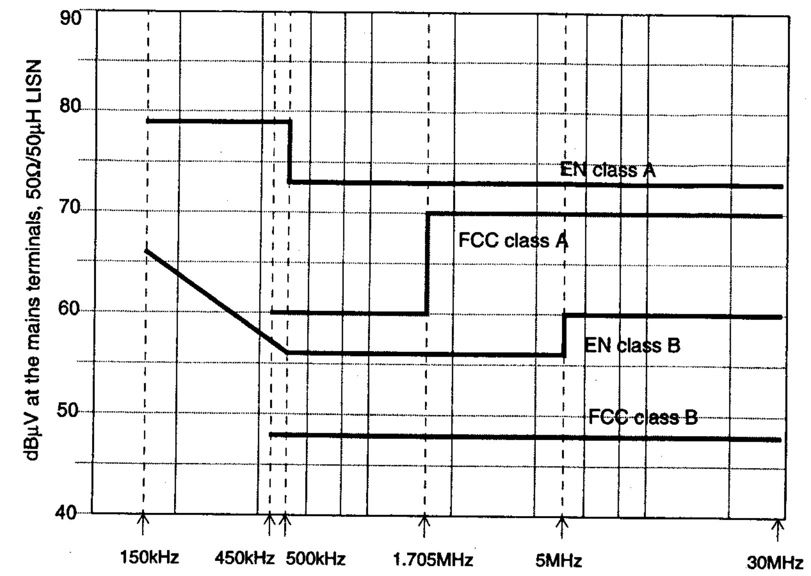
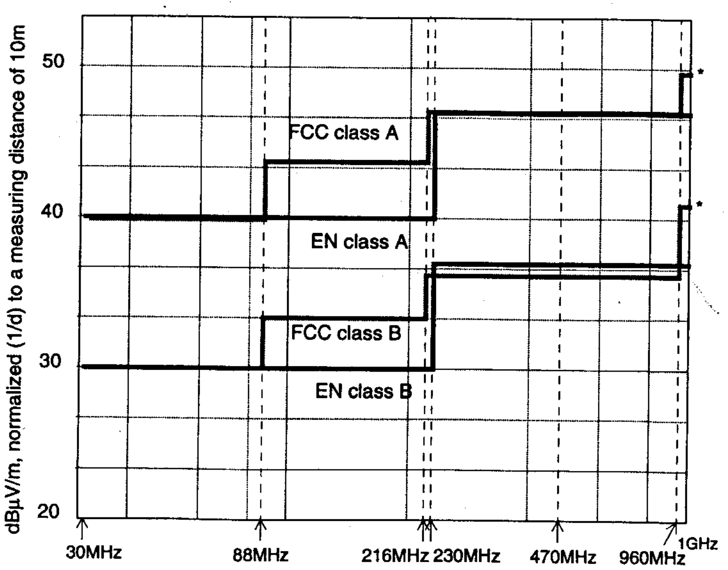


Figure 2.4 Conducted emission limits



*: see table 2.4

Figure 2.5 Radiated emission limits

Chapter 3

Emissions measurements

One of the aspects of electromagnetic compatibility that is most difficult to grasp is the raft of techniques that are involved in making measurements. EMC phenomena extend in frequency to well beyond 1GHz and this makes conventional and well-known techniques, established for low frequency and digital work, quite irrelevant. Development and test engineers must appreciate the basics of high frequency measurements in order to perform the EMC testing that will be demanded of them. This chapter and the next will serve as an introduction to the equipment, the test methods and some of the causes of error and uncertainty that attend EMC testing.

3.1 RF emissions

For ease of measurement and analysis, radiated emissions are assumed to predominate above 30MHz and conducted emissions are assumed to predominate below 30MHz. There is of course no magic changeover at 30MHz. But typical cable lengths tend to resonate above 30MHz, leading to anomalous conducted measurements, while measurements of radiated fields below 30MHz will of necessity be made in the near field if closer to the source than $\lambda/2\pi$ (see section 5.1.4.2), which gives results that do not necessarily correlate with real situations. In practice, investigations of interference problems have found that reduction of the noise voltages developed at the mains terminals has been successful in alleviating radio interference in the long, medium and short wave bands [80]. At higher frequencies, mains wiring becomes less efficient as a propagation medium and the dominant propagation mode becomes radiation from the equipment or wiring in its immediate vicinity.

Emissions testing requires that the equipment under test (EUT) is set up within a controlled electromagnetic environment under its normal operating conditions. If the object is to test the EUT alone, rather than as part of a system, its associated equipment (if any) must be separately screened from the measurement. Any ambient signals should be well below the levels to which the equipment will be tested.

The operating configuration is normally specified within emissions standards to be that which maximizes emissions. This is not always easy to predict and you may have to perform some preliminary tests while varying the configuration. Also, one configuration may generate high emissions in one part of the spectrum and another configuration may generate a different set of high emissions. It is the manufacturer's responsibility to specify the operating conditions that will be tested.

3.1.1 Measurement instrumentation

3.1.1.1 Measuring receiver

Conformance test measurements are normally taken with a measuring receiver, which is optimized for the purpose of taking EMC measurements. Typical costs for a complete receiver system to cover the range 10kHz to 1GHz can be anywhere between £15,000–£60,000.

Early measuring receivers were manually tuned and the operator had to take readings from the meter display at each frequency that was near to the limit line. This was a lengthy procedure and prone to error. The current generation of receivers are fully automated and can be software controlled via an IEEE-488 standard bus; this allows a PC-resident program to take measurements with the correct parameters over the full frequency range of the test, in the minimum time consistent with gap-free coverage. Results are stored in the PC's memory and can be processed or plotted at will.

The distinguishing features of a measuring receiver compared to a spectrum analyser are:

- lack of a wide spectrum display for instantaneous diagnostics – the receiver output is provided at a spot frequency;
- very much better sensitivity, allowing signals to be discriminated from the noise at levels much lower than the emission limits;
- robustness of the input circuits, and resistance to overloading;
- intended specifically for measuring to CISPR standards, with bandwidths, detectors and signal circuit dynamic range tailored for this purpose;
- frequency and amplitude accuracy better than the cheaper spectrum analysers;
- two units may be required, one covering up to 30MHz and the other covering 30–1000MHz.

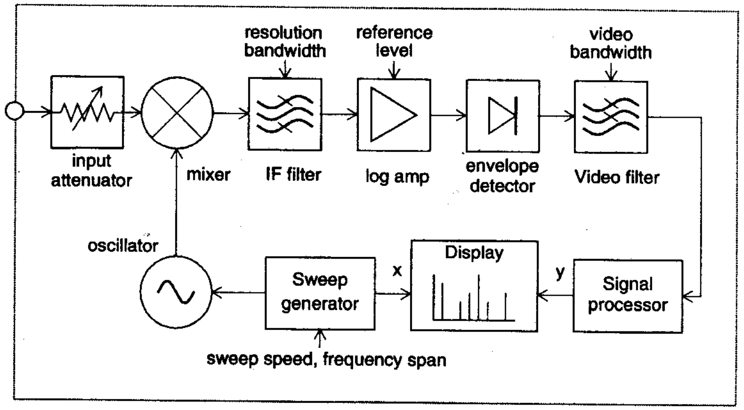
3.1.1.2 *Spectrum analyser*

A fairly basic spectrum analyser is considerably cheaper than a measuring receiver (typically £10–15,000) and is widely used for "quick-look" testing and diagnostics. The instantaneous spectrum display is extremely valuable for confirming the frequencies and nature of offending emissions, as is the ability to narrow-in on a small part of the spectrum. When combined with a tracking generator, a spectrum analyser is useful for checking the HF response of circuit networks.

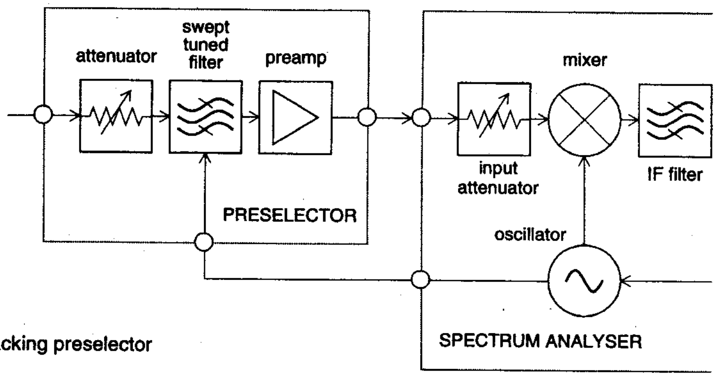
Basic spectrum analysers are not an alternative to a measuring receiver in a full compliance set-up because of their limited sensitivity and dynamic range, and susceptibility to overload. Figure 3.1(a) shows the block diagram of a typical spectrum analyser. The input signal is fed straight into a mixer which covers the entire frequency range of the analyser with no advance selectivity or preamplification. The consequences of this are threefold: firstly, the noise figure is not very good, so that when the attenuation due to the transducer and cable is taken into account, the sensitivity is hardly enough to discriminate signals from noise at the lower emission limits (see section 3.1.2.1 later). Secondly, the mixer diode is a very fragile component and is easily damaged by momentary transient signals or continuous overloads at the input. If you take no precautions to protect the input, you will find your repair bills escalating quickly. Thirdly, the energy contained in broadband signals can overload the mixer and drive it into non-linearity even though the energy within the detector bandwidth is within the instrument's apparent dynamic range.

Preselector

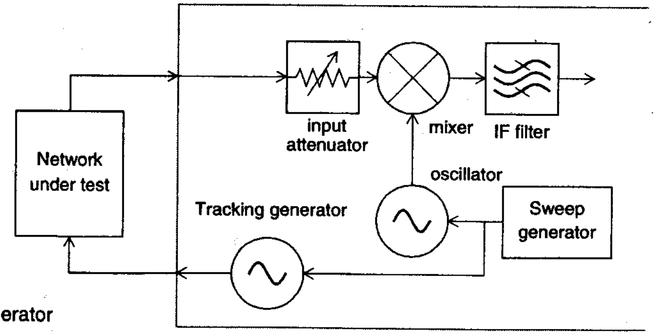
You can find instruments which offer a performance equivalent to that of a measuring



a) spectrum analyser



b) tracking preselector



c) tracking generator

Figure 3.1 Block diagram of spectrum analyser receiver, but the price then becomes roughly equivalent as well. A more satisfactory compromise for most companies is to enhance the spectrum analyser's front-end performance with a tracking preselector. The preselector (Figure 3.1(b)) is a separate unit which contains input protection, preamplification and a swept tuned filter which is locked to the spectrum analyser's local oscillator. The preamplifier improves the system noise performance to that of a test receiver. Equally importantly, the input protection allows the instrument to be used safely in the presence of gross overloads, and the filter reduces the energy content of broadband signals that the mixer sees, which improves the effective dynamic range.

The negative side of a preselector is that it can cost virtually as much as the spectrum analyser itself, doubling the cost of the system. There are manual preselectors available, but these are clumsy to use. But you can treat it as an upgrade. The analyser can be used on its own for diagnostics testing, and you can add a preselector when the time comes to make compliance measurements. Like the measuring receiver, modern spectrum analysers and preselectors can be software controlled via an IEEE-488 bus, and provided the system hardware is adequate you can perform the compliance testing in exactly the same way (using a PC for the data processing).

Tracking generator

Including a tracking generator with the spectrum analyser greatly expands its measuring capability without greatly expanding its price. With it, you can make many frequency-sensitive measurements which are a necessary feature of a full EMC test facility.

The tracking generator (Figure 3.1(c)) is a signal generator whose output frequency is locked to the analyser's measurement frequency and is swept at the same rate. The output amplitude of the generator is maintained constant within very close limits, typically less than ±1dB over 100kHz to 1GHz. If it provides the input to a network whose output is connected to the analyser's input, the frequency–amplitude response of the network is instantly seen on the analyser. The dynamic range is theoretically equal to that of the analyser (up to 120dB) but in practice is limited by stray coupling which cause feedthrough in the test jig.

