no protection is provided. ESD immunity is split into two categories. Firstly, the immunity of devices, or IC's, typically as described by the **JEDEC Human Body Model** (HBM) requirements. Secondly, immunity of complete systems that incorporate devices, according to **the IEC 61000-4-2** standard. The below sections will take a more detailed look at four of the above standards, which we have found over the years to be particularly relevant to capacitive sensing applications.

III) RADIATED IMMUNITY

A large number of intentional (cell-phones, Wi-Fi, gaming consoles) and unintentional (lightning, arcing of contactors, spark plugs, products not conforming to EMC standards) transmitters will likely operate in proximity to your capacitive sensing circuit. Ensuring immunity to these transmitters can be challenging. The reader is encouraged to peruse [3] for a proper overview. The present IEC 61000-4-3 was preceded by IEC 801-3, and is a generic standard, with a large number of product specific standards calling upon it, two examples being:

EN 55024: Information Technology Equipment (ITE) and Telecom Products & EN 55104-2: Household Appliances

Briefly, IEC 61000-4-3 require commercial products to be immune to radiated fields with strengths between 3V/m to 10V/m, which are 80% amplitude modulated with a 1kHz sine wave, and with frequency between 26MHz and 1GHz. Additionally, recent editions of the standard have called for further testing in the band between 1.4GHz and 6GHz, albeit not as a continuous sweep. For an excellent review of IEC 61000-4-3's past and future, refer to [4]. Just testing to the minimum requirements of IEC 61000-4-3 is not wise. Most EMC authorities advise a good margin. Given the possible future requirements [4], we normally advise to test up to 30V/m and 6GHz where possible.

Radiated immunity testing is normally done on an Open Area Test Site (OATS), in a fully Anechoic Chamber, in a Semi-Anechoic Chamber or in a GTEM cell that have been certified for conformance with an OATS. The capital outlay for all of these test facilities is high, reflected in their booking cost. In house alternatives to gauge immunity are:

- 1) Cellular telephones, which typically emit up to 2W at 900MHz / 1.8GHz (EU) or 1.9 / 2.45GHz (US); 2) Wi-Fi routers – 2.45GHz; 3) Zigbee or Bluetooth Transceivers, 2.45GHz band. (Higher power Zigbee modules emit up to 100mW); 4) All Industrial, Scientific, Medical (ISM) band transceivers – typically in the lower mW range; 5) Two way radios, also known as walkie-talkies, which emit up to a few Watt of RF; 6) E-Field and H-Fields probes to inject radiated fields into localized sections of the application

When using alternative radiated field sources such as these, they should be placed in as many locations and orientations, relative to your circuit under test, as possible. **Always ensure that you are not exceeding local legal radiation limits, which could have severe consequences, including loss of life.**

Following the below guidelines should help to ensure maximum immunity to radiated interference:

a) Decoupling capacitors: Proper decoupling of IC's is the first defense against radiated interference. However, for a specific capacitor value a resonant point exists, above which impedance increases again (Fig.1 left). Therefore, use a range of capacitors, placed as close as possible to the IC. Feed and return path for the capacitors should have minimum inductance (Fig. 1 right). Use 0402/ 0603 size 10pF, 100pF, 1nF, 100nF and 1µF if cost/space is not constrained, and 100pF and 1µF if money and board space is tight.

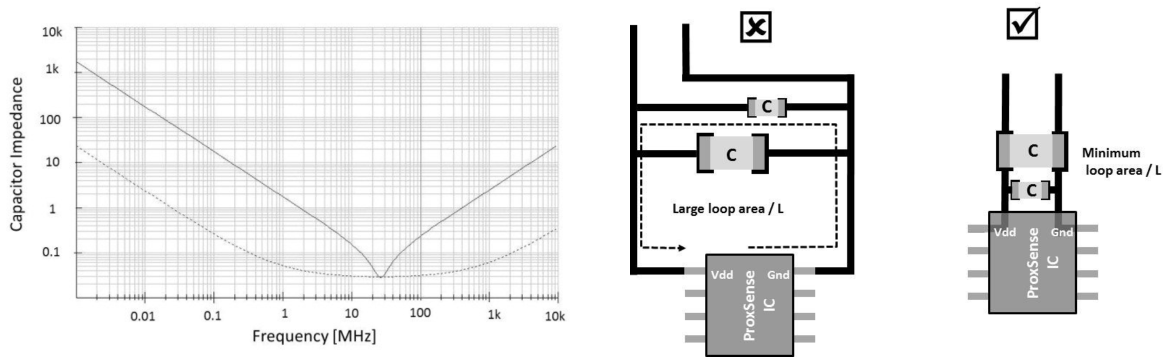


Figure 1: Typical impedance for surface mount 100nF, 0402 ceramic capacitor (left), and minimum inductance path between decouple C and IC, with smallest value C closest to IC (right)

b) RC- and LC-filters: Classical low-pass RC- and LC- filters can be used on supply and communication lines to provide -20dB/decade and -40dB/decade attenuation respectively. Cascade them to increase filtering.

