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A SURVEY OF EMI MEASUREMENT TECHNIQUES

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ABSTRACT

All electronic and electrical systems are potential sources of Electromagnetic Interference (EMI) and at the same time they can malfunction due to external EMI. Electromagnetic Compatibility (EMC) can be achieved by measuring the interference from equipment, characterised by standards or requirement and then designing the equipment to correctly function in the operational environment without causing EMI. Thus an accurate measurement of EMI is an important milestone in the road to the EMC. EMI measurements are divided into many categories imposed by EMI/EMC standards and requirements and they also impose measurement techniques and test setups, which are useful in determining the EMI. The problems in carrying out accurate measurement includes lack of reproducibility, interference to other systems and non-availability of customized test equipment for various type of EMI measurements. In this report, a survey of different EMI measurement techniques is presented to show, how associated problems can be minimised for low error EMI measurements, by proper understanding and interpretation of the test methods and specification limits. A review of the measurement techniques for accessing and innovative non-conventional techniques is also presented.

1. INTRODUCTION

The subject of EMI measurements may be considered to have begun in 1934, which was the year of formation of the International Special Committee on Radio Interference(CISPR) and the start of the period when several European countries began developing standards for the control of emissions from electrical equipment and suitable measurement techniques. Since then, measuring techniques have been developed to reproduce conditions obtaining in practical installations and also to the need to achieve consistent, reliable measurements [1]. The requirement for appropriate internationally accepted measurement techniques has become important in recent years with more types of equipment subjects to legal regulations, not only for control of emissions but also for incorporation of adequate immunity of transients, RF transmissions and electrostatic discharges [2].

In the profession of EMI/EMC it is often said that, "one measurement is worth a hundred predictions" [3]. Needs for achieving electromagnetic compatibility (EMC) in a cost effective way there is a focus on the development of the techniques for the measurement of noise and unwanted signal emissions from a wide variety of equipment [2]. Assessment of the susceptibility (immunity) of sensitive electronic equipment to electromagnetic disturbances, such as electrostatic discharges and RF transmissions, is equally important. To carry out a survey on different EMI measurement techniques it is necessary to have an understanding of EMI, EMC, their physical effects, standards/regulations pertaining to EMI control.

1.1 ELECTROMAGNETIC INTERFERENCE (EMI)

EMI is a phenomenon in which electrical/electronic equipment malfunction due to the interference caused by the surrounding electromagnetic (EM) environment. The EMI may occur due to following reasons,

1. The susceptibility (immunity) level of the equipment is high (low) due to poor EMC design.

2. The emissions from the surrounding EM environment exceed beyond specified or tolerable limits of the equipment.

A model of EMI coupling situation is illustrated in the fig. 1, where various types of EMI are generating.

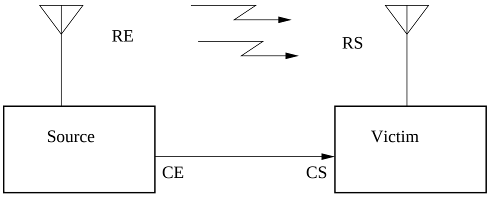

Fig. 1 A model of EMI coupling

1.2 ELECTROMAGNETIC COMPATIBILITY (EMC)

The threat of EMI is controlled by adopting the practices of EMC [2]. It can be defined as, "the ability of a device, equipment or system to function satisfactorily in it's electromagnetic environment without introducing intolerable electromagnetic interference to any other system in that environment". It is also termed as electromagnetic coherence. The term EMC has two aspects,

1. It describes the ability of electrical and electronic systems to operate without interfering with other systems.

2. It also describes the ability of such systems to operate as intended within a specified electromagnetic environment.

Effective EMC requires that the system is designed, manufactured and tested for a defined environment. The need for the testing, emphasizing on the appropriate measurement techniques.

1.3 Effects of EMI

The effects of EMI are variable in character and magnitude. It's effects range from minor annoyances due to engine ignition or household electrical grinder operation on broadcast reception to catastrophic failures/accidents due to corruption of safety critical control systems.

Some reported EMI examples are-

1) In Germany, in a particular make of car, the central door locking system and electric sunroof would operate when the car's mobile transmitter was used.

2) Perhaps the most tragic example is the fate of HMS Sheffield in the Falkland war, when the missile warning radar that could have detected the EXOCET missile which sank the ship was turned off because it interfered with the ship's satellite communications system [2].

1.4 Electromagnetic Environment

Sources of EMI can be divided into natural and man-made with, in most cases, the natural sources of radiation present at a much lower level than the man-made. Man-made noise can be intentional and non-intentional. The majority of non-intentional emissions occupy a wide range of the frequencies which we may call broadband. Intentional emissions such as radio, mobile communication are termed as narrow band.

1) Natural sources of Electromagnetic Noise:

Atmospheric noise produced by electrical discharge occurring during thunderstorms. Cosmic noise from the stars and galaxy.

2) Man made Electromagnetic Noise:

Arc welders, RF heaters, Industrial/Scientific/Medical/IT equipment, microwave ovens, electric motors, transmitters, radio, radars, jammers [3]

1.5 EMI Regulations, Standards and EMC directives

The gap between the EMI immunity of a system and the emission levels in the EM environment is being reducing rapidly in the recent years. Low immunity is a function of the adoption of modern VLSI technology to achieve new tasks faster and more accurately. At the same time more radio communications mean more transmitters and an increase in the average emission level which systems are exposed. The maintenance of some artificially-defined gap between susceptibility and emissions is the purpose of the application of EMI regulations/standards, and is the entirely worthy aim of the enforcement of the EMC directive [2]. In general there are two types of EMC directives,

1) For Commercial/Industrial requirements: These includes IEC, CENELEC (directives for CE-marking), CISPR, ANSI etc., [4-8].

Table 1, shows typical IEC 61000-4-X, emission and susceptibility requirements .

Table 1 IEC 61000-4-X, EMI measurement requirements [5]

Sl.No.	Test	Description
1	IEC 61000-4-2	Electrostatic Discharge (ESD), Air/Contact- discharge
2	IEC 61000-4-3	RF Radiated Immunity Test
5	IEC 61000-4-4	EFT, L,N and PE, 5/50 ns, 5 kHz Rep.
6	IEC 61000-4-5	Surge , 1.2/50 μs Pulse shape- L,N and PE
7	IEC 61000-4-6	RF Conducted Immunity

2) For Military requirements: These includes MIL-STD-461, MIL-STD-462, MIL-STD- 285 etc. These specifications are more stringent. Table 2, shows typical MIL-STD-461E, emission and susceptibility requirements [9].

Table 2 MIL-STD-461E, EMI measurement requirements [9]

Sl.No.	Test	Description
1	CE102	Conducted Emissions, Power Leads, 10 kHz to 10 MHz
2	CE106	Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz
3	RE101	Radiated Emissions, Magnetic Field, 30 kHz to 100 kHz
4	RE102	Radiated Emissions, Electric Field, 10kHz to 18 GHz
5	RS101	Radiated Susceptibility, Magnetic Field, 30 kHz to 100 kHz
6	RS103	Radiated Susceptibility, Electric Field, 10 kHz to 18 GHz
7	CS116	Conducted Sus., Cables/Power Leads, 10 kHz to 100 MHz

EMC specifications for any military installation are similar in terms of measurements of RF voltage, current and field strength and the permitted levels of emission are substantially lower and the ability to withstand the more hostile electromagnetic environment has to be much greater. Such requirements generally mean that the measurements must be made inside screened enclosures since the emission limits are comparable with or below ambient noise levels. However, EMI measurement techniques for both types of directives are almost same expect few variations in test methods and instrumentation.

2. INSTRUMENTATION

Investigation of EMC problems involves the measurement of complex waveforms varying considerably in amplitude and time. Methods of measurement have been devised to give constant, repeatable results. Measuring instruments for the frequency domain are based on radio receiver designs and the detecting and measuring circuits most commonly employ peak and quasi-peak detectors. The former is used in the determination of compliance with military specifications while the latter is extensively used in the determination of compliance with legal regulations and national standards. Many radio interference measuring receivers have facilities for bus control and can be used for automatic plotting of noise spectra. Spectrum analysers having similar facilities are extensively useful for the examination of spectrum over a very wide frequency range, e.g. the harmonics generator by local oscillators, RF heating equipment and digital signals. Full details of performance and design parameters of radio interference measuring receivers are given in MIL-STD-461E and CISPR 16 [1].

2.1 QUASI-PEAK MEASURING RECEIVERS

The basic definition of quasi peak measuring receiver is one which provide an indication which is a defined fraction of the peak value within the bandwidth of the receiver. This fraction approaching unity as the pulse repetition frequency of the signal increases.

2.2 PEAK MEASURING RECEIVERS

The same basic design principles are generally followed in peak measuring receivers although the control over design parameters is far less critical. The bandwidth is specified (MIL-STD-461E) and must be accurately known since the results are invariably expressed in terms of unit bandwidth. The receiver bandwidths are listed in Table-3.