You can use the tracking generator/spectrum analyser combination for several tests related to EMC measurements:

- characterize the loss of RF cables. Cable attenuation versus frequency must be accounted for in an overall emissions measurement
- perform open site attenuation calibration (section 3.1.3.1). The site loss between two calibrated antennas versus frequency is an essential parameter for open area test sites
- characterize components, filters, attenuators and amplifiers. This is an essential tool for effective EMC remedies
- make tests of shielding effectiveness of cabinets or enclosures
- determine structural and circuit resonances

3.1.1.3 Bandwidth

The actual value of an interference signal that is measured at a given frequency depends on the bandwidth of the receiver and its detector response. These parameters are rigorously defined in a separate standard that is referenced by all the commercial emissions standards that are based on the work of CISPR, notably EN 55011, 55013, 55014 and 55022. This standard is CISPR publication 16-1 [152].

CISPR 16-1 splits the measurement range of 9kHz to 1000MHz into four bands, and defines a measurement bandwidth for quasi-peak detection which is constant over each of these bands (Table 3.1). Sources of emissions can be classified into *narrowband*, usually due to oscillator and signal harmonics, and *broadband*, due to discontinuous switching operations, commutator motors and digital data transfer. The actual distinction between narrowband and broadband is based on the bandwidth occupied by the signal compared with the bandwidth of the measuring instrument. A broadband signal is one whose occupied bandwidth exceeds that of the measuring instrument. Thus a signal with a bandwidth of 30kHz at 20MHz (CISPR band B) would be classed as broadband, while the same signal at 40MHz (band C) would be classed as narrowband.

Quasi-peak detector	Frequency band A 9–150kHz	 B 0.15–30MHz	 C 30–300MHz	 D 300–1000MHz
6dB bandwidth, kHz	0.2	9	120	
Charge time constant, ms	45	1	1	
Discharge time constant, ms	500	160	550	
Pre-detector overload factor, dB	24	30	43.5	

Table 3.1 The CISPR 16-1 quasi peak detector and bandwidths

Noise level versus bandwidth

The indicated level of a broadband signal changes with the measuring bandwidth. As the measuring bandwidth increases, more of the signal is included within it and hence the indicated level rises. The indicated level of a narrowband signal is not affected by measuring bandwidth. Noise, of course, is inherently broadband and therefore there is a direct correlation between the "noise floor" of a receiver or spectrum analyser and its measuring bandwidth: minimum noise (maximum sensitivity) is obtained with the narrowest bandwidth. The relationship between noise and bandwidth is given by equation (3.1):

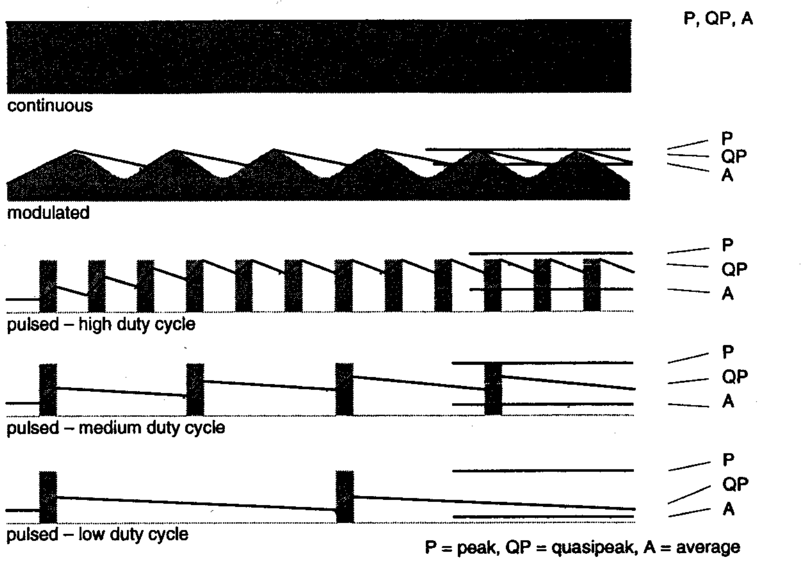
$$\text{Noise level change (dB)} = 10\log_{10}(BW_1/BW_2) \qquad (3.1)$$

For instance, a change in bandwidth from 10kHz to 120kHz would increase the noise floor by 10.8dB.

3.1.1.4 Detector function

There are three kinds of detector in common use in RF emissions measurements: peak, quasi peak and average. The characteristics are defined in CISPR 16-1 and are different for the different frequency bands.

Interference emissions are rarely continuous at a fixed level. A carrier signal may be amplitude modulated, and either a carrier or a broadband emission may be pulsed. The measured level which is indicated for different types of modulation will depend on the type of detector in use. Figure 3.2 shows the indicated levels for the three detectors with various modulation shapes.



NB the detector function refers to the signal's modulation characteristics. All detectors respond to the RMS value of the unmodulated RF voltage.

Figure 3.2 Indicated level versus modulation waveform for different detectors

Peak

The peak detector responds near-instantaneously to the peak value of the signal and discharges fairly rapidly. If the receiver dwells on a single frequency the peak detector output will follow the "envelope" of the signal, hence it is sometimes called an envelope detector. Military specifications make considerable use of the peak detector, but CISPR emissions standards do not require it at all. However its fast response makes it very suitable for diagnostic or "quick-look" tests, and it can be used to speed up a proper compliance measurement as is outlined in section 3.1.4.3.

Average

The average detector, as its name implies, measures the average value of the signal. For a continuous signal this will be the same as its peak value, but a pulsed or modulated signal will have an average level lower than the peak. EN 55022 [137] and its derivative standards call for an average detector measurement on conducted emissions, with limits which are 10–13dB lower than the quasi-peak limits. The effect of this is to penalize continuous emissions with respect to pulsed interference, which registers a lower level on an average detector [81]. A simple way to make an average measurement on a spectrum analyser is to reduce the post-detector "video" bandwidth to well below the lowest expected modulation or pulse frequency [86].

Quasi-peak

The quasi-peak detector is a peak detector with weighted charge and discharge times (Table 3.1) which correct for the subjective human response to pulse-type interference. Interference at low pulse repetition frequencies (PRF) is said to be subjectively less annoying on radio reception than that at high PRFs. Therefore, the quasi-peak response de-emphasizes the peak response at low PRFs, or to put it another way, pulse-type emissions will be treated more leniently by a quasi-peak measurement than by a peak measurement. But to get an accurate result, the measurement must dwell on each frequency for substantially longer than the QP charge and discharge time constants.

Since CISPR-based tests have historically been intended to protect the voice and broadcast users of the radio spectrum, they lay considerable emphasis on the use of the QP detector. There is a point of view which suggests that with the advent of digital telecommunications and broadcasting this will change, since digital signals are affected by impulsive interference in a quite different way. A study group within CISPR is looking at other means of detector weighting, but at the time of writing there is little to indicate that a new specification is imminent.

3.1.1.5 *Overload factor*

A pulsed signal with a low duty cycle, measured with a quasi-peak or average detector, should show a level that is less than its peak level by a factor which depends on its duty cycle and the relative time constants of the quasi-peak detector and PRF. To obtain an accurate measurement the signal that is presented to the detector must be undistorted at very much higher levels than the output of the detector. The lower the PRF, the higher will be the peak value of the signal for a given output level (Figure 3.3). Conventionally, the input attenuator is set to optimize the signal levels through the receiver, but the required pulse response means that the RF and IF stages of the receiver must be prepared to be overloaded by up to 43.5dB (for CISPR bands C and D) and remain linear. This is an extremely challenging design requirement and partially accounts for the high cost of proper measuring receivers, and the unsuitability of spectrum analysers for pulse measurements.

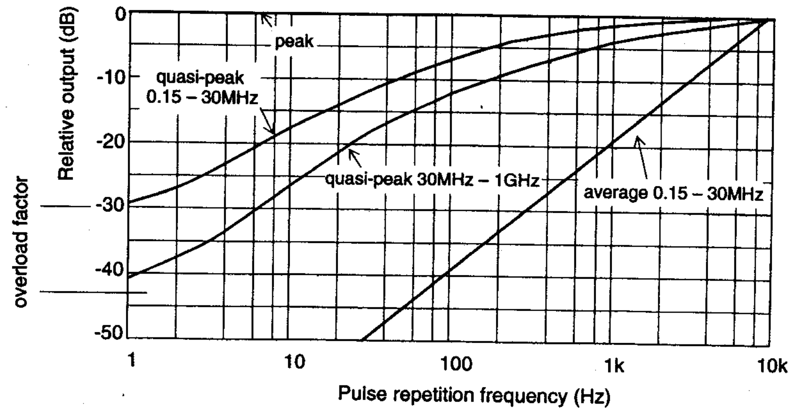


Figure 3.3 Relative output versus PRF for CISPR 16-1 detectors

The same problem means that the acceptable range of PRFs that can be measured by an average detector is limited. The overload factor of receivers up to 30MHz is only required to be 30dB, and this degree of overload would be reached on an average detector with a pulsed signal having a PRF of less than 300Hz. For this reason average detectors are only intended for measurement of continuous signals to allow for modulation or the presence of broadband noise, and are not generally used to measure impulsive interference.

3.1.1.6 *Measurement time*

Both the quasi-peak and the average detector require a relatively long time for their output to settle on each measurement frequency. This time depends on the time constants of each detector and is measured in hundreds of milliseconds. When a range of frequencies is being measured, the conventional method is to step the receiver at a step size of around half its measurement bandwidth, in order to cover the range fully without gaps (for the specified CISPR filter shape, the optimum step size is around 0.6 times the bandwidth, to give the largest step size consistent with maintaining the accuracy of measurement of any signal). For a complete measurement scan of the whole frequency range, as is required for a compliance test, the time taken is given by:

$$T = (\text{frequency span}/0.5 \cdot \text{bandwidth}) \cdot \text{dwell time per spot frequency} \qquad (3.2)$$

If the dwell time is restricted to three time constants, the time taken to do a complete quasi-peak sweep from 150kHz to 30MHz turns out to be 53 minutes. For an average measurement the scan time would be even longer, were it not for the way in which the average limit is applied. The difference between the quasi-peak and average limits is at most 13dB (in CISPR 22, class A) and this difference occurs at a PRF of 1.8kHz. The decisive value for lower PRFs is always the QP indication. Therefore the average indication only has to be accurate for modulated or pulsed signals above this PRF, and this can be ensured with only a short dwell time, such as 1ms.

But with quasi-peak, the dwell time must be increased to ensure that the peaks are captured and indicated correctly. It should be at least 1 second, if the signals to be measured are unknown. This has repercussions on the test method, as is discussed later in section 3.1.4. It places correspondingly severe restrictions on the sweep rate when you are using a spectrum analyser [39].

3.1.1.7 *Other measuring instruments*

Instruments have appeared on the market which fulfil some of the functions of a spectrum analyser at a much lower price. These may be units which convert an oscilloscope into a spectrum display, or which act as add-ons to a PC which performs the majority of the signal processing and display functions. Such devices are useful for diagnostic purposes provided that you recognize their limitations – typically frequency range, stability, bandwidth and/or sensitivity. The major part of the cost of a spectrum analyser or receiver is in its bandwidth-determining filters and its local oscillator. Cheap versions of these simply cannot give the performance that is needed of an accurate measuring instrument.

Even for diagnostic purposes, frequency stability and accuracy are necessary to make sense of spectrum measurements, and the frequency range must be adequate (150kHz–30MHz for conducted, 30MHz–1GHz for radiated diagnostics). Sensitivity matching that of a spectrum analyser will be needed if you are working near to the emission limits. The inflexibility of the cheaper units soon becomes apparent when you want to make detailed tests of particular emission frequencies.

3.1.2 Transducers

For any RF emissions measurement you need a device to couple the measured variable into the input of the measuring instrumentation. Measured variables take one of three forms:

- radiated electromagnetic field
- conducted cable voltage
- conducted cable current

and the transducers for each of these forms are discussed below.

3.1.2.1 *Antennas*

The basics of electromagnetic fields are outlined in section 5.1.4.1. Radiated field measurements can be made of either electric (E) or magnetic (H) field components. In the far field the two are equivalent, and related by the impedance of free space:

$$E/H = Z_0 = 120\pi = 377\Omega \qquad (3.3)$$

but in the near field they are unrelated. In either case, an antenna is needed to couple the field to the measuring receiver. Electric field strength limits are specified in terms of volts (or microvolts) per metre at a given distance from the EUT, whilst measuring receivers are calibrated in volts (or microvolts) at the 50Ω input. The antenna must therefore be calibrated in terms of volts output into 50Ω for a given field strength at each frequency; this calibration is known as the antenna factor.