c) Unused / Do-Not-Place Components: Tracks running to / from component sites which are not populated may form excellent RF antennas. Use 0Ω resistors to decouple tracks to unused component sites. Watch out for unused connectors, since their open-circuit status also enables realization of antennas.

d) Grounding & stitching: RF-currents avoid inductances and seek capacitances. Without a low inductance ground, RF-currents may not be shunted to ground correctly, negating all effort with decoupling capacitors, filters and other tricks you felt were quite clever. The following summarizes grounding:
   - Thin ground track = BAD; Wide ground track = BETTER; Ground place with number of slots to accommodate other tracks = GOOD; Solid ground plane only interrupted by via's = BEST; Solid ground plane only interrupted by via's, and stitched to ground plane opposite = BEST of the BEST

   Grounding is an extensive topic that can fill volumes, so the above needs to be critically applied. Ensure that you do not create islands of ground in your design. Stich sections on different layers together with via's.

e) Loops & Following the current path: The maxim "Follow the current" is well worth applying. Ensure you do not create loops by tracing paths as far as possible. Consider virtual interference sources or coupling points.

f) Capacitive Sense Pads: Tracks leading to capacitive sense pads are inherently unconnected on the pad side. Therefore, radiated interference easily couples into your design via these tracks, so keep them as short and as thin as possible. (It should also improve capacitive sensing sensitivity). Try increasing the series resistance between pad and capacitive sensing IC's to impede the noise. (With some industry offerings, series resistance of up to 10kΩ will still give good performance.)

Sometimes, the strength of the radiated fields is too much and it swamps whatever diligence has been applied. In such cases, the capability to sense excessively high radiated fields, and halt any logic outputs is invaluable for immunity. Industry offerings exist where such capability has been integrated into the capacitive sensing IC.

IV) CONDUCTED IMMUNITY

In a certain sense, the conducted immunity standard IEC 61000-4-6 is an extension of the radiated immunity standard IEC 61000-4-3. The conducting part of the title can be misleading, as the standard refers to interference that has been induced into cabling by radiated fields. It is not practical to test for radiated immunity at 150kHz to 80MHz, due to the size of the required antennas. (At 30MHz, wavelength is 10m, so a half-wave dipole antenna would be 5m long!) So interference is injected into cables as if it has been induced by radiated fields. The standard also allow testing up to 230MHz, should the DUT and its cables have dimensions less than a quarter wavelength. Similarly, the lower frequency (150kHz) may be raised if the device is small enough. Normally, the specific product committee decides what frequencies pertain.

Injection of interference may be done via three alternatives, according IEC 61000-4-6. The first is via the use of so-called CDN's, or couple-decouple networks. One may also use an Electromagnetic Clamp, which is what the name implies. Or one may use what is known as Bulk Current Injection (BCI), which uses specific current clamps. A difference between the standard and real world threats is the fact that interference only gets injected into one cable at a time according to the standard. In reality, radiated interference couples simultaneously to all the cabling of a given application. Another gap in the standard is testing for common mode currents only, which may be addressed in future editions, as differential mode currents due to illuminating fields are quite possible.

In terms of the level of the conducted interference, things are not entirely unambiguous. The standard specifies leveling during setup for 1V, 3V and 10V, all RMS values, into a 150Ω load that is connected to the ground reference plane. However, no mention is made of the 80% amplitude modulation with a 1kHz sine wave carrier that the standard requires when actual immunity testing is done. So the exact level while testing is not known, also since the cables impedance into a device is seldom 150Ω. For more information, please refer to IEC 61000-4-6. To help insure a pass for IEC 61000-4-6, most of the guidelines for radiated immunity hold. In addition, with the test being a common-mode test, sufficient grounded copper area, especially for the power supply section, is important. Typically, good filtering in the power supply will help attain immunity.

V) ELECTRICAL FAST TRANSIENT BURST (EFT/B)

The origin for EFT/B immunity requirements can be found in the basic circuit shown by Fig. 2, common to a large number of applications. Whenever a substantial current along an inductive path is interrupted by a mechanical switch, arcing and a burst of high voltage spikes are generated, as the switch opens [2].