Table 3 Receiver bandwidths requirements [9]

Frequency Range	6 dB BW	Dwell Time	Min. Measurement Time
30 Hz - 1 kHz	10 Hz	0.15 sec	0.015 sec/Hz
1 kHz - 10 kHz	100 Hz	0.015 sec	0.15 sec/kHz
10 kHz - 150 kHz	1 kHz	0.015 sec	0.015 sec/kHz
150 kHz - 30 MHz	10 kHz	0.015 sec	1.5 sec/MHz
30 MHz - 1 GHz	100 kHz	0.015 sec	0.15 sec/MHz
Above 1 GHz	1 MHz	0.015 sec	15 sec/GHz

The detector may be a peak voltmeter, which takes the same form as a quasi-peak detector but with very short charge time and considerably longer discharge time. In the case of impulsive interference the maximum amplitude within the bandwidth of the receiver is indicated irrespective of repetition frequency. The response of the direct-reading peak meter with respect to repetition frequency is substantially flat, possibly falling to about 1 dB below peak at a repetition frequency of 1 Hz. The expression of the results in terms of unit bandwidth leads directly to the need for correct identification of the interfering signal.

2.3 Spectrum analysers

The swept frequency spectrum analyzer is capable of providing a visual display of amplitude against frequency over very wide frequency range. This capability is inherently well suited to the examination of the spectral distribution of narrow band signals. Spectrum analysers may be used in a variety of EMC investigations and are exceptionally useful in the measurement of harmonics from nonsinuodiual waveform generators and the spectral content of digital signals. Most analysers have multiple bandwidth capability, which enables detailed examination of complex waveforms to be performed.

3. EMI Measurement Techniques

The emission from the equipment can be propagated via conducted path (power cables, signal/control cables) and from radiated path (air). Hence the evolution of techniques for the measurement of EMI generated by electrical equipment has been influenced by propagation conditions. Investigation of interference problems has shown that the domestic and industrial mains wiring provides a propagation medium (conducted) where, transmission in the frequency range up to 10 MHz is accompanied by relatively little attenuation.

At higher frequencies the mains wiring becomes less efficient, as the propagation medium as the attenuation increases rapidly above about 30 MHz. The dominant propagation mode at these higher frequencies then becomes direct radiation from the device or circuit itself or from the wiring in the immediate vicinity of the source of disturbance. The methods of measurements of emissions thus divide at 30 MHz. At lower frequencies the technique is to determine the RF voltage at the mains terminals of the source of disturbance and at higher frequencies to measure the strength of the field radiated from the device and its associated wiring.

For ease of measurement and analysis, radiated emissions are assumed to predominate above 30 MHz and conducted emissions are assumed to predominate below 30 MHz. There is, of course, no magic changeover at 30 MHz. But typical cable lengths tend to resonate above 30 MHz, leading to anomalous conducted measurements, while measurements of radiated fields below 30 MHz will necessarily be made in the near-field, if it is closer to the source than a distance of $\frac{\lambda}{2\Pi}$. Near-field measurement results may not correlate with real situations [2].

3.1 CONDUCTED EMISSION MEASUREMENT TECHNIQUES

Various methods have been specified for conducted EMI voltage and current measurement with conditions defined by terminating lines in an artificial mains network for line impedance stabilization network (LISN) or by RF short circuits (feed through or bushing capacitor). Recent revisions of standards have tended to concentrate on RF current measurement. There is a distinct advantage of RF current measurements. Using this method, the disruption to the circuit under test is small and all interconnecting cables, signal and control leads can be treated in addition to primary power lines. RF current is measured with clamp-on ferrite-cored current transformer (Current Probe). It is vitally important that the conditions of measurement are specified in detail, particularly the length and disposition of all leads.

The layout for conducted EMI measurement technique is shown in fig. 2. Typical specification limits for conducted emission comparing MIL-STD limits with commercial limits is shown in fig. 3.

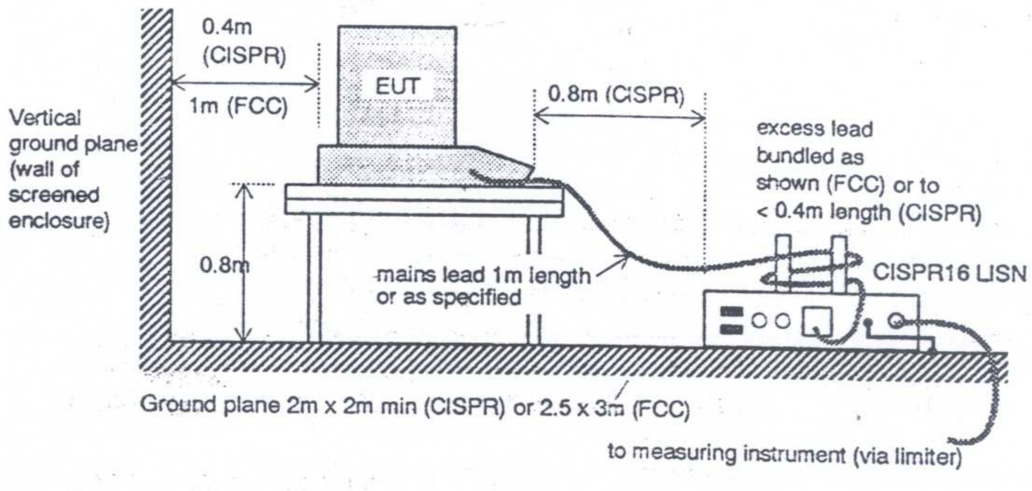

Fig. 2 Conducted emission measurement test layout & setup [2]

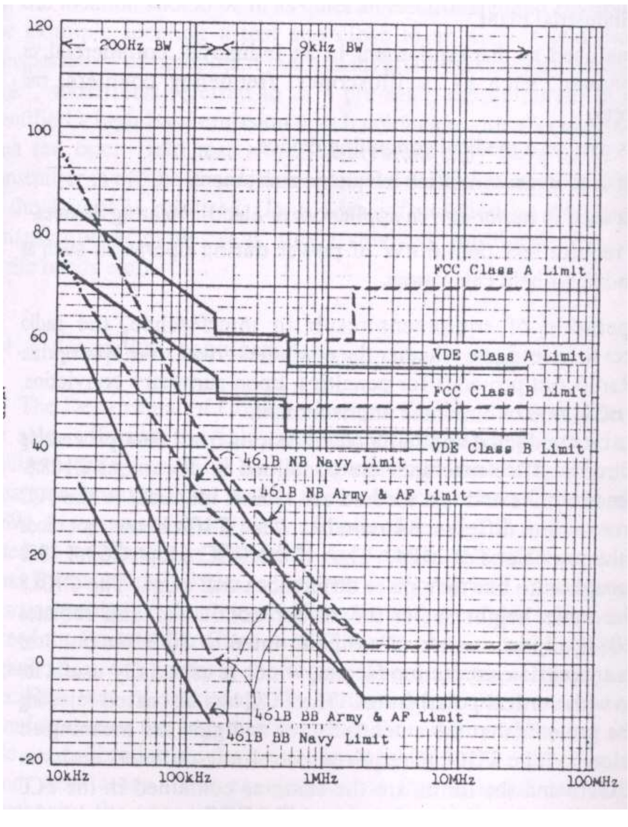

Fig. 3 Conducted emission specifications limits for various standards [3]

The emission measurement can be done with either LISN method or with CP method depending upon the EMC regulation being adopted. The test setup is simple and minimum in terms of the test equipment and accessories. The only vital requirement is for a ground plane of at least 2X2 meters, extending at least 0.5 meter beyond the boundary of the EUT (Equipment Under Test). It is convenient, but not essential to make the measurements in a screened enclosure, since this will minimize the amplitude of extraneous ambient signals. For conducted emission test, the principal requirement is the placement of the EUT with respect to the ground plane, the LISN or current probe and the position and layout of the mains cable and earth connections.

3.1.1 LISN BASED (VOLTAGE REFERENCED-RF VOLTAGE) MEASUREMENT

In the frequency range of 30 MHz, the conditions of measurement of conducted EMI voltage are controlled by supplying power to the EUT through the artificial mains network, which defines the impedance across which the voltage measurement is made. This network provides sufficient isolation to maintain the impedance characteristics throughout the frequency range and to reduce extraneous noise on the mains supplies which might cause errors in measurement. A circuit diagram of the LISN and it's impedance characteristics in Fig. 4.