Although the CISPR 16-1 reference antenna is a tuned dipole, it also allows the use of broadband antennas, which remove the need for re-tuning at each frequency. The two most common broadband devices historically have been the biconical, for the range 30–300MHz, and the log periodic, for the range 300–1000MHz. Some antennas have different frequency ranges, but it is always possible to combine a biconical and a log periodic to cover the range 30–1000MHz. In fact, the two structures have been combined into one with a means of ensuring that the feed is properly defined over the whole frequency range, and this type is now available commercially. It is known, unsurprisingly, as the BiLog. Its major advantage, particularly appreciated by test houses, is that an entire radiated emissions (or immunity) test can be done without changing antennas, with a consequent improvement in speed and reliability.

The advantage of the tuned dipole is that its performance can be accurately predicted, but because it can only be applied at spot frequencies it is not used for everyday measurement but is reserved for calibration of broadband antennas, site surveys, site attenuation measurements and other more specialized purposes.

Antenna factor

Those who use antennas for radio communication purposes are familiar with the specifications of gain and directional response, but these are of only marginal importance for EMC emission measurements. The antenna is always oriented for maximum response. Antenna factor is the most important parameter, and each calibrated broadband antenna is supplied with a table of its antenna factor (in dB/m) versus frequency. Antenna calibration is treated in more detail in section 3.1.5.3. Typical antenna factors for a biconical and a log periodic are shown in Figure 3.4. To convert the measured voltage at the instrument terminals into the actual field strength at the antenna you have to add the antenna factor and cable attenuation (Figure 3.5). Cable attenuation is also a function of frequency.

$$E = 4\pi \cdot 10^{-7} \cdot N \cdot A \cdot 2\pi F \cdot H \qquad (3.4)$$

where N is the number of turns in the loop
A is the area of the loop, m^2
F is the measurement frequency, Hz
H is the magnetic field, Amps/metre

The low impedance of the loop does not match the 50Ω impedance of typical test instrumentation. Also, the frequency dependence of the loop output makes it difficult to measure across more than three decades of frequency. These disadvantages are overcome by including as part of the antenna a preamplifier which corrects for the frequency response and matches the loop output to 50Ω. The preamp can be battery powered or powered from the test instrument. Such an "active" loop has a flat antenna factor across its frequency range. Its disadvantage is that it can be saturated by large signals, and some form of overload indication is needed to warn of this.

The Van Veen loop

A disadvantage of the loop antenna as it stands is its lack of sensitivity at low frequencies. An alternative method [32] is to actually surround the EUT with the loop; in its practical realization, three orthogonal loops of 2–4m diameter are used with the current induced in each being sensed by a current transformer, and the three signals are measured in turn by the test receiver. This is the large loop antenna (LLA) or Van Veen loop, named after its inventor, and it is already specified in EN 55015, the standard for lighting equipment.

3.1.2.3 *Artificial mains network*

To make conducted voltage emissions tests on the mains port, you need an artificial mains network (AMN) or Line Impedance Stabilizing Network (LISN) to provide a defined impedance at RF across the measuring point, to couple the measuring point to the test instrumentation and to isolate the test circuit from unwanted interference signals on the supply mains. The most widespread type of LISN is defined in CISPR 16-1 and presents an impedance equivalent to 50Ω in parallel with 50μH across each line to earth (Figure 3.7). Others are also defined, but the 50Ω/50μH version has become the norm.

Note that its impedance is not defined above 30MHz, partly because commercial conducted measurements are not required above this frequency (aerospace and automotive standards do call for conducted tests above 30MHz, but use different circuit values) but also because component parasitic reactances make a predictable design difficult to achieve. CISPR 16-1 includes a suggested circuit (Figure 3.8) for each line of the LISN, but it only actually *defines* the impedance characteristic. The main impedance determining components are the measuring instrumentation input impedance, the 50μH inductor and the 5Ω resistor. The remaining components serve to decouple the incoming supply. A common addition is a high-pass filter between the LISN output and the receiver, cutting off below 9kHz, to prevent the receiver from being affected by high level harmonics of the mains supply itself. Of course, this filter has to maintain the 50Ω impedance and have a defined (preferably 0dB) insertion loss at the measured frequencies.

Earth current

A large capacitance (in total around 12μF) is specified between line and earth, which when exposed to the 240V line voltage results in around 0.9A in the safety earth. This

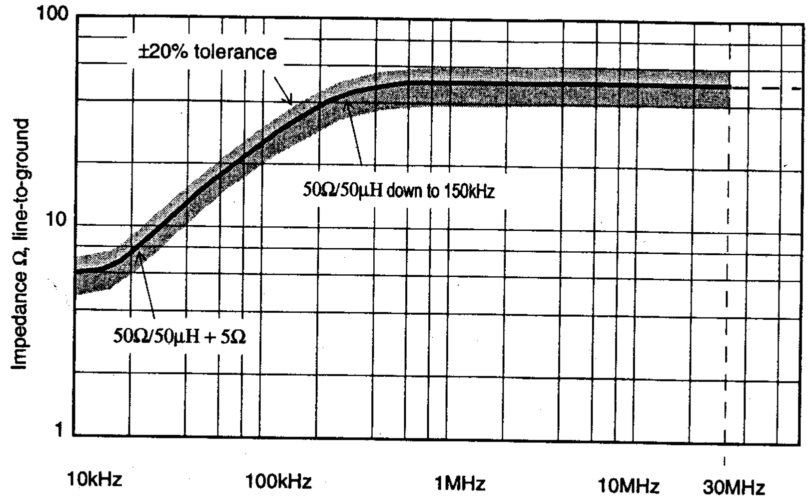


Figure 3.7 LISN impedance versus frequency

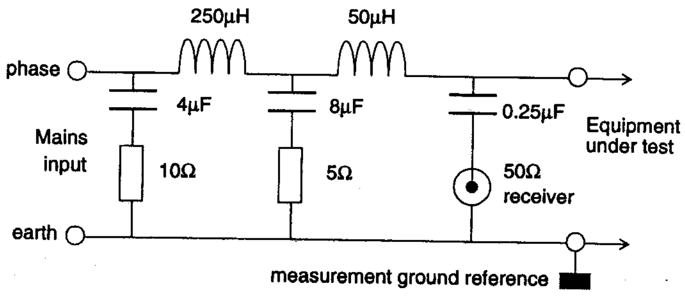


Figure 3.8 LISN circuit per line

level of current is lethal, and the unit must therefore be solidly connected to earth for safety reasons. If it is not, the LISN case, the measurement signal lead and the equipment under test (EUT) can all become live. As a precaution, you are advised to bolt your LISN to a permanent ground plane and not allow it to be carried around the lab! A secondary consequence of this high earth current is that LISNs cannot be used directly on mains circuits that are protected by earth leakage or residual current circuit breakers. Both of these problems can be overcome by feeding the mains to the LISN through an isolating transformer.

Diagnostics with the LISN

As it stands, the LISN does not distinguish between differential mode (line to line) and common mode (line to earth) emissions (see section 5.2.2); it merely connects the measuring instrument between phase and earth. A modification to the LISN circuit

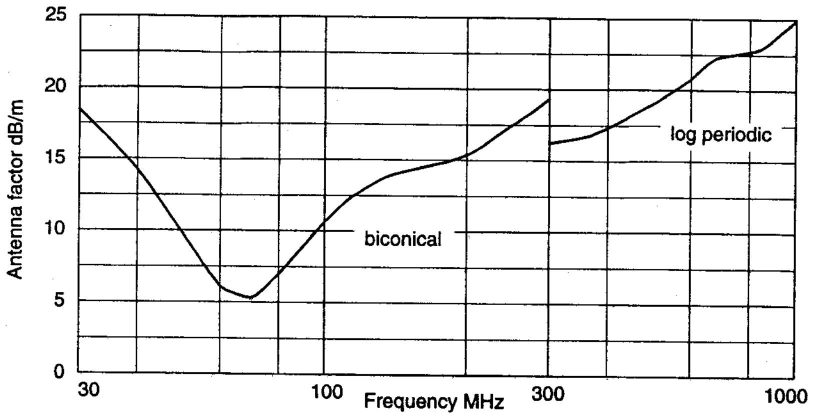
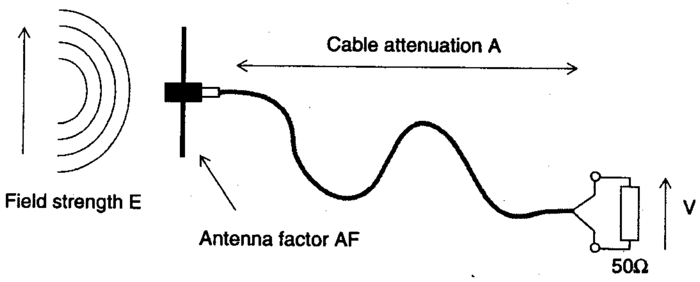


Figure 3.4 Typical antenna factors



E (dBμV/m) = V (dBμV) + AF (dB/m) + A (dB)

Figure 3.5 Converting field strength to measured voltage

System sensitivity

A serious problem can arise when using an antenna with a spectrum analyser for radiated tests. Radiated emission compliance tests are typically made at 10m distance and the most severe limit in the usual commercial standards is the EN Class B level, which is 30dBμV/m below 230MHz and 37dBμV/m above it. The minimum measurable level will be determined by the noise floor of the spectrum analyser (see section 3.1.1.3) which for a 120kHz bandwidth is typically +13dBμV. To this must be added the antenna factor and cable attenuation in order to derive the overall measurement system sensitivity. Taking the antenna factors already presented, together with a typical 3dB at 1GHz due to cable attenuation, the overall system noise floor rises to 41dBμV/m at 1GHz as shown in Figure 3.6, which is 4dB *above* the limit line.

The CISPR 16-1 requirement on sensitivity is that the noise contribution should affect the accuracy of a compliant measurement by less than 1dB. This implies a noise floor below the measured value by at least 6dB.

Thus full radiated class B compliance measurements *cannot be made with a spectrum analyser alone*. Three options are possible: reduce the measuring distance to 3m, which may raise the limit level by 10dB, but this increases the error and still gives hardly enough margin at the top end; or, use a preamplifier or preselector to lower the effective system noise floor, by a factor equal to the preamp gain less its noise figure, typically 20–25dB; or use a test receiver, which has a much better inherent sensitivity.

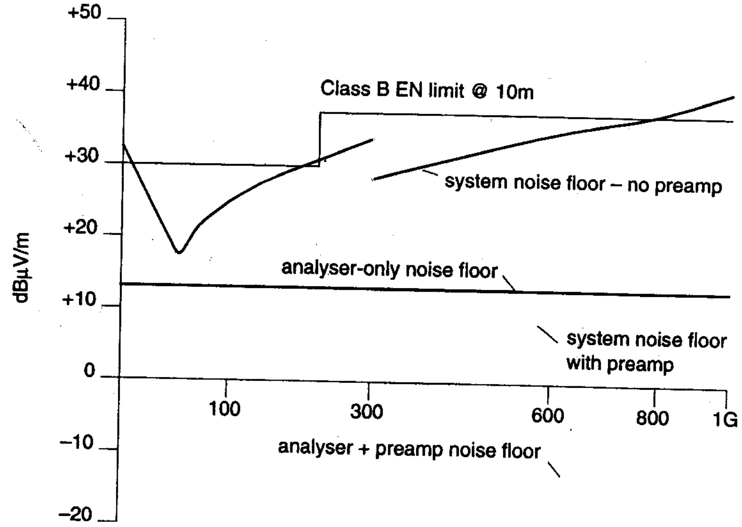


Figure 3.6 System sensitivity

Polarization

In the far field the electric and magnetic fields are orthogonal (Appendix C, section C.3). With respect to the physical environment each field may be vertically or horizontally polarized, or in any direction in between. The actual polarization depends on the nature of the emitter and on the effect of reflections from other objects. An antenna will show a maximum response when its plane of polarization aligns with that of the incident field, and will show a minimum when the planes are at right angles. The plane of polarization of both biconical and log periodic is in the plane of the elements. CISPR emission measurements must be made with linearly polarized antennas; circularly-polarized antennas, such as the log spiral, a broadband type favoured for military RF immunity testing, are outlawed for emissions tests by CISPR 16-1.