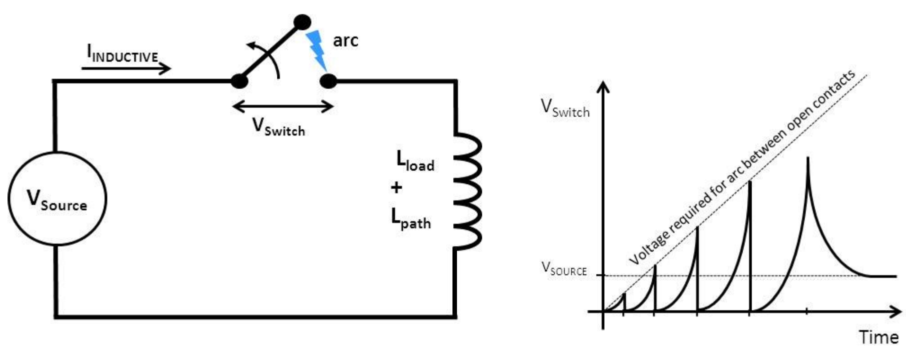


Figure 2: High frequency transients due to arcing contacts in an inductive path

Such bursts of transients are especially prevalent in heavy industry and electrical switching installations. But even in a typical residential setting, something like a power drill will generated similar interference. To provide a common basis for EFT/B immunity testing, the IEC published 61000-4-4, which specifies approximately three bursts of transients per second, with each burst containing 75 transients. The transient pulse repetition frequency within a burst may be either 5kHz or 100kHz. According the standard, the latter may be more representative of real world threats. However, traditionally, 5kHz has been used, and it is up to the specific product committee to decide which will apply. Rise times of the transients are on the order of nanoseconds, implying frequencies of a few hundred MHz. Table 1 lists immunity levels for the common mode voltage applied between mains supply cables, and the local earth plane as required by IEC 61000-4-4.

Table 1: EFT/B immunity levels required by IEC 61000-4-4

Level:	Description:	Example & characteristics:	Immunity up to:

Level 1	Well protected environment	Server rooms, stringent layout principles and filtering applied	0.5V
Level 2	Protected environment	Control room, with some filtering. Also typical environment for consumer and commercial applications of ProxSense design	1kV
Level 3	**Industrial environment**	**Industrial plant, no transient filtering, cables in close proximity to each other**	**2kV**
Level 4	Severe industrial environment	HV Substations, Power Plants. High current contactor switching	4kV

For some applications, testing with coupling to auxiliary cables, using a prescribed capacitive coupling cable clamp, may be necessary. But for most capacitive sensing applications, only testing with coupling to mains cables is required. To understand how to guard against EFT/B, we have to investigate the paths of the mainly capacitive interference currents. This is discussed in depth by [2]. Following the below should improve overall EFT/B immunity:

- It is best to reflect the EFT/B energy back to the source using inductance, capacitance or a combination of the two, along with dissipative elements, as early as possible, i.e. during the power supply input stages.
- A large ground plane in the power supply input stage helps to reflect EFT/B energy back to its source.
- Failing the above, care must be taken that sufficient grounded copper is provided in the capacitive sensing part of the design, to channel the capacitive EFT/B interference currents. If not, these currents may flow via the capacitive sensing pads to the large ground plane underneath, causing havoc.
- Capacitive EFT/B interference currents will typically flow via the ESD protection diodes present on most capacitive sensing device pins.
- Blind application of RC and LC low-pass filters will not help. Careful analysis is necessary to ensure such filters are placed in interference current paths, due to the mainly common mode nature of EFT/B.
- If allowed by the sensitivity budget, increase series resistance to Cx pads to 10 kΩ.
- If allowed by the sensitivity budget, use hashed copper pours to fill pads of Cx electrodes in surface capacitance applications.
- Long, thin tracks to Cx electrodes may improve EFT/B immunity. (But will reduce Radiated Immunity.)
- Additional, discrete ESD diodes external to the capacitive sensing device may assist to improve EFT/B immunity, as a part of interference currents may be then flow external to the IC.

***** EFT/B testing, either strictly according to the IEC 61000-4-4 standard, or using some alternative test, typically involve hazardous voltages. Basic electrical safety principles should be applied.**

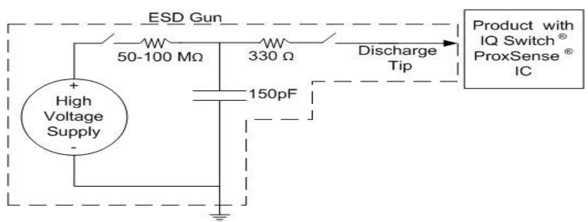
VI) ELECTROSTATIC DISCHARGE (ESD)

IC's are inherently susceptible to ESD damage, either occurring during the process of assembling them onto boards, packaging or in the field. Currently, several methods exist to rate IC (note, not application or system) immunity to ESD, the most common being:

- **HBM (Human Body Model)** - Simulates a person being charged and then discharging from a bare finger to ground via the circuit under test.
- **MM (Machine Model)** - Simulates a charged manufacturing machine, discharging via the device to ground.
- **CDM (Charged Device Model** - Simulates an integrated circuit becoming charged and discharging to a grounded metal surface.