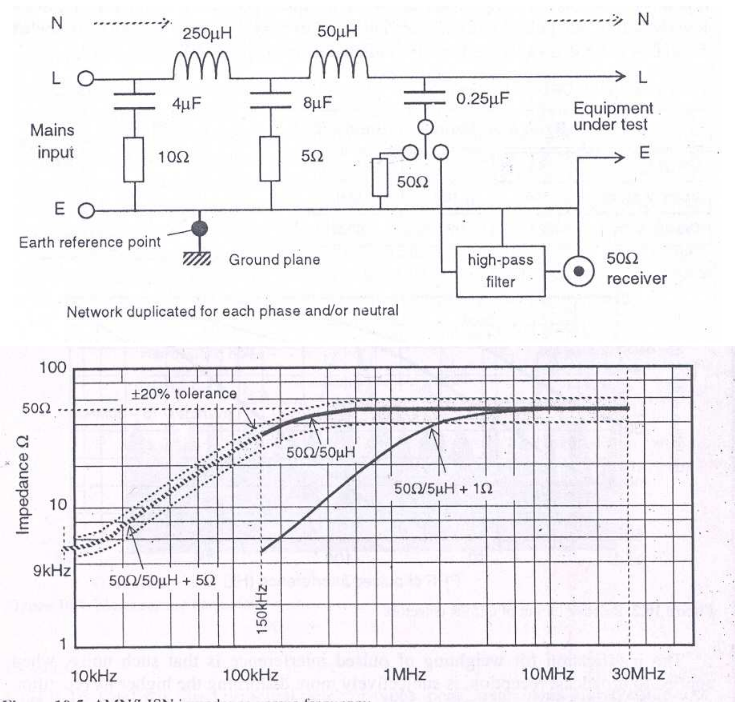

Fig. 4 LISN and it's characteristics [7, 12]

The parameters of the mains network are determined after analysis of many measurements of the RF impedance of mains supplies in household, industrial and other locations. Mean values were found to approximate to an equivalent circuit consisting of 50 Ω in parallel with 50 μH. Furthermore, reasonable agreement was found between similar measurements in several countries and so the network was adopted by CISPR and is now specified for RF voltage measurement in many national standards and legal regulations including BS 800 and CISPR Publication 16 [10]. The impedance is essentially defined by the inductance 50 μH and the 50 Ω resistive input impedance of the measuring receiver. Filtering and isolation are provided by high pass filter.

The basic test setup for the LISN based (voltage referenced) measurement is shown in fig. 5. This test method is applicable to the CISPR/FCC regulations. The power source impedance is modeled as 0.1 Ω. The power and return lines from the power source are connected to the EUT through LISN.

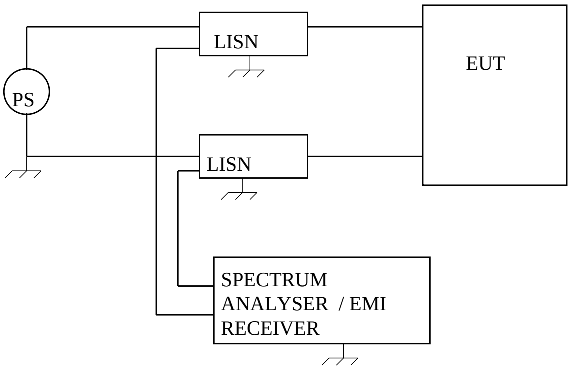

Fig. 5 LISN based conducted emission measurement [10]

The LISNs are grounded through their cases to the chassis ground or ground plane. The LISN provides a constant impedance from 10 kHz to 1 GHz.

3.1.2 CP BASED (CURRENT REFERENCED - RF CURRENT) MEASUREMENT

Although RF current measurements are not generally specified for control of emissions, there are many applications where such measurements have distinct advantages. The techniques of current measurement involve ferrite-cored current transformers, more commonly known as current probes, which can be clamped or clipped over conductors, mains leads, cable forms etc.

Thus direct connection to the cable under test is avoided and the disturbance to the circuit is minimal since the insertion impedance due to the probe is generally less than 0.5 Ω. The measurement is performed by joining the secondary winding to a measuring receiver or spectrum analyzer and the probe is calibrated by measurement of the transfer impedance as a function of frequency so that the voltage reading on the receiver is converted directly into RF current. Various probes are commercially available to cover the frequency range from 20 Hz to 1000 MHz, but are most extensively used in the range 10 kHz-100 MHz. The transfer impedance varies considerably with frequency but values range up to about 5 Ω so that RF currents of less than 0.2 μA can be measured with a microvolt sensitive receiver. The applications for current measurements are in the determination of propagation conditions in complex installations, particularly where disturbance to the circuit operation is not possible, assessment of the relative magnitude of symmetric and asymmetric current flow, which is of great assistance in the design of suppression circuits, and in general diagnostic techniques in solving problems of interaction between circuits [10].

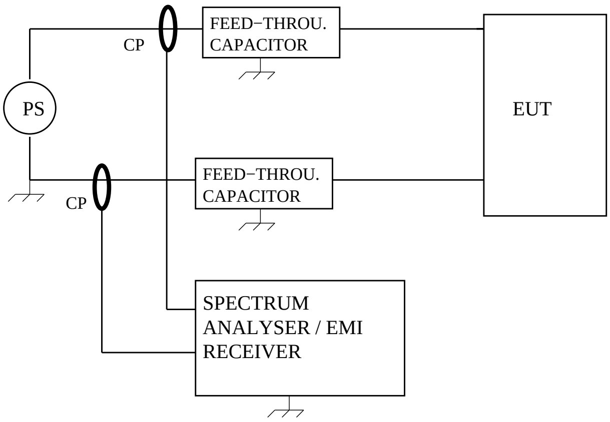

Fig. 6 Current probe based conducted emission measurement [10]

The basic test setup for the CP based (current referenced) measurement is shown in fig. 6. This test method is applicable for the military requirement. The test setup is much like that of LISN, but 10 μF feed-through type capacitors are connected between the power and return lines and ground instead of the LISN. The 10 μF feed-through capacitors are virtually short circuits to the ground for frequencies above 10 kHz. A suitable clamp-on ferrite-cored current transformer (Current Probe) is placed over the test leads or cables for measurement of RF current (conducted emission).

Comparison between LISN and CP method

The one problem with above two methods (LISN and CP) is that, a comparison between them is very difficult. The FCC, VDE and BS standards all use the LISN method but have different limit levels and slightly different test setup requirements. However one may compare MIL-STD 461 limits to FCC and VDE limits with a conversion factor to convert decibels above 1 μA. The rationale for the conversion is that, for 1 μA through the 50 Ω impedance of the LISN will create 50 μV across the LISN. After measurement, 34 dB {20 log (50)} can be added to the MIL-STD 461 limit across the whole frequency range. For high impedance EMI sources, this comparison is fairly accurate, but for low impedance sources the comparison is erroneous [10].

Although in the standards it is not clearly mentioned about the length of the cable of EUT, it has been a practice for EMC engineers to keep it minimum (1 meter). The suspicion that electrically long cables may play a role in the determination of CE levels grounds on the bandwidth of interest for CE assessment. During CE measurements it has been recorded that emissions at the LISN terminals may differ significantly (more than 10-15 dB) from those at EUT terminals, when a long power cable connects these two devices. Such differences are due to the distributed parameter nature of the power cable in the frequency range of interest and are influenced by the geometrical/electrical characteristics of the power cable cross section. This problem can be minimised by using a frequency-domain transmission-line model of the the emission test setup along with the modeling of long power cables. The emissions contributed due to extra length are then deducted from the emission-plot of the EUT with the extra length. From the experimental standpoint, the standards foresee that, during CE measurement, the EUT shall be configured, installed, arranged and operated in a manner consistent with actual application. The power cable of 1 meter is assumed and the flexible cables with larger lengths, the excess length shall be folded back and forth so to form a bundle at the centre of the cable [11].

3.2 RADIATED EMISSION MEASUREMENT TECHNIQUES

Measurements of the field strength radiated by equipment ranging from electrical generators to sensitive radio receivers, as levels down in 30 μV/m require precise definition of the practical arrangement, if repeatable results are to be achieved. The radiated emissions measurements require a measuring antenna (dipole) to convert the incident field strength to a voltage which can be measured by the EMI receiver or spectrum analyser. The limits for radiated emissions are expressed in dBμV/m and those few standards which require magnetic field below 30 MHz quote them in dBμA/m [12]. The basic principle of measuring radiated emission is shown in fig. 7 . The antenna factor AF and the cable attenuation A are added to the indicated voltage V to give the true field strength value.

$$\mathrm{E}\ (\mathrm{dB}\mu\mathrm{V/m}) = \mathrm{V}\ (\mathrm{dB}\mu\mathrm{V}) + \mathrm{AF}\ (\mathrm{dB/m}) + \mathrm{A}\ (\mathrm{dB}) \qquad \text{(eq. 3.2.a)}$$

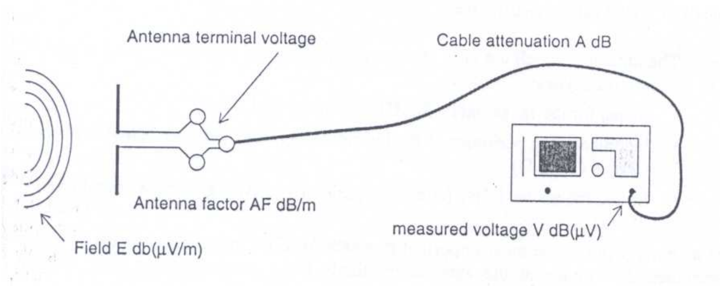

Fig. 7 Radiated emission measurement using dipole [12]

Radiated electric-field measurements are required to be made from 10 kHz to 18 GHz with antennas appropriate to the range, for example unbalanced rod with ground plane up to 30 MHz, biconical (30 - 200 MHz), log periodic up to 1 GHz and horn antennas at higher frequencies. All must be broad band. The fig. 8 shows some of the antennas used in the measurement of radiated emission. Each broad band antenna is calibrated and supplied with a table of its antenna factor versus frequency. It is apply for an incident field in the same plane of polarization as the antenna, and with the antenna terminals loaded with its specified impedance (usually 50 Ω) [12]. The fig. 9 shows typical antenna factor variation as a function of various frequencies.