3.1.2.2 The loop antenna

The majority of radiated emissions are measured in the range 30 to 1000MHz. A few standards call for radiated measurements below 30MHz. In these cases the magnetic field strength is measured, using a loop antenna. Measurements of the magnetic field give better repeatability in the near field region than do measurements of the electric field, which is easily perturbed by nearby objects. The loop is merely a coil of wire which produces a voltage at its terminals proportional to frequency, according to Faraday's law:

(Figure 3.9) allows you to detect either the sum or the difference of the live and neutral voltages, which correspond to the common mode and differential mode voltages respectively [105]. This is not required for compliance measurements but is very useful when making diagnostic tests on mains filters.

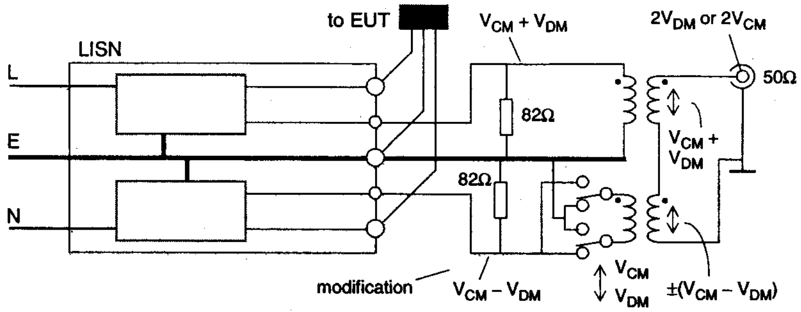


Figure 3.9 Modifying the LISN to measure differential or common mode

3.1.2.4 Other networks for conducted emissions

The third edition of EN 55022 has provisions for tests on telecommunications ports. The preferred method uses a particular variant of impedance stabilizing network (ISN) which is designed to mimic the characteristics of category 3 and 5 data cables, as defined in ISO/IEC 11801. This network has a common mode impedance of 150Ω and a carefully controlled longitudinal conversion loss, that is, the parameter which determines the conversion from differential mode signal to common mode interference currents. Since the requirements can apply to other types of cables, other coupling methods are allowed, but they are not particularly well defined.

3.1.2.5 Absorbing clamp and current probe

As well as measuring the emissions above 30MHz directly as a radiated field you can also measure the interference currents on connected cables and relate these to the accepted field strength levels. Standards which apply primarily to small apparatus connected only by a mains cable – notably EN 55014 – specify the measurement of interference power present on the mains lead. This has the advantage of not needing a large open area for the tests, but it should be done inside a fairly large screened room and the method is somewhat clumsy. The transducer is an absorbing device known as a ferrite clamp.

The ferrite absorbing clamp (often referred to as the MDS-21 clamp) consists of a current transformer using two or three ferrite rings, split to allow cable insertion, with a coupling loop (Figure 3.10). This is backed by further ferrite rings forming a power absorber and impedance stabilizer, which clamps around the mains cable to be measured. It is calibrated in terms of output power versus input power, i.e. insertion loss. The purpose of the ferrite absorbers is to attenuate reflections and extraneous signals that would otherwise appear at the current transformer. The lead from the current transformer to the measuring instrument is also sheathed with ferrite rings to attenuate screen currents on this cable. Because the output is proportional to current flowing in common mode on the measured cable, it can be used as a direct measure of noise power, and the clamp can be calibrated as a two-port network in terms of output power versus input power.

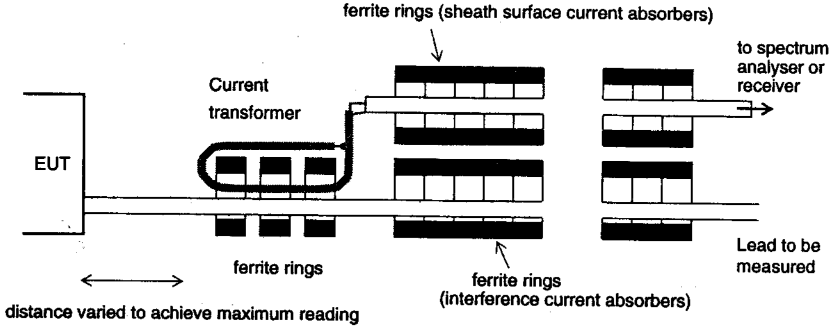


Figure 3.10 The ferrite absorbing clamp

CISPR 16-1 specifies the construction, calibration and use of the ferrite clamp. As well as its use in certain compliance tests, it also lends itself to diagnostics as it can be used for repeatable comparative measurements on a single cable to check the effect of circuit changes. There is considerable interest in using the clamp as a replacement for many radiated emissions tests, especially in situations such as with small EUTs where the emissions are substantially due to the cables. It has been suggested [121] that the clamp should be used to "pre-test" such EUTs, with the application of a suitable empirically-derived correction factor, so that they need only be subjected to a radiated test at the most critical emitting frequencies. A further common use for the clamp is to be applied to the further end of connected cables, both in radiated emissions and immunity tests, to damp the cable resonance and reduce variations due to cable termination. The clamp output is not connected when it is used in this way. Although this is a convenient method if a clamp is already to hand, using a string of 6–10 large snap-on ferrite sleeves is just as effective.

Current probe

Also useful for diagnostics is the current probe, which is essentially the same as the absorbing clamp except that it doesn't have the absorbers. It is simply a clamp-on, calibrated wideband current transformer. Military specifications call for its use on individual cable looms, and the third edition of EN 55022 giving test methods for telecoms ports also requires a current probe for some versions of the tests. CISPR 16-1 includes a specification for the current probe. Because the current probe does not have an associated absorber, the RF common mode termination impedance of the line under test should be defined by an impedance stabilizing network, which must be transparent to the signals being carried on the line.

Both the ferrite clamp and the current probe have the great advantage that no direct connection is needed to the cable under test, and disturbance to the circuit is minimal below 30MHz since the probe effect is no more than a slight increase in common mode impedance. Note though, that at higher frequencies, the effect of the common mode coupling capacitance between probe and cable becomes significant.

3.1.2.6 *Near field probes*

Very often you will need to physically locate the source of emissions from a product. A set of near-field (or "sniffer") probes is used for this purpose. These are so-called because they detect field strength in the near field, and therefore two types of probe are needed, one for the electric field (rod construction) and the other for the magnetic field (loop construction). It is simple enough to construct adequate probes yourself using coax cable (Figure 3.11), or you can buy a calibrated set. A probe can be connected to a spectrum analyser for a frequency domain display, or to an oscilloscope for a time domain display.

Probe design is a trade-off between sensitivity and spatial accuracy. The smaller the probe, the more accurately it can locate signals but the less sensitive it will be. You can increase sensitivity with a preamplifier if you are working with low-power circuits. A good magnetic field probe is insensitive to electric fields and vice versa; this means that an electric field probe will detect nodes of high dv/dt but will not detect current paths, while a magnetic field probe will detect paths of high di/dt but not voltage points.

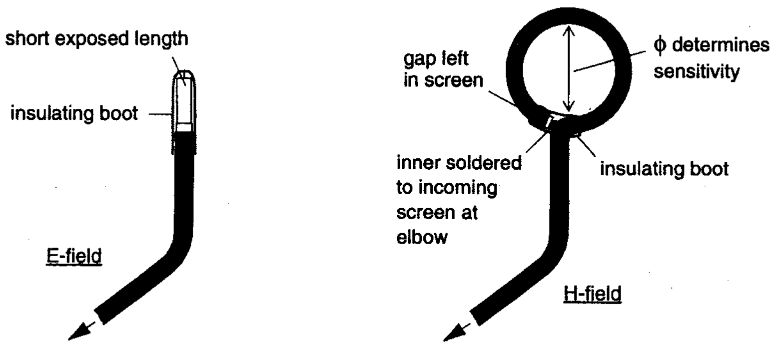


Figure 3.11 Do-it-yourself near field probes

Near-field probes can be calibrated in terms of output voltage versus field strength, but these figures should be used with care. Measurements cannot be directly extrapolated to the far field strength (as on an open site) because in the near field one or other of the E or H fields will dominate depending on source type. The sum of radiating sources will differ between near and far fields, and the probe will itself distort the field it is measuring. Perhaps more importantly, you may mistake a particular "hot spot" that you have found on the circuit board for the actual radiating point, whereas the radiation is in fact coming from cables or other structures that are coupled to this point via an often complex path. Probes are best used for tracing and for comparative rather than absolute measurements.

3.1.2.7 *Near field scanning devices*

A particular implementation of a near field probe is the planar scanning device, such as EMSCAN$^{\text{TM}\dagger}$. This was developed and patented at Bell Northern Research in Canada and now has competitors from other manufacturers. In principle it is essentially a planar array of tiny near field current probes arranged in a grid form on a multilayer pcb [58].

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† EMSCAN is a trademark of Northern Telecom, Canada.

The output of each current probe can be switched under software control to a frequency selective measuring instrument, whose output in turn provides a graphical display on the controlling workstation. Competitive devices can also use a single probe positioned by X-Y stepper motors, in the same way as an X-Y plotter.

The device is used to provide a near-instantaneous two dimensional picture of the RF circulating currents within a printed circuit card placed over the scanning unit. It can provide either a frequency versus amplitude plot of the near field at a given location on the board, or an x-y co-ordinate map of the current distribution at a given frequency. For the designer it can instantly show the effect of remedial measures on the pcb being investigated, while for production quality assurance it can be used to evaluate batch samples which can be compared against a known good standard.

3.1.2.8 *The GTEM for emissions tests*

Use of the GTEM for radiated RF immunity testing is covered in section 4.1.1.4. It can also be used for emissions tests with some caveats. The GTEM is a special form of enclosed transmission line which is continuously tapered and terminated in a broadband RF load. This construction prevents resonances and gives it a flat frequency response from DC to well beyond 1GHz. An EUT placed within the transmission line will couple closely with it and therefore radiated emissions can be measured directly at the output of the cell. The great advantages of this technique are that no antenna or OATS is needed, the frequency range can be covered in a single sweep, and ambients are eliminated.

However, what is required for compliance tests is a measure of the radiated emissions as they would be found on an OATS. This requires that the GTEM measurements are correlated to OATS results. This is done in software and the model is described in [134]. In fact, three scans are done with the EUT in orthogonal orientations within the cell. The software then derives at each frequency an equivalent set of elemental electric and magnetic dipole moments, and then re-calculates the far-field radiation at the appropriate test distance from these dipoles.

The limitation of this model is that the EUT must be "electrically small", i.e. its dimensions are small when compared to a wavelength. Connected cables pose a particular problem since these often form the major radiating structure, and are of course rarely electrically small, even if the EUT itself is. Good correlation has been found experimentally for small EUTs without cables [40][103], but the correlation worsens as larger EUTs, or EUTs with connected cables, are investigated. In practice it seems that the GTEM is a useful device for making radiated emissions measurements provided that this limitation is realized and some margin is allowed for the extra uncertainty of the correlation.

3.1.3 Facilities

3.1.3.1 *Radiated emissions*

At present, radiated emissions compliance testing should be done on an open area test site (OATS). The characteristics of a minimum standard OATS are defined in EN 55022 and in clause 5.6 of CISPR 16-1. Such a site offers a controlled RF attenuation characteristic between the emitter and the measuring antenna (known as site attenuation). In order to avoid influencing the measurement there should be no objects that could reflect RF within the vicinity of the site. The CISPR test site dimensions are shown in Figure 3.12.

The ellipse defines the area which must be flat and free of reflecting objects, including overhead wires. In practice, for good repeatability between different test sites a substantially larger surrounding area free from reflecting objects is advisable. This means that the room containing the control and test instrumentation needs to be some distance away from the site. An alternative is to put this room directly below the ground plane, either by excavating an underground chamber or by using the flat roof of an existing building as the test site.