The HBM is sufficient for a controlled ESD environment, like an assembly floor, but completely inadequate for application or system level testing, where ESD levels, both voltages and currents, can be much greater. Therefore, a different standard, IEC61000-4-2 is used by industry for systems / applications. **HBM and IEC61000-4-2** are two very different standards designed for different purposes. There are several differences between the HBM and IEC61000-4-2 standards that are immediately obvious:

- The amount of current and I^2R power released during a voltage strike, for instance the peak current discharged during an 10KV HBM strike is less than the peak current discharged during a 2KV IEC61000-4-2 strike. The difference in current is critical to whether the DUT will survive the ESD strike, as high current levels can cause junction failures and metallization traces to melt.
- The rise time of the voltage strike. The HBM model specifies a rise time of 25nS. An IEC pulse has a rise time of less than 1 nS and dissipates most of its energy in the first 30nS. If protection circuitry takes 25nS to respond, the device rated using the HBM specification will be destroyed.
- The number of voltage strikes repeated in the tests. HBM requires 3 positive and 3 negative strikes to be discharged on each pin specified in the test. IEC61000-4-2 requires 10 positive and 10 negative strikes.



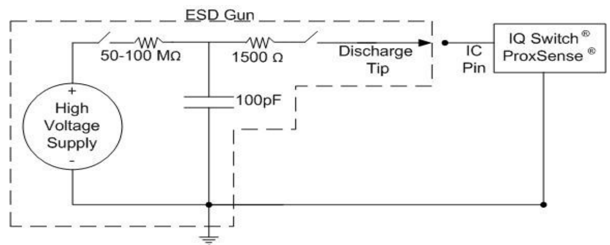


Figure 3: IEC61000-4-2 (left) and **HBM** (right) ESD test setups.

ESD Protection Methods

i) **Series Rx:** Capacitive sense electrodes are usually exposed. Placing a series resistor (R_X) between the sense IC and electrode (C_X) can improve system ESD immunity. This limits peak currents and helps dissipate some of the power. Capacitive sensing solutions are available with sufficient SNR that up to 10kΩ series resistance can be tolerated. Taking dimensions and air breakdown into consideration, it is advised that multiple 0603 or 1206 components are used for protection above 4.6kV.

ii) **Overlays:** These isolate the capacitive sensing electrode pad from the user and generally increase the robustness of a design, enabling the design to withstand higher levels of ESD. Typical overlay materials include Perspex/Plexi-glass (17.7kV/mm breakdown), standard window glass (7.8kV/mm breakdown) and other plastic / non-conductive materials.

iii) **TVS diodes:** TVS diodes have been successfully integrated into projects assisted by the authors. These are typically only required if ESD strikes are able to directly penetrate the Cx electrode pins on the sensing device. This can occur if sense antennas or shield wires are exposed, if the ESD strike bends around an overlay or if there are defects in the overlay. Implementing TVS diodes may influence the sensitivity of the design, as this establishes a parasitic capacitance on the Cx pin. The influence on sensitivity by a known capacitance will differ in every design. It is recommended that when using TVS diodes, selecting a component with the lowest possible capacitance value is necessary

System designers need to be familiar with the differences between various ESD test standards. For system level ESD ratings, always use the IEC61000-4-2 standard. Most ESD ratings found on the datasheets of capacitive sensing ICs are HBM ratings and most ICs are rated at 2KV-4kKV HBM. Refer to [5] for further guidelines on ESD.

iv) CONCLUSION

This article has touched on the various generic EMC standards that pertain to capacitive sensing applications. It reviewed four of the more prevalent EMC threats to capacitive sensing applications. The information given in this article is intended to serve as a starting point to help ensure compliance for a given capacitive sensing application.

References

[1] – www.azoteq.com
[2] – Azoteq Application Note AZD051 – " Electrical Fast Transient Burst Guidelines"

[3] – Azoteq Application Note AZD015 – " Radiated Immunity Guidelines for ProxSense Designs"
[4] – Amplifier Research Application Note #43 – "Test beyond the specs"
[5] – Azoteq Application Note AZD013 – ESD Guidelines
[6] – Azoteq Application Note AZD008 – Overlay Guidelines
[7] – Tim Williams, Keith Armstrong, EMC Testing, 7 Part Series, www.compliance-club.com