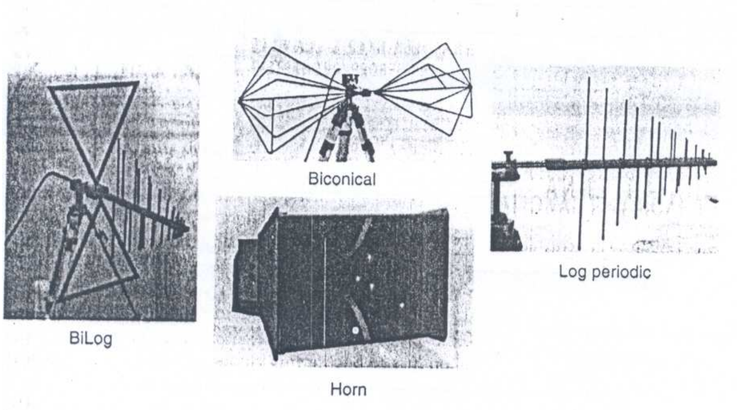

Fig. 8 Various types of EMI measurement antennas [12]

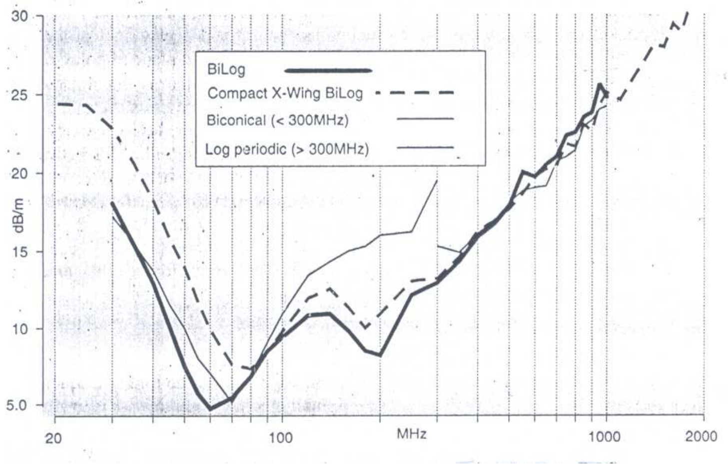

Fig. 9 Typical antenna factor versus frequency [12]

All radiated emission measurements much be performed inside screened enclosures to eliminate disturbance due to external noise and broadcast transmission but this requirement brings its own problems due to the internal reflection of signals, cavity resonant effects and the establishment of standing wave patterns. All contributes to the establishment of standing wave patterns, which are the causes of the uncertainty and errors. Ideally the screened enclosure should be made anechoic by the installation of sufficient resistive damping materials lining the walls, floor and ceiling so that equivalent free space conditions are obtained. There are disadvantages, the prime one being the enormous cost. In the defence standard the measuring arrangement is well defined with the same terminating networks, lead length and disposition specified and with the measuring antenna installed at a distance of 1 meter from the nearest face of the equipment under test [9]. In many test laboratories panels of carbon loaded plastic foam are disposed around the equipment under test so that reflections are reduced.

Open-field sites are subject to the vagaries of the climate and may be restricted in use by ambient levels of noise and broadcast signals. Test site requirements are given in general terms in standards such as MIL-STD, and CISPR 16, which deal with measuring techniques and instrumentation, and more precise details are given in the equipment standards (e.g. CISPR22) [7]. The test site is required to be reasonably flat and free from reflecting objects over an area defined by an ellipse having a major axis twice the separation distance d between source and measuring antenna. It is usual for the site to be equipped with a turntable, on which the equipment under test is mounted to enable, the direction of maximum radiation to be readily determined. In some specifications, the measuring antenna is required to be adjusted in height over a distance of 1 to 4 meters in order to achieve maximum interaction between the direct and the ground reflected wave [1]. The basic test setup for the radiated emission measurement is shown in fig. 10.

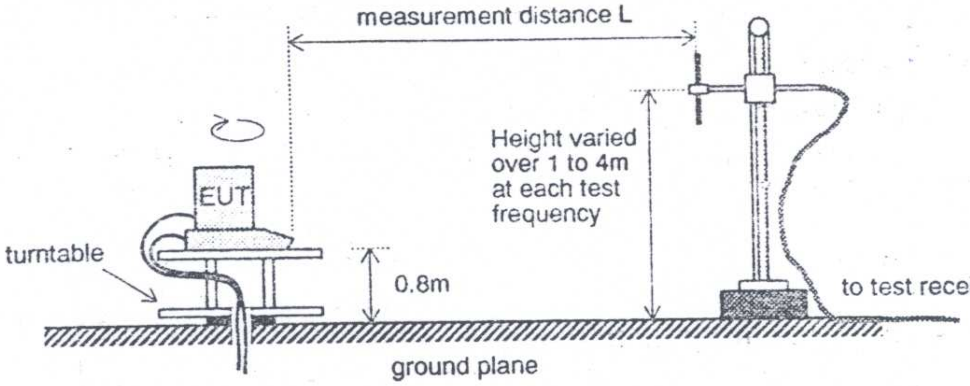

Fig. 10 Radiated emission measurement layout & setup [2]

This test method is applicable for the military requirement as well as other commercial EMC regulations. However, there is a substantial variation in distance between the EUT and receiving antenna and the test sites. In MIL-STD the distance is 1 meter in shielded enclosure, while in other standards the distance may vary from 1, 3, 10 and 30 meters depending on the type of equipment.

Fig. 11 shows typical specification limits of radiated emissions for MIL-STD and other EMC regulations. It is clear from the limits that MIL-STD is more stringent for EMC regulations.

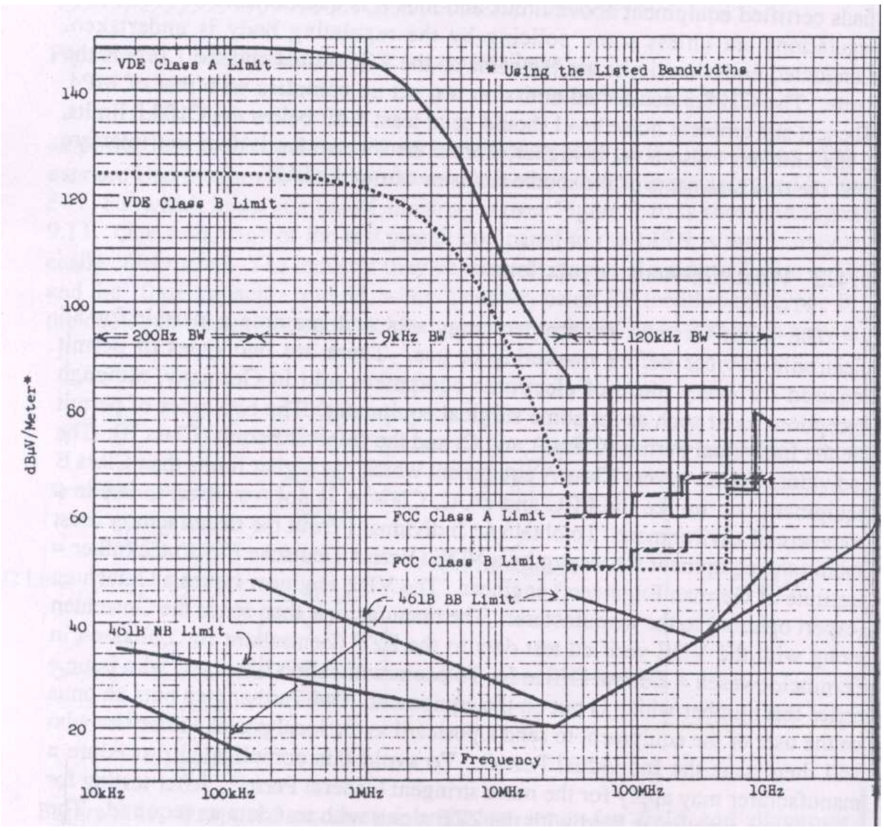

Fig. 11 Radiated emission specifications limits for various standards [3]

3.3 SUSCEPTIBILITY OR IMMUNITY (CONDUCTED AND RADIATED) MEASUREMENT TECHNIQUES

In EMI/EMC terminology, the words "susceptibility" and "immunity", are used interchangeably, depending on the context. The susceptibility, is the measure of EMI levels for which an equipment is malfunctioning. The immunity, is the general ability of the equipment to function satisfactorily and reliably in it intended environment. In this modern age the electromagnetic environment is becoming increasingly hostile due to the crowding of the frequency spectrum, proximity of operation of transmitters and increasing use of man-made materials in air-conditioned premises with low humidity environment. Again, the electronics is generally more vulnerable to disturbance, plastics enclosures provide little or no screening and solid-state circuits and devices are inherently more sensitive to transients, ESD etc.