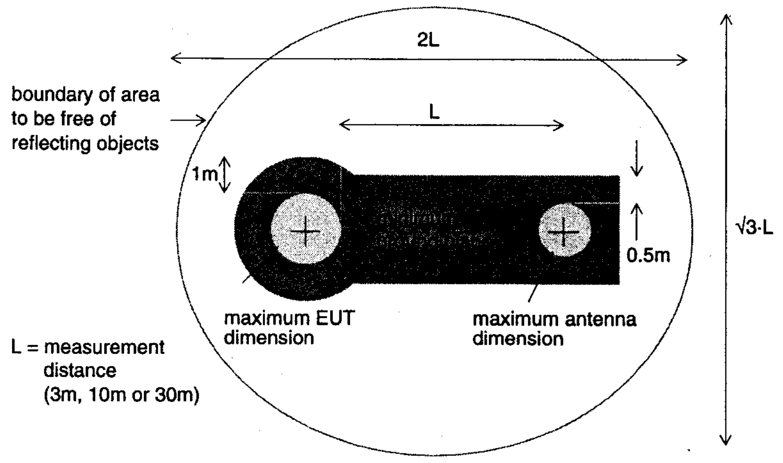


Figure 3.12 The CISPR OATS

Ground plane

Because it is impossible to avoid ground reflections, these are regularized by the use of a ground plane. The minimum ground plane dimensions are also shown in Figure 3.12. Again, an extension beyond these dimensions will bring site attenuation closer to the theoretical; scattering from the edges contributes significantly to the inaccuracies, although these can be minimized by terminating the edges into the surrounding soil [87]. Close attention to the construction of the ground plane is necessary. It should preferably be solid metal sheets welded together, but this may be impractical. Bonded wire mesh is suitable, since it drains easily and resists warping in high temperatures if suitably tensioned. For RF purposes it must not have voids or gaps that are greater than 0.1λ at the highest frequency (i.e. 3cm). Ordinary wire mesh is unsuitable unless each individual overlap of the wires is bonded. CISPR 16-1 suggests a ground plane surface roughness of better than 4.5cm.

Measuring distance

The measurement distance d between EUT and receiving antenna determines the overall dimensions of the site and hence its expense. There are three commonly specified distances, 3m, 10m and 30m. In EN 55022 the measuring distance is defined between the boundary of the EUT and the reference point of the antenna, although EN 55011 prefers to define it to the centre of the turntable. Confidence checks can be carried out on a 3m range, on the assumption that levels measured at 10m will be 10dB lower (field strength should be proportional to 1/d). This assumption is not entirely valid at the lower end of the frequency range, where 3m separation is approaching the near field, and indeed experience shows that a linear 1/d relationship is more optimistic than is found in practice.

3.1.3.2 *Validating the site: NSA*

Site attenuation is the insertion loss measured between the terminals of two antennas on a test site, when one antenna is swept over a specified height range, and both antennas have the same polarization. This gives an attenuation value in dB at each frequency for which the measurement is performed. Transmit and receive antenna factors are subtracted from this value to give the Normalized Site Attenuation (NSA), which should be an indication only of the performance of the site, without any relation to the antennas or instrumentation.

NSA measurements are performed for both horizontal and vertical polarizations, with the transmit antenna positioned at a height of 1m (for broadband antennas) and the receive antenna swept over the appropriate height scan. CISPR standards specify a height scan of 1–4m for 3m and 10m sites. The purpose of the height scan, as in the test proper, is to ensure that nulls caused by destructive addition of the direct and ground reflected waves are removed from the measurement. Note that the height scan is *not* intended to measure or allow for elevation-related variations in signal emitted directly from the source, either in the NSA measurement or in a radiated emissions test.

Figure 3.13 shows the geometry and the basic method for an NSA calibration. Referring to that diagram, the procedure is to record the signal with points [1] and [2] connected, to give V_{DIRECT}, and then via the antennas over the height scan, to give V_{SITE}. Then NSA in dB is given by

$$NSA = V_{DIRECT} - V_{SITE} - A_{FT} - A_{FR} \qquad (3.5)$$

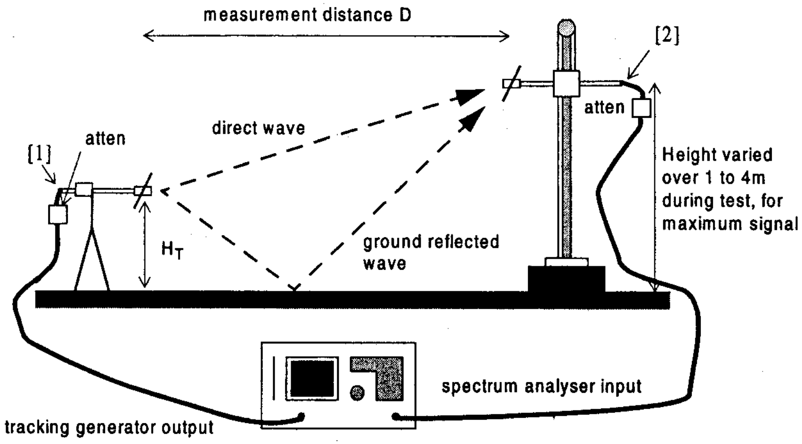
where A_{FT} and A_{FR} are the antenna factors

CISPR 16-1, and related standards, includes the requirement that

> A measurement site shall be considered acceptable when the measured vertical and horizontal NSAs are within ±4dB of the theoretical normalized site attenuation

and goes on to give a table of theoretical values versus frequency for each geometry and polarization (the values differ between horizontal and vertical because of the different ground reflection coefficients). This is the yardstick by which any actual site is judged; the descriptions in 3.1.3.1 above indicate how this criterion might be achieved, but as long as it *is* achieved, any site can be used for compliance purposes. Vice versa, a site which does not achieve the ±4dB criterion cannot be used for compliance purposes no matter how well constructed it is. Note that the deviation from the theoretical values cannot be used as a "correction factor" to "improve" the performance of a particular site. This is because the NSA relates to a specific emitting source, and the site attenuation characteristics for a real equipment under test may be quite different.

In choosing the ±4dB criterion, it is assumed by CISPR that the instrumentation uncertainties (due to antenna factors, signal generator and receiver, cables etc.) account for three-quarters of the total and that the site itself can be expected to be within ±1dB of the ideal. This has a crucial implication for the method of carrying out an NSA measurement. If you reduce the instrumentation uncertainties as far as possible you can substantially increase the chances of a site being found acceptable. Conversely, if your



Record received signal with points [1] and [2] connected and via antennas

Figure 3.13 Geometry and set-up for an NSA measurement

method has greater uncertainties than allowed for in the above table, *even a perfect site will not meet the criterion.* Clearly, great attention must be paid to the method of performing an NSA calibration. The important aspects are:

- Antenna factors – suitable for the geometry of the method, not free-space
- Antenna balance and cable layout – to minimize the impact of the antenna cables
- Impedance mismatches – use attenuator pads on each antenna to minimize mismatch error

3.1.3.3 *Radiated measurements in a screened chamber*

Open area sites have two significant disadvantages, particularly in a European context – ambient radiated signals, and weather. These are discussed again in section 3.1.5.5. These disadvantages have prompted great interest in using sheltered facilities, and in particular screened chambers.

Alternative sites to the standard CISPR open area test site are permitted provided that errors due to their use do not invalidate the results. As you might expect, their adequacy is judged by performing an NSA measurement. However, an extra requirement is added, which is to insist that the NSA is checked over the *volume* to be occupied by the largest EUT. This can require up to 20 separate NSA sweeps – five positions in the horizontal plane (centre, left, right, front and back) with two heights and for two polarizations each. As before, the acceptability criterion is that none of the measurements shall exceed ±4dB from the theoretical.

The problem with screened chambers for radiated measurements is that reflections occur from all six surfaces and will substantially degrade the site attenuation from EUT to measuring antenna. For any given path, significant nulls and peaks with amplitude variations easily exceeding 30dB will exist at closely-spaced frequency intervals. Equally importantly, different paths will show different patterns of nulls and peaks, and small changes within the chamber can also change the pattern, so there is no real possibility of correcting for the variations. If you have to look for radiated emissions within a screened chamber, do it on the basis that you will be able to find frequencies at which emissions exist, but will not be able to draw any firm conclusions as to the amplitude of those emissions.

To be able to make anything approaching *measurements* in a screened chamber, the walls and ceiling reflections must be damped. This is achieved by covering these surfaces with radio absorbing material (RAM). RAM is available as ferrite tiles, carbon loaded foam pyramids, or a combination of both, and it is quite possible to construct a chamber using these materials which meets the volumetric NSA requirement of ±4dB. Enough such chambers have been built and installed that there is plenty of experience on call to ensure that this is achieved. The snag is that either material is expensive, and will at least double the cost of the installed chamber. A comparison between the advantages and disadvantages of the three options is given in Table 3.2.

Table 3.2 Comparison of absorber materials

	Ferrite tiles	**Pyramidal foam**	**Hybrid**
Size	No significant loss of chamber volume	Substantial loss of chamber volume	Some loss of chamber volume
Weight	Heavy; requires ceiling reinforcement	Reinforcement not needed	Heavy; requires ceiling reinforcement
Fixing	Critical – no gaps, must be secure	Not particularly critical	Critical – no gaps, must be secure
Durability	Rugged, no fire hazard	Tips can be damaged, possible fire hazard	Some potential for damage and fire
Performance	Good mid-frequency, poor at band edges	Good at high frequency, poor at low frequency	Can be optimized across whole frequency range

Partial lining of a room is possible but produces partial results. It may, though, be an option for pre-compliance tests. Figure 3.14 shows an example of a chamber NSA which falls substantially outside the required criterion but is still quite a lot better than a totally unlined chamber.

The FAR proposal

So far, we have discussed chambers which mimic the characteristics of an open area site, that is they employ a reflective ground plane and a height scan. This makes them a direct substitute for an OATS, allows them to be used in exactly the same way for the same standards, and generally avoids the question of whether the OATS is the optimum method for measuring radiated emissions.

In fact, it isn't. It was originally proposed as a means of dealing with the unavoidable proximity of the ground in practical test set-ups, in the US, where difficulties with ambient signals and the weather are less severe than in Europe. However, developments over the past ten years in absorber materials have made it quite practical and cost-effective to construct a small fully-anechoic room (FAR), that is, with absorber on the floor as well, which can meet the volumetric ±4dB NSA criterion. This environment is as near to free space as can be achieved. Its most crucial advantage is that, because there is no ground plane, there is no need for an antenna height scan.

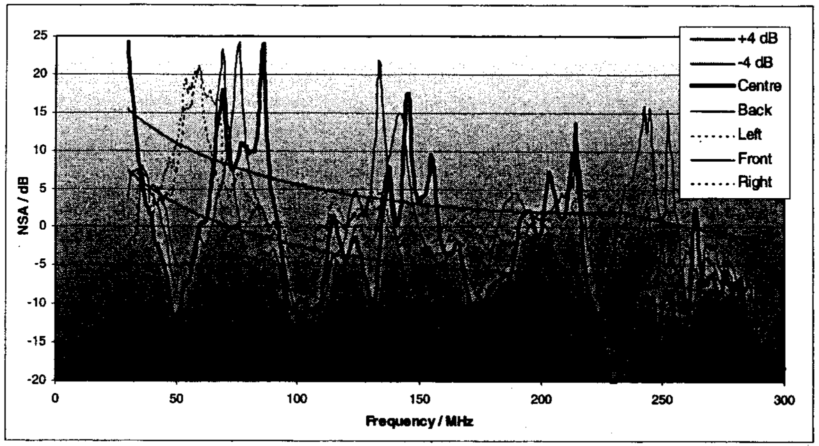


Figure 3.14 Example of a poor chamber NSA (vertical polarization, 1m height)

This eliminates a major source of uncertainty in the test (see section 3.1.5) and generally allows for a faster and more accurate measurement.

Considerable work has been put in during the last few years to develop a standard for defining the test method in a FAR, and the detailed criteria that must be met by the room itself. This has resulted in a document, prEN 50147-3 [145], which at the time of writing is still under development. Since it will have to co-exist with the standard CISPR test method for some time to come, much of the concern surrounding its development has been to ensure as far as possible that it produces results that are comparable to the OATS method, and that the necessary adjustment to the limit levels (because of the elimination of the reflected signal) is carefully validated.

3.1.3.4 Conducted emissions

By contrast with radiated emissions, conducted measurements need the minimum of extra facilities. The only vital requirement is for a ground plane of at least 2m by 2m, extending at least 0.5m beyond the boundary of the EUT. It is convenient but not essential to make the measurements in a screened enclosure, since this will minimize the amplitude of extraneous ambient signals, and one wall or the floor of the room can then be used as the ground plane. Non-floor-standing equipment should be placed on an insulating table 40cm above the ground plane.