Immunity level measurement is the most rapidly expanding aspect to EMC and, at the same time, it contains the most difficult requirements to implement. The need for assessments of immunity arose initially in respect of reliable operation of industrial process control instrumentation and it is in this area that certain methods were originally developed and described in international standards (MIL-STD 461B,C,D,E and IEC 61000-4-x) . The test and assessment requirements are applied now to equipment for legal metrology, e.g. petrol pumps and weighting machines, and to radio and television receivers. The difficulties with immunity assessments are in developing tests with realistic representation of practical installation, and in the selection of environment. Currently specified test procedure are electrostatic discharge (ESD), RF transmissions and mains disturbances such as short duration transients. As with all immunity / susceptibility testing, the criteria of acceptability is a matter of agreement between the user and the manufacturer. The equipment under test is subjected to disturbances at the required level and must perform correctly with in tolerances usually specified in the manufacturers literature. It is therefore necessary to select certain critical parameters on which the performance of EUT is accessed, during the immunity tests.

3.3.1 Electrostatic discharge Susceptibility Measurement

The measuring procedure described in IEC Publication IEC 61000-4-2 is intended to simulate the situation of an operator becoming electro statically charged due to movement across nylon carpet or some similar charging mechanism and then discharging into a sensitive circuit through conducting metal work. The test setup diagram for the ESD measurement is shown in Fig. 12.

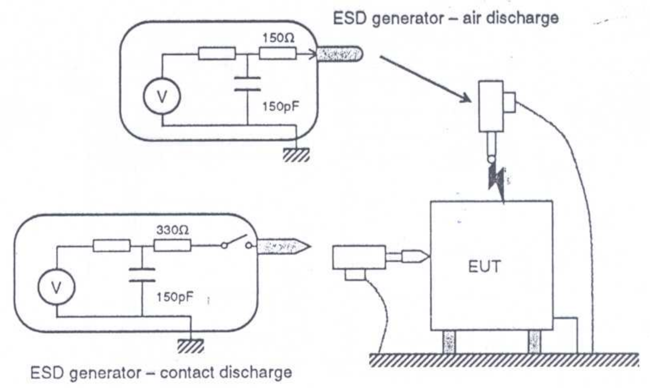

Fig. 12 ESD susceptibility measurement test setup [12]

The specifications recommend test levels between 2 and 15 kV, a current waveform defined by 0.7-1 ns rise time and 3.75 A/kV peak value. The guidance is given as to the selection of test level in terms of the relative humidity and the extent of use of man-made fibers in the intended installation [5].

3.3.2 RADIATED SUSCEPTIBILITY MEASUREMENT

To measure the susceptibility of the EUT, RF power is fed into a parallel plate transmission line which is terminated at the far end in its characteristic impedance. The EUT then subjected to the transverse (TEM) wave generated between the plates. An adjustment of the input power, enabling the appropriate value of field strength has to be maintained. Suitable monitoring of the field is necessary, particularly in the frequency range of 1 GHz. This method has its limitations, particularly in terms of the upper frequency limit, but it is currently the one, which has achieved the status of international agreement.

Tests at higher frequencies can be made by generating fields in screened enclosures at short distances from log periodic and other broadband antennas. Strictly, all such tests should be performed in screened enclosures to avoid the possibility of interference to other users of the spectrum. Recent investigations have led the development and specification in the defence standard MIL-STD-461E (CS114 and CS115) of current injection methods using ferrite cored current transformers with satisfactory performance up to 400 MHz. These methods are applicable to all cables (power, signal an control) and to cable forms in addition to single conductors; hence the term bulk current injection (BCI) has come into common use. The evolution of this test method is due to the difficulties existing in the aircraft and missiles EMC clearance, where large size of the system can not be covered with a single antenna.

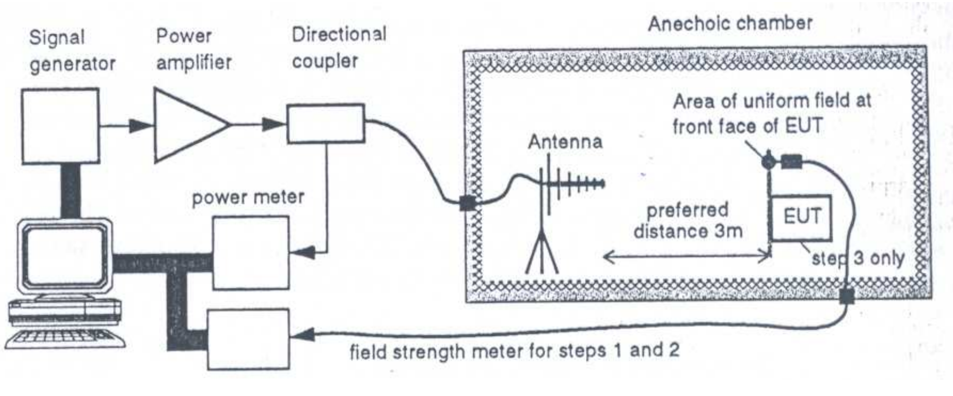

Fig. 13 Radiated susceptibility measurement layout & test setup [9, 12]

The general principle of the radiated susceptibility measurement technique is illustrated in Fig. 13, where the electric field is generated in the closed loop. Its full details are specified in MIL-STD-461E.

3.3.3 FAST TRANSIENTS SUSCEPTIBILITY MEASUREMENT

Immunity to fast, i.e. short duration, transients due to switching operations on mains supplies has been a subject of increasing importance since the introduction of semiconductors into domestic and industrial electronics. However, the development of suitable measuring procedures for assessment of immunity has only recently been brought to the stage of achieving international agreements. Assessments are made by installing equipment for test in a circuit enabling direct capacitive injection on the mains leads or in a jig/clamp such that injection is via distributed capacitance. The coupling capacitors in the circuit arrangement are 33 pF while the distributed capacitance in the clamp varies between 50 and 200 pF.

The characteristics of the fast transients to be applied are defined in details in the document IEC 61000-2-2. The repetition frequency of the transients with-in the 15 ms burst is 5 kHz for amplitudes up to 1 kV and 2.5 kHz for amplitudes of 2 kV and above. These characteristics must be verified prior to the tests by joining the fast transient generator to an oscilloscope having a bandwidth of at least 100 MHz through a 50 Ω attenuator. It is usual to apply such transients for a period of one minute, during which there is to be no damage or malfunction in the operation of the equipment under test [5].

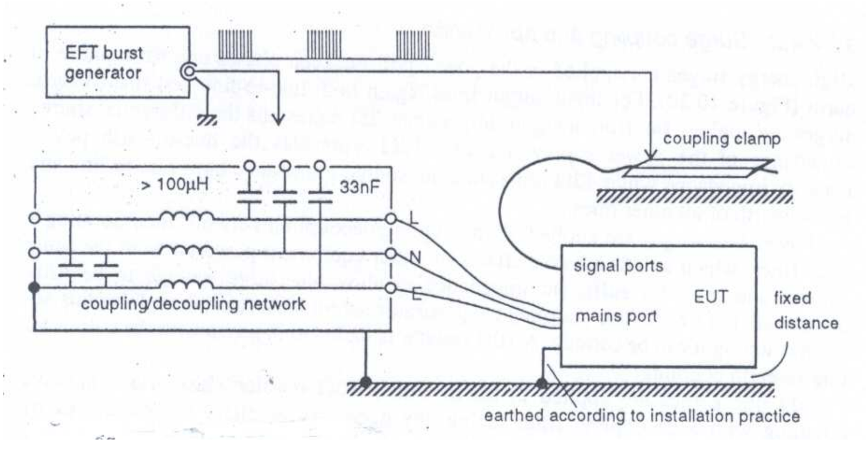

Fig. 14 EFT susceptibility (immunity) measurement layout and test setup [5, 12]

The test layout for the measurement of the susceptibility of the EUT to the electrical fast transients is shown in Fig. 14 and the details of the technique are specified in IEC standard, IEC 61000-4-2.

3.4 OTHER NOVEL EMI MEASUREMENT Techniques

Apart from the standards defined EMI measurement techniques and tests limits, which are also known as compliance testing, many attempts have been made to measure EMI in non-conventional manner. Although, these methods does not have compliance (acceptability) with any EMC regulations or standards, they play a significant role in determining component-level EMC. Here a review of such two techniques have been taken to encourage the utilization of these up-comping, but not so popular techniques.

3.4.1 MEASUREMENT OF RADIATED EMI FROM VLSI DEVICES

Most of the EMC regulations are for product level EMI measurements. That means EMI measurements are being done on the finished products for their compatibility. At compliance level, non-conformity of the product to the EMC regulations can cause a huge loss in terms of money and time. So it is very useful to measure EMI at component level also, because they are the building blocks of any equipment. For VLSI designer it has been a challenge to design VLSI component with low levels of EMI. Here a review of such measurement techniques for the EMI evaluation (radiated emission) of VLSI devices has been under taken.

At the heart of almost every EMI/EMC problem is the source of emissions. These emissions may be causing problems in the surrounding environment through direct radiated interference; they may be showing themselves indirectly through emissions emanating from the module harness; or they may show themselves by creating functional problems within the module circuitry itself. In all cases, the designer needs a method for identifying and then characterizing these emissions [13].

Here three methods are discussed for the EMI measurement. All are concerned primarily with emissions generated by VLSI devices such as microprocessors, ASICs and other large scale devices that use high speed clocks. Two of the methods to be described are essentially similar, but differ in the frequency range that they address. The third method is complementary to the first two in that, once having characterized the spectrum of concern, the designer can use this method to investigate the geometry of the emissions at the device package and die level [14].

The Fischer mini-TEM cell has been available for some time now, and has seen use both by end users of VLSI devices, and by manufacturers of the devices. The frequency range is 10 kHz to 1.5 GHz. The basic idea is that the device to be measured is attached to a multi-layer PC board with the device on the side interior to the cell, and all supporting circuitry on the flip side, outside the cell. Because the device can now be considered a part of the cell structure, the device itself does not, to any appreciable degree, perturb the field structure within the cell. One then obtains quite good spectral measurements that can be correlated with the open area test sites and anechoic enclosure measurements.

The Lindgren OmniCell is a GTEM structure constructed to perform a measurement similar to the Fischer cell. The Lindgren cell extends the range of the measurement to 7-8 GHz, for correlatible measurements, and to 16 GHz for comparative measurements.

The "DaimlerChrysler Surface Scan", is a technique for scanning a VLSI device at the package and the die level. Both the magnetic and the electric near fields can be measured. For magnetic measurements, a simple loop fashioned from rigid coax is used and oriented in two orthogonal directions, the resulting data are then combined to arrive at the total magnetic near-field. The electric probe is a truncated rigid coax. Both probes are placed to within 100-200 μm of the surface of the device to be measured. 10,000 scan points are typically accumulated at each frequency of interest. This results in scan steps of approximately 70-100 μm. Structural resolution has been determined to be on the order of 100-200 μm. While it cannot resolve individual transistors, it does offer a means for scanning and characterizing functional areas within the device, such as PLL, CPU, memory, A/D, etc. Additionally, the Vdd/Vss topology and related emissions can be measured [14]. Fig. 15, shows a photographic view of all three measurement devices i.e a) Fischer mini-TEM cell b) Lindgren OmniCell c) DaimlerChrysler Surface Scan.

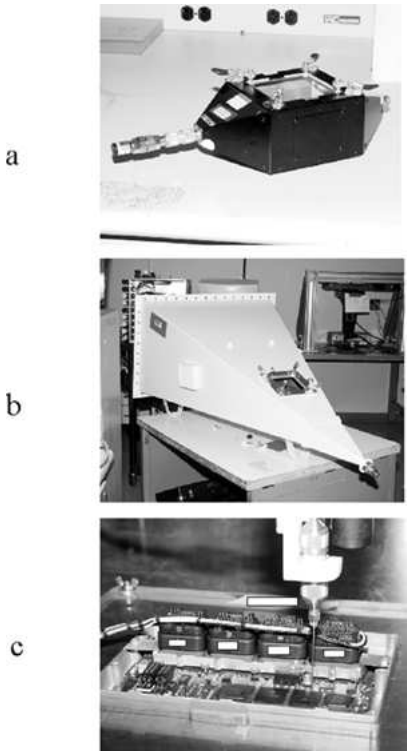

Fig. 15 Measurement devices for radiated emission [14]

Fig. 16 shows a set of measurements taken in both the mini-TEM and the OmniCell GTEM. The measurements were made using an electrically small electric monopole, and an electrically small magnetic loop. Observation of the resulting plots shows that both devices have a linear response through the range of measurement. However, the GTEM is clearly more monotonic than is the mini-TEM above 1200 MHz. Equally obvious is that either device can be used in the range 100-1200 MHz without any fear of one device giving a set of data different from the other device.

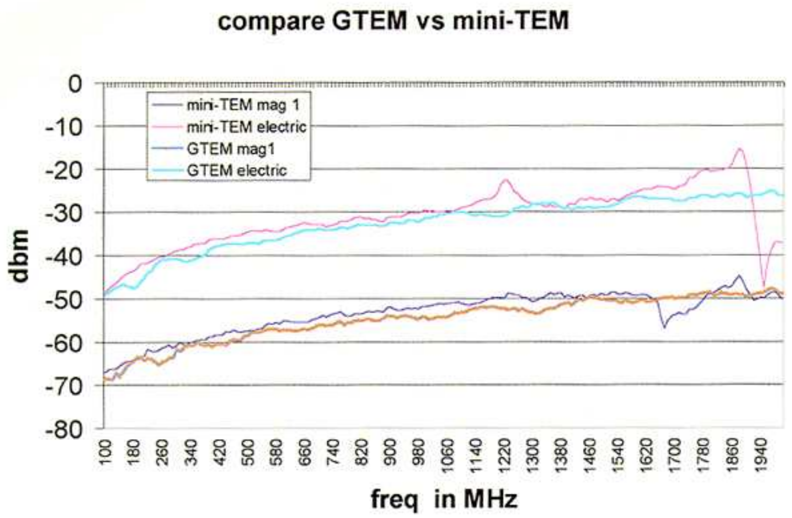

Fig. 16 Measurement results from mini-TEM & GTEM cell [14]

Figure 17 is a comparison of measurements made in the GTEM, and in the mini-TEM, of a 16 bit micro controller running at 16 MHz, over the range 500-1000 MHz. Because of the density of spectral components it is difficult to do a point by point comparison of the results. Figure 5 is a plot of the same data sets, but the spectrum have been smoothed using a 16 point moving average.

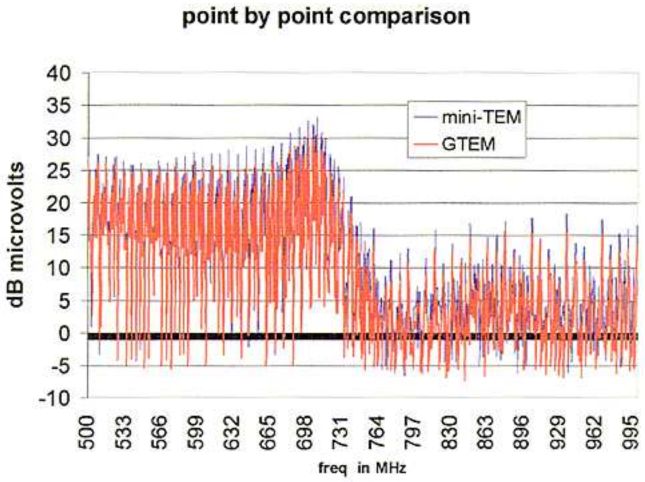

Fig. 17 Comparison of measurement results for 16-bit micro controller running at 16 MHz [14]

A special kind of the image processing can be done with the data array generated with surface scan. Here, it has been taken the discrete array of the measured magnetic field at 64 MHz, imported it to Mathematica, a commercial software package, and generated a continuous function of two variables. This function then differentiated to arrive at a secondary function related to the magnetic density over the VLSI device. Measurement results are shown in the figs. 18 and 19.

Figure 18, shows surface scan images of a 16-bit micro controller, operating at 16 MHz, scanned over the entire BGA package at 32 MHz, magnetic and electric near field.

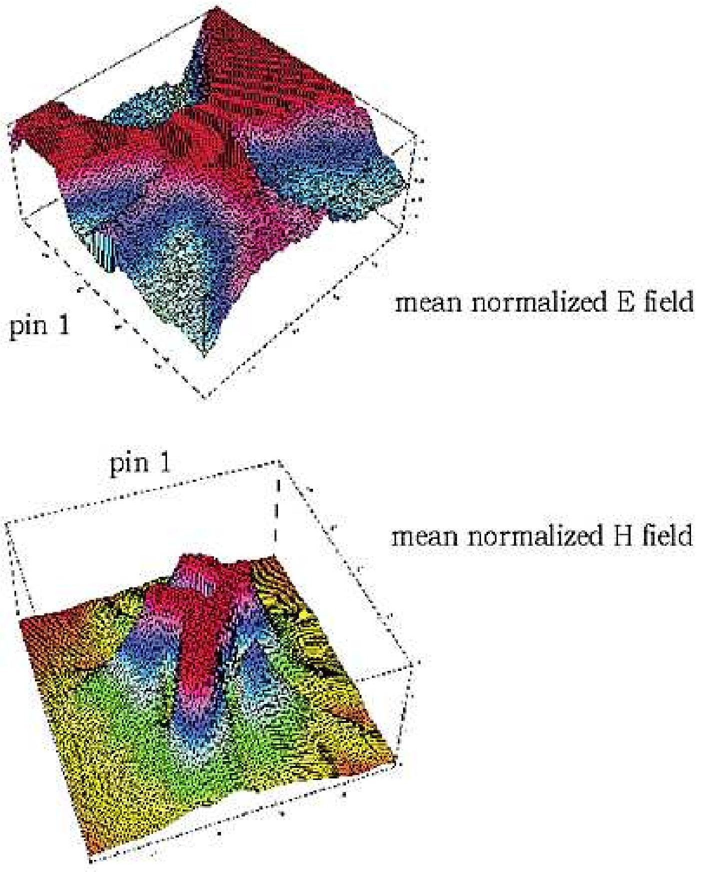

Fig. 18 Surface scan images of 16-bit micro controller at 32 MHz, E & H near field [14]

Fig. 19 shows surface scan images of a 16 bit micro controller operating at 16 MHz, scanned over the entire BGA package at 80 MHz, magnetic and electric near field.