Testing cable interference power with the absorbing clamp, according to EN55014, requires that the clamp should be moved along the cable by at least a half wavelength, which is 5m at 30MHz. This therefore needs a 5m "racetrack" along which the cable is stretched; the clamp is rolled the length of the cable at each measurement frequency while the highest reading is recorded. There is no guidance in the standards as to whether the measurement should or should not be done inside a screened room. There are likely to be substantial differences one to the other, since the cable under test will couple strongly to the room and will suffer from room-induced resonances in the same manner as a radiated test, though to a lesser extent. For repeatability, a quasi-free space environment would be better, but will then suffer from ambient signals.

3.1.3.5 Pre-compliance and diagnostic tests

Full compliance with the EMC Directive can be achieved by testing and certifying to harmonized European standards. However the equipment and test facilities needed to do this are quite sophisticated and often outside the reach of many companies. The alternative is to take the product to be tested to a test house which is set up to do the proper tests, but this itself is expensive, and to make the best use of the time some preliminary if limited testing beforehand is advisable.

This consideration has given rise to the concept of "pre-compliance" testing. "Pre-compliance" refers to tests done on the production unit (or something very close to it) with a test set-up and/or test equipment that may not fully reflect the standard requirements. The purpose is to:

- avoid or anticipate unpleasant surprises at the final compliance test
- adequately define the worst-case EUT configuration for the final compliance test, hence saving time
- if the results show sufficient margin, to substitute for the final compliance test

Diagnostics

Although you will not be able to make accurate radiated measurements in a laboratory environment, it is possible to establish a minimum set-up in one corner of the lab at which you can perform emissions diagnostics and carry out comparative tests. For example, if you have done a compliance test at a test house and have discovered one particular frequency at 10dB above the required limit, back in the lab you can apply remedial measures and check each one to see if it gives you a 15dB improvement (5dB margin) without being concerned for the absolute accuracy. While this method is not absolutely foolproof, it is often the best that companies with limited resources and facilities can do.

The following checklist suggests a minimum set-up for doing this kind of in-house diagnostic work:

- unrestricted floor area of at least 5m x 3m to allow a 3m test range with 1m beyond the antenna and EUT;
- no other electronic equipment which could generate extraneous emissions (especially computers) in the vicinity, the EUT's support equipment should be well removed from the test area;
- no mobile reflecting objects in the vicinity, or those which are mobile should have their positions carefully marked for repeatability;
- an insulating table or workbench at one end of the test range on which to put the EUT, with a LISN bonded to the ground plane beneath it;
- equipment consisting of a spectrum analyser, limiter, antenna set and insulating tripod;
- antenna polarization maintained at horizontal, and the EUT cables stretched out horizontally and taped to the table facing it, since this reduces errors due to reflections and ground proximity.

Once this set-up is established it should not be altered between measurements on a given EUT. Since the antenna is at a fixed height, there should be no ground plane and the floor should not be metallic, since floor reflections should be attenuated as far as possible. This will give you a reasonable chance of repeatable measurements even if their absolute accuracy cannot be determined.

3.1.4 Test methods

The major part of all the basic standards referred to in Chapter 2 consists of recipes for carrying out the tests. Because the values obtained from measurements at RF are so dependent on layout and method, these have to be specified in some detail to generate a standard result. This section summarizes the issues involved, but to actually perform the tests you are recommended to consult the relevant standard carefully.

3.1.4.1 Layout

For conducted emissions, the principal requirement is placement of the EUT with respect to the ground plane and the LISN, and the disposition of the mains cable and earth connection(s). Placement affects the stray coupling capacitance between EUT and the ground reference, which is part of the common mode coupling circuit, and so must be strictly controlled. Figure 3.15 shows the layout for conducted emissions testing.

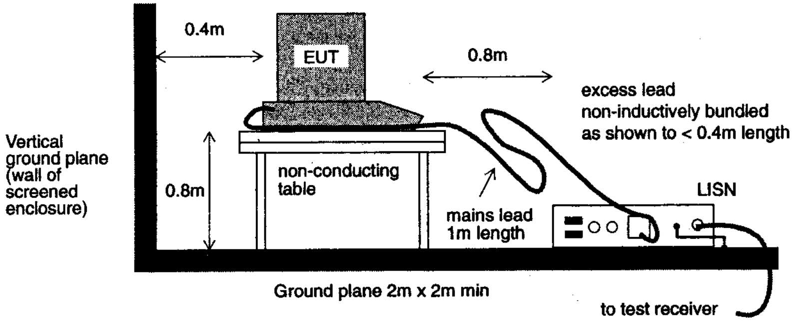


Figure 3.15 Layout for conducted emission tests

Radiated emissions to EN 55022 require the EUT to be positioned so that its boundary is the specified distance from the measuring antenna. "Boundary" is defined as "an imaginary straight line periphery describing a simple geometric configuration" which encompasses the EUT. A non-floor-standing EUT should be 0.8m above the ground plane. The EUT will need to be rotated through 360° to find the direction of maximum emission, and this is usually achieved by standing it on a turntable. If it is too big for a turntable, then the antenna must be moved around the periphery while the EUT is fixed. Figure 3.16 shows the general layout for radiated tests.

3.1.4.2 Configuration

Once the date for an EMC test approaches, the question most frequently asked of test house engineers is "what system should I test?" The configuration of the EUT itself was not well specified in the first version of EN 55022 (which is regarded as the root standard for emissions testing), although the current (third) version based on CISPR 22:1997 rectifies this: it specifies both the layout and composition of the EUT in great detail, especially if the EUT is a personal computer or peripheral. Factors which will affect the emissions profile from the EUT, and which if not specified in the chosen standard should at least be noted in the test report, are:

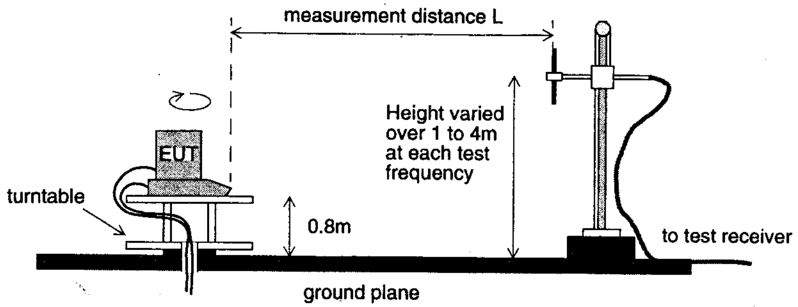


Figure 3.16 Layout for radiated emission tests

- number and selection of ports connected to ancillary equipment: you must decide on a "typical configuration". Where several different ports are provided each one should be connected to ancillary equipment. Where there are multiple ports for connection of identical equipment, only one need be connected provided that you can show that any additional connections would not take the system out of compliance
- disposition of the separate components of the EUT, if it is a system; you should experiment to find the layout that gives maximum emissions within the confines of the supporting table top, or within typical usage if it is floor standing
- layout, length, disposition and termination practice of all connecting cables; excess cable lengths should be bundled (not looped) near the centre of the cable with the bundle 30–40cm long. Lengths and types of connectors should be representative of normal installation practice
- population of plug-in modules, where appropriate; as with ancillary equipment, one module of each type should be included to make up a minimum representative system. Where you are marketing a system (such as a data acquisition unit housed in a card frame) that can take many different modules but not all at once, you may have to define several minimum representative systems and test all of them
- software and hardware operating mode; all parts of the system should be exercised, e.g. equipment powered on and awaiting data transfer, and sending/receiving data in typical fashion. You should also define displayed video on VDUs and patterns being printed on a printer
- use of simulators for ancillary equipment is permissible provided that its effects on emissions can be isolated or identified. Any simulator must properly represent the actual RF electrical characteristics of the real interface
- EUT grounding method: should be that specified in your installation instructions. If the EUT is intended to be operated ungrounded, it must be

tested as such. If it is grounded via the safety earth (green and yellow) wire in the mains lead, this should be connected to the measurement ground plane at the mains plug (for conducted measurements, this will be automatic through the LISN).

The catch-all requirement in all standards is that the layout, configuration and operating mode *shall be varied so as to maximize the emissions*. This means some exploratory testing once the significant emission frequencies have been found, varying all of the above parameters – and any others which might be relevant – to find the maximum point. For a complex EUT or one made up of several interconnected subsystems this operation is time consuming. Even so, you must be prepared to justify the use of whatever final configuration you choose in the test report.

Information technology equipment

The requirements for testing information technology equipment and peripherals are specified in some depth. The minimum test configuration for any PC or peripheral must include the PC, a keyboard, an external monitor, an external peripheral for a serial port and an external peripheral for a parallel port. If it is equipped with more than the minimum interface requirements, peripherals must be added to all the interface ports unless these are of the same type, and provided that the addition of identical cables would not affect the test results by more than 2dB. The support equipment for the EUT should be typical of actual usage.

3.1.4.3 Test procedure

The procedure which is followed for an actual compliance test, once you have found the configuration which maximizes emissions, is straightforward if somewhat lengthy. Conducted emissions require a continuous sweep from 150kHz to 30MHz at a fixed bandwidth of 9kHz, once with a quasi-peak detector and once with an average detector. If the average limits are met with the quasi-peak detector there is no need to perform the average sweep. Radiated emissions require only a quasi-peak sweep from 30MHz to 1GHz with 120kHz bandwidth, with the receiving antenna in both horizontal and vertical polarization. EN 55022 requires that the six frequencies of highest emission level are reported.

Maximizing emissions

But most importantly, for each significant radiated emission frequency, i.e. where the measured level is within say 10dB of the limit, the EUT must be rotated to find the maximum emission direction *and* the receiving antenna must be scanned in height from 1 to 4m to find the maximum level. If there are many emission frequencies near the limit this can take a very long time. With a test receiver, automatic turntable and antenna mast under computer control, software can be written to perform the whole operation. This removes one source of operator error and reduces the test time, but not substantially.

A further difficulty arises if the operating cycle of the EUT is intermittent: say its maximum emissions only occur for a few seconds and it then waits for a period before it can operate again. Since the quasi peak or average measurement is inherently slow, with a dwell time at each frequency of hundreds of milliseconds, interrupting the sweep or the azimuth or height scan to synchronize with the EUT's operating cycle is necessary and this stretches the test time further. If it is possible to speed up the operating cycle to make it continuous, as for instance by running special test software, this is well worthwhile in terms of the potential reduction in test time.

Fast pre-scan

A partial way around the difficulties of excessive test time is to make use of the characteristics of the peak detector (see section 3.1.1.4 and 3.1.1.6). Because it responds instantaneously to signals within its bandwidth the dwell time on each frequency can be short, just a few milliseconds at most, and so using it will enormously speed up the sweep rate for a whole frequency scan. Its disadvantage is that it will overestimate the levels of pulsed or modulated signals (see Figure 3.2). This is a positive asset if it is used on a qualifying pre-scan in conjunction with computer data logging. The pre-scan with a peak detector will only take a few seconds and all frequencies at which the level exceeds some pre-set value lower than the limit can be recorded in a data file. These frequencies can then be measured individually, with a quasi peak and/or average detector, and subjecting each one to a height and azimuth scan. Provided there are not too many of these spot frequencies the overall test time will be significantly reduced, as there is no need to use the slow detectors across the whole frequency range.

You must be careful, though, if the EUT emissions include pulsed narrowband signals with a relatively low repetition rate – some digital data emissions have this characteristic – that the dwell time is not set so fast that the peak detector will miss some emissions as it scans over them. The dwell time should be set no less than the period of the longest known repetition frequency in the system. It is also advisable to do more than one pre-scan, with the EUT in different orientations, to ensure that no potentially offending signal is lost, for instance through being aligned with a null in the radiation pattern.

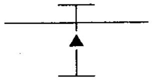
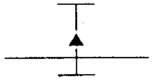
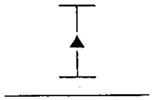
A further advantage of the pre-scan method is that the pre-scan can be done (and usually is) inside a screened room, thereby eliminating ambients and the difficulties they introduce. The trade-off is that to allow for the amplitude inaccuracies, a greater margin below the limit is needed.

3.1.5 Sources of uncertainty

EMC measurements are inherently less accurate than most other types of measurement. Whereas, say, temperature or voltage measurement can be refined to an accuracy expressed in parts per million, field strength measurements in particular can be in error by 10dB or more. It is always wise to allow a margin of about this magnitude between your measurements and the specification limits, not only to cover measurement uncertainty but also tolerances arising in production. UKAS, the body which accredits UK EMC test houses, issues guidelines on determining measurement uncertainty [173] and it requires test houses to report – or at least estimate – their own uncertainties but for EMC tests it does not define acceptable levels of uncertainty. Amongst other things this document suggests that, if there is no other specification criterion, guidance or code of practice, test houses express their results in one of four ways, as shown in Table 3.3.

Cases B and C in the table, whilst being metrologically sound, are clearly not helpful to manufacturers who want a simple statement of pass or fail. However, CISPR have circulated a draft document on accounting for measurement uncertainty [154] which prescribes that for emissions tests the measurement uncertainty should be taken into account in determining compliance. But it goes on to give a total uncertainty figure U_{cispr} for each of the principal emissions tests (Table 3.4). If the test house's declared uncertainty is less than or equal to this value, then direct comparison with the limit is acceptable (cases A and D with an effective measurement uncertainty of zero). If the

Table 3.3 Statements of compliance with specification

Case A	Case B	Case C	Case D
			 upper limit
The product complies	The measured result is below the specification limit by a margin less than the measurement uncertainty; it is not therefore possible to determine compliance at a level of confidence of 95%. However, the measured result indicates a higher probability that the product tested complies with the specification limit.	The measured result is above the specification limit by a margin less than the measurement uncertainty; it is not therefore possible to determine compliance at a level of confidence of 95%. However, the measured result indicates a higher probability that the product tested does not comply with the specification limit.	The product does not comply

uncertainty is greater, then the test result must be increased by the excess before comparison with the limit – effectively penalizing manufacturers who use test houses with large uncertainties.

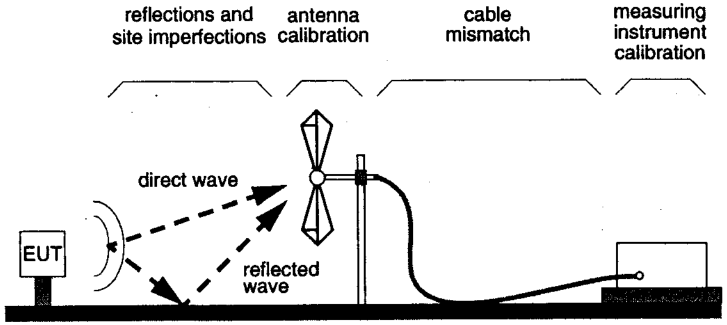


Figure 3.17 Sources of error in radiated emissions tests

Table 3.4 CISPR uncertainties according to CISPR/A/256/CD

Measurement	U_{cispr}
Conducted disturbance, mains port, 9–150kHz	4.0dB
Conducted disturbance, mains port, 150kHz–30MHz	3.6dB
Disturbance power, 30–300MHz	4.5dB
Radiated disturbance, 30–300MHz	5.1dB

This section discusses how measurement uncertainties arise (Figure 3.17).

3.1.5.1 *Instrument and cable errors*

Modern self-calibrating test equipment can hold the uncertainty of measurement at the instrument input to within ±1dB. To fully account for the receiver errors, its pulse amplitude response, variation with pulse repetition rate, sine-wave voltage accuracy, noise floor and reading resolution should all be considered. Input attenuator, frequency response, filter bandwidth and reference level parameters all drift with temperature and time and can account for a cumulative error of up to 5dB at the input even of high quality instrumentation. To overcome this a calibrating function is provided. When this is invoked, absolute errors, switching errors and linearity are measured using an in-built calibration generator and a calibration factor is computed which then corrects the measured and displayed levels. It is left up to the operator when to select calibration, and this should normally be done before each measurement sweep. Do not invoke it until the instrument has warmed up – typically 30 minutes to an hour – or calibration will be performed on a "moving target". A good habit is to switch the instruments on first thing in the morning and calibrate them just before use.

The attenuation introduced by the cable to the input of the measuring instrument can be characterized over frequency and for good quality cable is constant and low. Uncertainty from this source should be accounted for but is normally not a major contributor. The connector can introduce unexpected frequency dependent losses; the conventional BNC connector is particularly poor in this respect and you should perform all measurements whose accuracy is critical with cables terminated in N-type connectors, properly tightened (and not cross-threaded) against the mating socket.

Mismatch error

When the cable impedance, nominally 50Ω, is coupled to an impedance that is other than a resistive 50Ω at either end it is said to be mismatched. A mismatched termination will result in reflected signals and the creation of standing waves on the cable. Both the measuring instrument input and the antenna will suffer from a degree of mismatch which varies with frequency and is specified as a Voltage Standing Wave Ratio (VSWR). Appendix C (section C.2) discusses VSWR further. If either the source or the load end of the cable is perfectly matched then no errors are introduced, but otherwise a mismatch error is created which is given by:

$$\text{error} = 20\log_{10}(1 \pm \Gamma_L \cdot \Gamma_S) \tag{3.6}$$

where Γ_L and Γ_S are the source and load reflection coefficients

As an example, an input VSWR of 1.5:1 and an antenna VSWR of 4:1 gives a mismatch error of ±1dB. The biconical in particular can have a VSWR exceeding 15:1 at the extreme low frequency end of its range. For most measurements, mismatch errors are masked by other sources of error. When the best accuracy is needed, minimize the mismatch error by including an attenuator pad of 6 or 10dB in series with one or both ends of the cable, at the expense of measurement sensitivity.

3.1.5.2 *Conducted test factors*

Mains conducted emission tests use a LISN/AMN as described in section 3.1.2.3. Uncertainties attributed to this method include the quality of grounding of the LISN to the ground plane, the variations in distances around the EUT, and inaccuracies in the LISN parameters. Although a LISN theoretically has an attenuation of nearly 0dB across most of the frequency range, in practice this can't be assumed and you should include a voltage attenuation factor derived from the network's calibration certificate. In some designs, the attenuation at extremes of the frequency range can reach several dB. Mismatch errors, and errors in the impedance specification, should also be considered.

3.1.5.3 Antenna calibration

One method of calibrating an antenna is against a reference standard antenna, normally a tuned dipole on an open area test site [25]. This introduces its own uncertainty, due to the imperfections both of the test site and of the standard antenna – ±0.5dB is now achievable – into the values of the antenna factors that are offered as calibration data. An alternative method of calibration known as the Standard Site Method [117] uses three antennas and eliminates errors due to the standard antenna, but still depends on a high quality site.

Further, the physical conditions of each measurement, particularly the proximity of conductors such as the antenna cable, can affect the antenna calibration. These factors are worst at the low frequency end of the biconical's range, and are exaggerated by antennas that exhibit poor balance. When the antenna is in vertical polarization and close to the ground plane, any antenna imbalance interacts with the cable and distorts its response. Also, proximity to the ground plane in horizontal polarization can affect the antenna's source impedance and hence its antenna factor. Varying the antenna height above the ground plane can introduce a height-related uncertainty in antenna calibration of up to 2dB [89].

These problems are less for the log periodic at UHF because nearby objects are normally out of the antenna's near field and do not affect its performance, and the directivity of the log periodic reduces the amplitude of off-axis signals. On the other hand the smaller wavelengths mean that minor physical damage, such as a bent element, has a proportionally greater effect. Also the phase centre (the location of the active part of the antenna) changes with frequency, introducing a distance error, and since at the extreme of the height scan the EUT is not on the boresight of the antenna its directivity introduces another error. Both of these effects are greatest at 3m distance. An overall uncertainty of ±4dB to allow for antenna-related variations is not unreasonable, although this can be improved with care.

The difficulties involved in defining an acceptable and universal calibration method for antennas that will be used for emissions testing have led to the formation of a CISPR/A working group to draft such a method. It is proposed to standardize on a free-space antenna factor determined by a fixed-height 3-antenna method on a validated calibration test site. Details of the proposal can be found in [69].

3.1.5.4 Reflections and site imperfections

The antenna measures not only the direct signal from the EUT but also any signals that are reflected from conducting objects such as the ground plane and the antenna cable. The field vectors from each of these contributions add at the antenna. This can result in an enhancement approaching +6dB or a null which could exceed –20dB. It is for this reason that the height scan referred to in section 3.1.4.3 is carried out; reflections from the ground plane cannot be avoided but nulls can be eliminated by varying the relative distances of the direct and reflected paths. Other objects further away than the defined CISPR ellipse will also add their reflection contribution, which will normally be small (typically less than 1dB) because of their distance and presumed low reflectivity.

This contribution may become significant if the objects are mobile, for instance people and cars, or if the reflectivity varies, for example trees or building surfaces after a fall of rain. They are also more significant with vertical polarization, since the majority of reflecting objects are predominantly vertically polarized.

Antenna cable

With a poorly balanced antenna, the antenna cable is a primary source of error [88],[89]. By its nature it is a reflector of variable and relatively uncontrolled geometry close to the antenna. There is also a problem caused by secondary reception of common mode currents flowing on the sheath of the cable. Both of these factors are worse with vertical polarization, since the cable invariably hangs down behind the antenna in the vertical plane. They can both be minimized by choking the outside of the cable with ferrite sleeve suppressors spaced along it, or by using ferrite loaded RF cable (section 8.1.6.3). If this is not done, measurement errors of up to 5dB can be experienced due to cable movement with vertical polarization. However, modern antennas with good balance, which is related to balun design, will minimize this problem.

3.1.5.5 Human and environmental factors

The test engineer

It should be clear from section 3.1.4 that there are many ways to arrange even the simplest EUT to make a set of emissions measurements. Equally, there are many ways in which the measurement equipment can be operated and its results interpreted, even to perform measurements to a well defined standard – and not all standards are well defined. In addition, the quantity being measured is either an RF voltage or an electromagnetic field strength, both of which are unstable and consist of complex waveforms varying erratically in amplitude and time. Although software can be written to automate some aspects of the measurement process, still there is a major burden on the experience and capabilities of the person actually doing the tests.

Some work has been reported which assesses the uncertainty associated with the actual engineer performing radiated emission measurements [113]. Each of four engineers was asked to evaluate the emissions from a desk-top computer consisting of a processor, VDU and keyboard. This remained constant although its disposition was left up to the engineer. The resultant spread of measurements at various frequencies and for both horizontal and vertical polarization was between 2 and 15dB – which does not generate confidence in their validity! Two areas were recognized as causing this spread, namely differences in EUT and cable configurations, and different exercising methods.

The tests were repeated using the same EUT, test site and test equipment but with the EUT arrangement now specified and with a fixed antenna height. The spread was reduced to between 2 and 9dB, still an unacceptably large range. Further sources of variance were that maximum emissions were found at different EUT orientations, and the exercising routines still had minor differences. The selected measurement time (section 3.1.1.6) can also have an effect on the reading, as can ancillary settings on the test receiver and the orientation of the measurement antenna.

Ambients

The major uncertainty introduced into EMC emissions measurements by the external environment, apart from those discussed above, is due to ambient signals. These are signals from other transmitters or unintentional emitters such as industrial machinery, which mask the signals emitted by the EUT. On an OATS they cannot be avoided, except by initially choosing a site which is far from such sources. In a densely populated country such as the UK this is wishful thinking. A "green-field" site away from industrial areas, apart from access problems, almost invariably falls foul of planning constraints, which do not permit the development of such sites – even if they can be found – for industrial purposes.

Another Catch-22 situation arises with regard to broadcast signals. It is important to be able to measure EUT emissions within the Band II FM and Bands IV and V TV broadcast bands since these are the very services that the emission standards are meant to protect. But the *raison d'être* of the broadcasting authorities is to ensure adequate field strengths for radio reception throughout the country. The BBC publish their requirements for the minimum field strength in each band that is deemed to provide coverage [1] and these are summarized in Table 3.5. In each case, these are (naturally) significantly higher than the limit levels which an EUT is required to meet. In other words, assuming country-wide broadcast coverage is a fact, *nowhere* will it be possible to measure EUT emissions on an OATS at all frequencies throughout the broadcast bands because these emissions will be masked by the broadcast signals themselves.