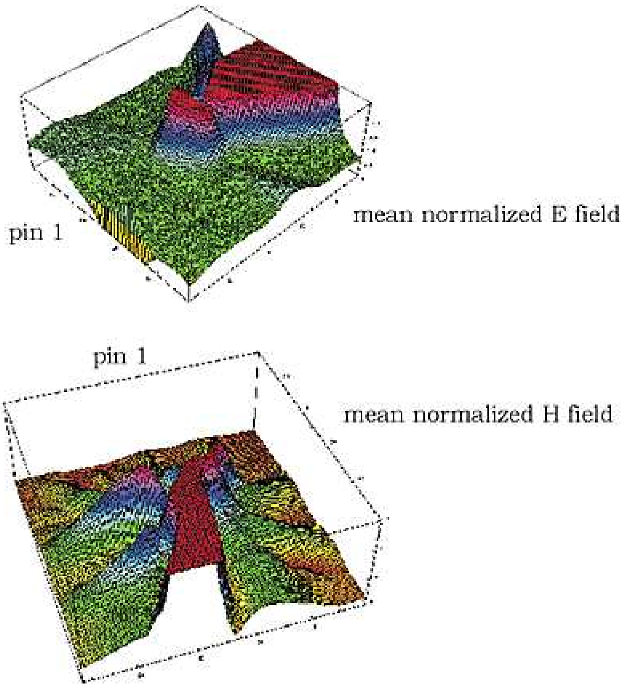

Fig. 19 Surface scan images of 16-bit micro controller at 80 MHz, E & H near field [14]

These images are comprised of 10,000 scan points taken over the surface of the entire BGA package, 17 x 27 mm, with the probe at a distance of 150 μm. The peaks have been truncated to better show some of the underlying detail.

Using these methods, further detail within the package, and deep within the die, can be seen. For instance, certain Vdd and Vss pin pairs can be seen to be more pronounced than others. Using this technique on a different device, and working with the manufacturer, it is possible to reduce the module level emissions by 8-10 dB by rearranging the functional floor plan and modifying the power and ground feed to the digital core of the device [14].

By working at the VLSI device level to reduce system and module level EMI, the designer can have a large economic impact on the EMC of a product. By characterizing and mapping the emissions from the dominant source in a module, the EMC engineer may be able to identify and thereby mitigate EMI at the package and die level. By reducing the EMI at the source, the cost and the time to achieve the EMC at PCB level or system can be minimised, thereby reducing the manufacturing cost and design-to-market time [14].

3.4.2 NUMERICAL MODELING OF EMI MEASUREMENT

The numerically modeled EMI can give a platform for the non-destructive testing of the various critical components used in aerospace, missiles and spacecrafts. Thus reliability of those components is assured. The analytical approach for numerical modeling is characterized by two major aspects. First the solution is general and exact. A general solution is obtained, normally in the form of a mathematical relation which then can be used for analysis, studies and calibration. Second, derivation of the model involves rather standard mathematical relations of different relevant electromagnetic equations.

The discharge current and the transient fields of an electrostatic discharge (ESD) in the contact mode can be numerically simulated using finite-difference time domain (FDTD) method. The simulated data, then compared to measured data (using multi decade broadband field and current sensors) for calibration. The simulation is very useful because the ESD test is a destructive test.

Here one example of such modeling of the EMI susceptibility test is taken here. For numerical modeling, the ESD susceptibility measurement technique has been taken. In this technique, the immunity of the EUT for ESD is tested using ESD generators. Most of the generators are built to meet the specifications spelled out in IEC 61000-4-2. ESD can disturb equipment by it's current and associated electric and magnetic fields. The level is a 0.7-1 ns rise time and 3.75 - 5 kV with 50-100 A for a contact mode discharge [5].

1) Numerical Approach: The FDTD method is used to predict the EMI in contact mode from a ESD generator. A commercial FDTD software package can be used [16]. The calculation and memory size set a lower practical limit on the amount of detail that can be modeled. The main advantage of this method is the ability to predict the discharge current and the related fields just based on the geometry and charging voltage. The FDTD model includes the physical geometry of the generator, the relay, pulse forming filter, ground strap and lumped elements. For fidelity, the cell size varies from 2 mm within the generator to 10 mm at the boundary, the typical domain size being 120X120X55 cm. Larger and smaller domains have been used for investigating the convergence of the result [15]. Fig. 20 shows the the model with details.

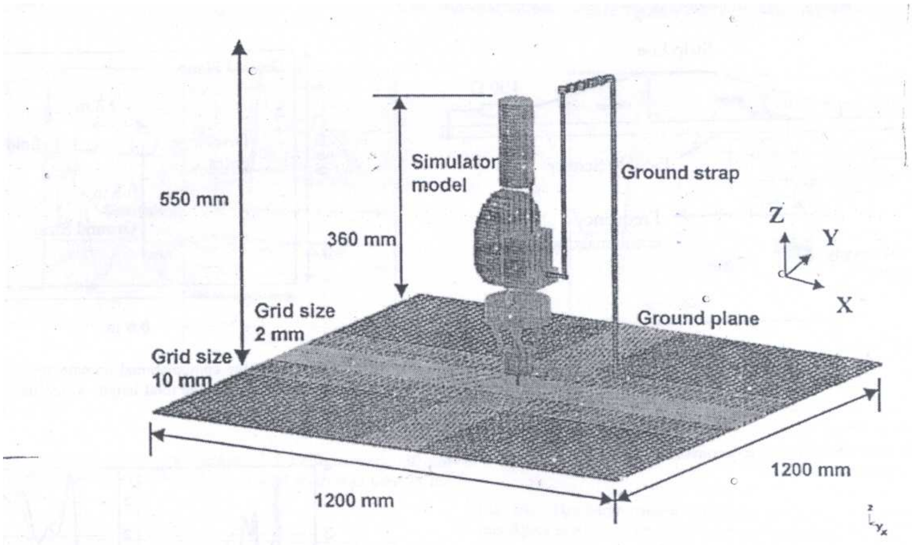

Fig. 20 A numerical model of the ESD generator [15]

The ability to handle time-dependent material is introduced in the FDTD code. The code is modified such that the material parameters acts a function of time. In this way the physical process of charging and discharging can be modeled accurately. The process, in general, is as follows.

1. The material properties and their time history are given by the user before program start.
2. In every time step the program checks the time histories to determine if the material properties need to be changed.
3. If so the present E and H fields are stored, the material details are updated and the previous E and H fields are applied to the modified geometry as initial start values.
4. The fields are updated using FDTD update equations then step 2 to 4 are repeated.

Using the code, the structure is charged by a 1 ns full width-at-half maximum (FWHM) Gaussian current pulse that is introduced by a line source connected to the 110 pF capacitor. Then the charged ESD generator is discharged in contact mode on the ground plane or a component. To accelerate the stabilization of the electrostatic field the conductivity of the metallic structure is varied accordingly. Fidelity of data, needs between 4000-8000 time steps until the field is sufficiently stabilized. Depending on the domain size and the boundary conditions, calculation times vary between 15 min to

8 hours on a 2.2 GHz PC. For this simulation there are 8 million cells in the largest calculations. [15]

2) Measurement setup: Field and current sensors were mounted on the wall of a 3x3x4 m shielded room. The physical generator is discharged on the outside of the room while the instrumentation is within the room This prevents the coupling into the instrumentation and their cables. The measurement setup is shown in fig. 21.

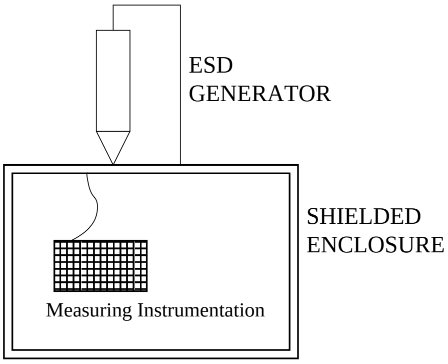

Fig. 21 ESD measurement test setup[15]

The results of actual measurement, numerical modeling simulation and reference mathematical calculation are shown in fig. 22.

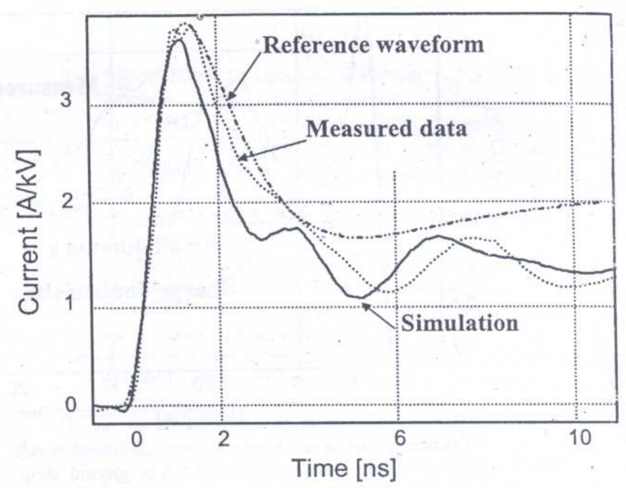

Fig. 22 Comparative results of measurement, simulation and reference measurements [15]

The simulation result is low-pass filtered using a second order 1.5 GHz filter to yield a bandwidth similar to the actual measurement. The result of the simulation is compared with the measured data in Table 4.

Table 4 Comparison data of simulation and actual measurement [15]

Parameters	Measured Data	Simulated Data
Rise Time	0.8 ns	0.8 ns
1st peak current	3.74 A/kV	3.77 A/kV
2nd peak time	19.8 ns	18.5 ns
2nd peak current	2.51 A/kV	2.55 A/kV

Similar others numerically modeled EMI can also be simulated for a number of EMI tests requirements, particularly for susceptibility measurements of critical components. Thus numerical modeling can convert a destructive test into a non-destructive test.

3.5 EMI MEASUREMENT TECHNIQUES FOR ASSESSMENTS

Achievement of electromagnetic compatibility may be started in simple steps as,

1) Reduction of interactions between systems,
2) Knowledge of the EM environment in which equipment is to be installed
3) Installation of adequate protective measures to ensure satisfactory operation and to minimize degradation of that environment.

Thus, additional measurements to determine EM environmental levels and the assessment of the performance of suppression components, filters and EM screening can help to achieve EMC in a cost effective manner. Here, a review of such measurement techniques has been presented.

3.5.1 SUPPRESSION COMPONENTS AND FILTERS

Determination of the performance of suppression components (e.g. Elastomer, Honey-comb vents, conductive gaskets etc.) and filters is of great importance in ensuring that their installations will produce the required reduction in noise or unwanted signals. Over suppression will be uneconomic and may be technically undesirable and it is difficult to reproduce practical installation conditions. The standard methods for measurement of filter and component performance is therefore, to determine the insertion loss in a circuit of defined impedance.

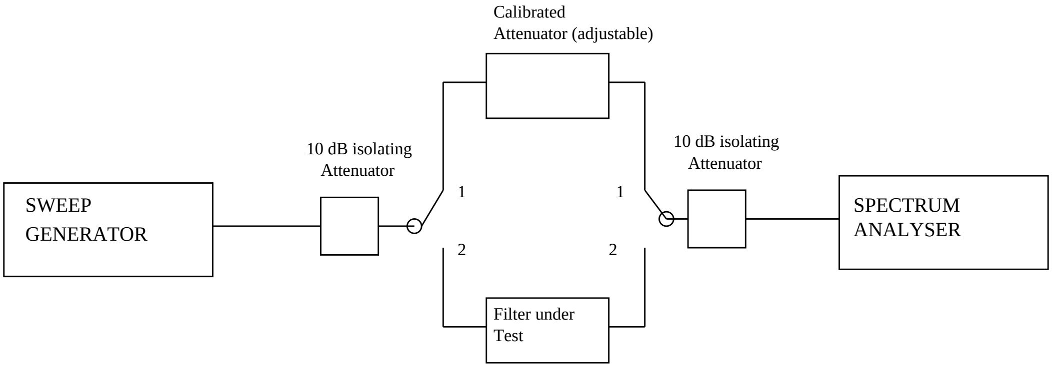

Fig. 23 Measurement of filter performance [1]

The details of test circuits and procedures are given in CISPR 17 and a measurement setup for the same is shown in fig. 23. The methods described the frequency range from 10kHz to 100MHz and may be extended to 1 GHz with some limitations.

3.5.2 Electromagnetic screening

In the same way as for filters, knowledge of the performance capability of screening enclosures and screening material is of great importance in assessing the levels of the protection that can be provided against EMI. The generalized technique of screening assessment is to measure the RF field between suitable antennas, one is transmitting and other is receiving. First a open field is established and then attenuated fields are measured with one antenna located in the enclosure (screen) under test. The ratio of the results provides a measure of the screening attenuation and the tests may be performed over a very wide frequency range from 10 kHz to 10 GHz. The method is described in the MIL-STD-285 and ANSI. Similar techniques are applied to the measurement of the screening attenuation offered by materials such as conducting coating, mesh and foil, provided that panel of such materials can be made available. These panels are then used to replace one wall in a copper or aluminum enclosure and the measuring technique is applied in the same way.

3.5.3 Site Surveys

The performance of immunity test to assess whether, an item of equipment will be capable of reliable operation in a particular environment is very much dependent on information on the levels of field strength, mains disturbances etc. which are likely to occur. Such information may be obtained, by measurement of the fields strength from transmitters whose locations is known. Surveys of the field strength of transmissions are often required in order to determine the suitability of a site for computer installation. Hazards arising from RF power induced in structures of oil and gas installation and in the wiring systems of Electro Explosive Devices (EED) can be prevented, if prior survey report is available. These types of measurements are made using measuring receivers or spectrum analysers together with antennas, preferably broadband, from 10 kHz to 10 GHz.

3.5.4 Diagnostic techniques

It is popularly known as pre-compliance testing. In some respects, the major objectives in any EMC investigation are to remove the unwanted interaction between source an receiver. Thus, if the unwanted interaction can be removed by suppression and segregation, then the EMI problem may be solve without the need for measurement. Diagnostic techniques aims on the same objective. For the measurement, a small loop probe (sniffer probe) can be used to pickup the electric field component which also adds the directional properties to the measurement. Such a loop is joined to a sensitive receiver or spectrum analyzer and moved around the circuit or system to determine the area of maximum response. Also, the same loop can be energized from a signal generator or from a wide band noise source and again used to identify areas of maximum sensitivity.

4. Conclusions

After literature study and review, it is found that various types of EMI measurement techniques are available and defined in the standards. The choice of selection of a technique is depend on the individual requirements and/or EMC compliance requirements and hence a careful choice is obvious. Improper measurement techniques and the non-conformity of the test setup, can lead a measurement into domain of large errors.

In this report, it has been brought out that the measurement results obtained from one technique may not confirm with the results of another technique for the same parameter measurement, unless a correction factor is applied for the correlation. Problems in carrying out a measurement can easily be solved with the evolution of new techniques, as mentioned in the report. The measurement techniques for the of assessment of EMI suppression components have a significant role in achieving EMC. However, there are gray areas, like error-free measurement of common-mode and differential mode conduced emission separately, and there is a scope for the development of low cost, innovative measurement techniques for the same.

From the report following precautions can be summarised for low error and reproducible measurements,

1) Careful study of the relevant standard for the applicable measurement is necessary. It contains detailed information regarding instrumentation, measurement layouts, test setups, procedures and specification limits.

2) Measurement results can deviate from the expected results, if layout and test setup are not followed as per the standards. Hence, a careful study and understanding of the measurement technique along with test setup is necessary.

3) Regular checking and calibration of test accessories like cables, connectors, antennas and instruments are necessary. They can introduce errors, if regular check is ignored.

As a successful designer of electronic systems, one has to give due importance and considerations to the electromagnetic compatibility (EMC). EMC can be achieved in a cost and time effective manner by simplified and innovative EMI measurement techniques.

Appendix-1 List of Abbreviations and Acronyms

1. **EM** Electromagnetic
2. **EMI** Electromagnetic Interference
3. **EMC** Electromagnetic Compatibility
4. **LISN** Line Impedance Stabilisation Network
5. **CP** Current probe
6. **ESD** Electrostatic Discharge
7. **EFT** Electrical Fast Transients
8. **TEM** Transverse EM
9. **GTEM** Giga hertz
10. **CE** Conducted Emission
11. **RE** Radiated Emission
12. **CS** Conducted Susceptibility
13. **RS** Radiated Susceptibility
14. **RF** Radio Frequency
15. **IEC** International Electro-technical Committee
16. **CISPR** International Special Committee on Radio Interference
17. **CENELEC** The European Organisaion for Electro-technical Standardisaion
18. **ANSI** American National Standards Institute
19. **VDE** Verband Deutscher Elektrotechniker (German Standard)
20. **MIL-STD** Military Standards

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