Service	Frequency range	Minimum acceptable field strength
Long wave	148.5–283.5kHz	5mV/m
Medium wave	526.5–1606.5kHz	2mV/m
VHF/FM band II	87.5–108MHz	54dBμV/m
TV band IV	471.25–581.25MHz	64dBμV/m
TV band V	615.25–853.25MHz	70dBμV/m

Source: [1]

Table 3.5 Minimum broadcast field strengths in the UK

The only way around the problem of ambients is to perform the tests inside a screened chamber, which is straightforward for conducted measurements but for radiated measurements is subject to severe inaccuracies introduced by reflections from the wall of the chamber as discussed earlier. An anechoic chamber will reduce these inaccuracies and requirements for anechoic chambers are being introduced into the standards, as mentioned in section 3.1.3.3, but a proper anechoic chamber will be prohibitively expensive for most companies. The method of pre-scan in a non-anechoic chamber discussed in section 3.1.4.3 goes some way towards dealing with the problem, but doesn't solve the basic difficulty that a signal that is underneath an ambient on an OATS cannot be accurately measured.

Emissions standards such as EN 55022 recognize the problem of ambient signals and in general require that the test site ambients should not exceed the limits. When they do, the standard allows testing at a closer distance such that the limit level is increased by the ratio of the specified distance to the actual distance. This is usually only practical in areas of low signal strength where the ambients are only a few dB above the limits. Some relief can be gained by orienting the site so that the local transmitters are at right angles to the test range, taking advantage of the antennas' directional response at least with horizontal polarization.

When you are doing diagnostic tests the problem of continuous ambients is less severe because even if they mask some of the emissions, you will know where they are and can tag them on the spectrum display. Some analysis software performs this task automatically. Even so, the presence of a "forest" of signals on a spectrum plot confuses the issue and can be unnerving to the uninitiated. Transient ambients, such as from portable radios or occasional broadband sources, are more troublesome because it is harder to separate them unambiguously from the EUT emissions. Sometimes you will need to perform more than one measurement sweep in order to eliminate all the ambients from the analysis.

Ambient discrimination by bandwidth and detector

A proposed amendment to CISPR 16-2 [155] attempts to address the problem of ambients from another angle. This distinguishes between broadband and narrowband EUT emissions in the presence of broadband or narrowband ambient noise. If both the ambient noise and the EUT emissions are narrowband, a suitably narrow measurement bandwidth is recommended, with use of the peak detector. The measurement bandwidth should not be so low as to suppress the modulation spectra of the EUT emission. If the EUT noise is broadband, the measurement cannot be made directly underneath a narrowband ambient but can be taken either side, and the expected actual level interpolated.

When the ambient disturbance is broadband, bandwidth discrimination is not possible, but a narrowband EUT emission may be extracted by using the average detector with a narrower measuring bandwidth that maximizes the EUT disturbance-to-ambient ratio. The average detector should reduce the broadband level without affecting the desired EUT narrowband signal, as long as the EUT signal is not severely amplitude or pulse modulated; if it is, some error will result.

Broadband EUT disturbances in the presence of broadband ambients cannot be directly measured, although if their levels are similar (say, within 10dB) it is possible to estimate the EUT emission through superposition, using the peak detector.

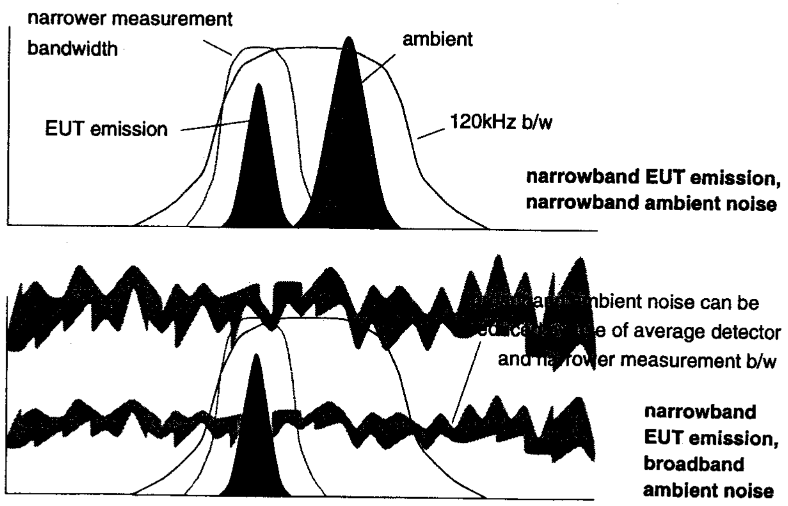


Figure 3.18 Ambient discrimination on the basis of bandwidth

Weather

The other environmental factor that affects open area emissions testing, particularly in Northern European climates, is the weather. Some weatherproof but RF-transparent structure is needed to cover the EUT to allow testing to continue in bad weather. The structure can cover the EUT alone, for minimal cost, or can cover the entire test range. Fibreglass and plastics are favourite materials. Wood is not preferred, because the reflection coefficient of some grades of wood is surprisingly high [89]. You may need to make allowance for the increased reflectivity of wet surfaces during and after precipitation.

3.2 Mains harmonic and flicker emission

Harmonic components of the AC supply input current to an item of equipment arise from non-linearities of the load over a single cycle of the input voltage. The EMC Directive includes requirements for measuring harmonic emissions as embodied in IEC 61000-3-2 (EN 61000-3-2), which covers all electrical and electronic equipment with an input current up to 16A per phase and supersedes the earlier IEC 555-2. The generation and control of mains harmonics are discussed further in section 5.4.

Although the harmonic frequency range under consideration extends only up to 2kHz (the 40th harmonic of 50Hz), and therefore does not by any stretch of the imagination need to employ RF measurement techniques, there are many aspects of the measurement which are not entirely obvious and should be considered further. In the late 1990s the harmonics standard came under withering attack from several directions. There are three main interested parties: the supply authorities, who are keenly interested in preserving their networks from distortion; the manufacturers, who are equally keen to avoid expensive penalties resulting from harmonic limitation on their power supplies; and the test houses, who are keen to have a standard which will enable them to test accurately, completely and repeatably. The anomalies and gaps in the original edition of the standard allowed each of these parties ample opportunity for, to put it kindly, combative discussion. Several working groups later, some kind of resolution has worked itself out and, at the time of writing, testing may be carried out to the original 1995 document or to that document with a CENELEC common modification, amendment A14, for equipment placed on the market in Europe. The nature of the common modification is drastic, and is discussed in the following sections.

3.2.1 Equipment

The original IEC 61000-3-2 defines the method of measurement and each item of test equipment is specified. Figure 3.19 shows the basic measurement circuit, and its components are:

- an AC source;
- a current transducer;
- a wave analyser.

3.2.1.1 AC supply source

To make a harmonic measurement with the required accuracy you need a source with very low distortion, high voltage stability and settability and low impedance. In general the public mains supply will not be able to meet these requirements. IEC 61000-3-2 requires that the voltage must be stable to within ±2% of the selected level during the measurement, and the frequency within 0.5% of nominal. The harmonic distortion must be less than 0.9% at third harmonic, 0.4% at 5th, 0.3% at 7th, 0.2% at 9th and 0.1% at all others. The measuring impedance Z_M should create a voltage drop of less than 0.15V peak. The source impedance is not specified, but the total set-up is not allowed an error at any harmonic frequency of more than 5% of the permissible limits.

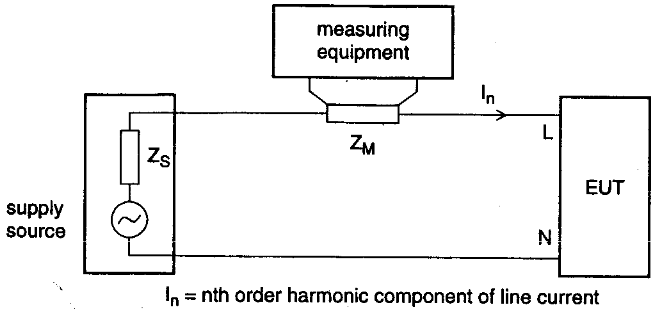


Figure 3.19 Mains harmonic emission measurement circuit

To meet these requirements typical test equipment uses a power amplifier driven by a 50Hz sine-wave oscillator, with negative feedback to maintain the low output impedance. The output may be fed through a power transformer for voltage step-up purposes, but the transformer reactance must not be allowed to affect the output impedance at the higher harmonic frequencies. Variacs are not recommended for the same reason. The amplifier will need to be large to cope with the full range of loads – the standard covers equipment rated up to 16A, which is a power level of 3680W at 230V, although for in-house use your product range may not approach this level and a smaller amplifier would suffice. For high power and highly distorting loads the "model" AC source becomes quite difficult to realize. Including the maximum allowable transitory harmonics for class B equipment, legitimate peak currents can be around 40A, although some equipment can substantially exceed this, and the source should be able to deliver this power level without distortion. If the measured harmonics are well over or under the limit then voltage distortion is a minor consideration, but it becomes important for borderline cases.

3.2.1.2 Current transducer

The current transducer couples the harmonic current I_n to the measuring instrument, and it can be either a current shunt or a current transformer. In both cases, the transducer impedance Z_M is added to the source output impedance and the two together must cause negligible variation in the load current harmonic structure. A shunt of less than 0.1Ω impedance and a time constant less than 10μs is acceptable, but does not provide any isolation from the measuring circuit. A current transformer does offer isolation, but will need to be calibrated at each harmonic frequency and may suffer from saturation when the measured current includes a DC component.

3.2.1.3 Wave analyser

The wave analyser measures the amplitude of each harmonic component I_n for n = 2 to 40. According to the original standard it can be either a frequency domain type, using selective filters or a spectrum analyser, or a time domain type using digital computation to derive the discrete Fourier transform (DFT). The error in measuring a constant value must be less than 5% of the permissible limit. IEC 61000-3-2 defines the requirements for time domain instrumentation rather differently to those for the frequency domain type. A14 proposes to delete the requirements in this standard and redirect them instead to IEC 61000-4-7, which is a companion standard defining the reference instrument for harmonics measurement. The intention of this standard is to outlaw frequency domain instruments and only to allow DFT types. In practice, all commercial harmonic analysers are of this sort.

When the harmonic components fluctuate while the measurement is being made, the response at the indicating output should be that of a first order low pass filter with a time constant of 1.5 seconds. IEC 61000-4-7 includes more specific details of the smoothing algorithm which performs this function on the discrete data values.

3.2.2 Test conditions

Special test conditions for some types of equipment are given in IEC 61000-3-2, including TV receivers, audio amplifiers, VCRs, lighting equipment and various household appliances. Independent lamp dimmers and other phase-control devices should be set for a firing angle of 90°. Information technology equipment is tested with the equipment configured to its rated current.

The original standard required that other equipment should be operated by setting its user controls or program mode to give the maximum harmonic amplitude for each successive harmonic component in turn. If followed to the letter, this procedure would require an excessive amount of time and effort for a complete test. A14 replaces this with the altogether more reasonable requirement to conduct the test in the mode *expected* to produce the maximum total harmonic current under normal operating conditions, which simply regularizes a situation which prevails at most test laboratories anyway.

3.2.3 Equipment classification and limits

The original standard established four classes of equipment:

- Class B for portable tools;
- Class C for lighting equipment, including dimmers;
- Class D for equipment having the "special wave shape" of input current, and an active input power less than or equal to 600W;
- Class A for everything else, and particularly balanced three-phase equipment.

The "special wave shape" is defined by an envelope as shown in Figure 3.20 and is effectively a means of distinguishing electronic power supply circuits, which normally draw their current for less than a third of the supply half-cycle. The harmonic limits are quoted as absolute values for Class A, whatever the input power, and as a set of sliding values proportional to input power for Class D. Figure 3.21 shows these limits graphically. For equipment with an input rating greater than 600W the Class A limits, being fixed, become proportionately more severe as the input power increases.

3.2.3.1 Class D membership

The definition of Class D has caused more problems for the standard than virtually any

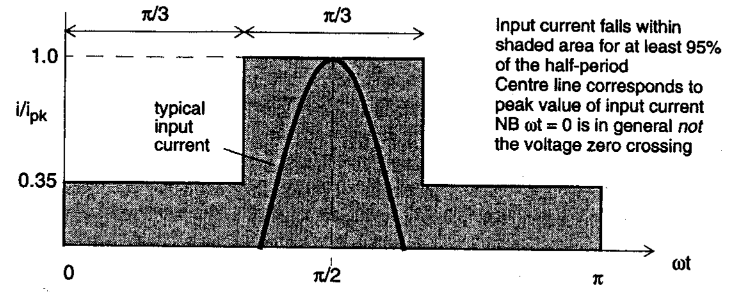


Figure 3.20 The special wave shape for IEC 61000-3-2 Class D

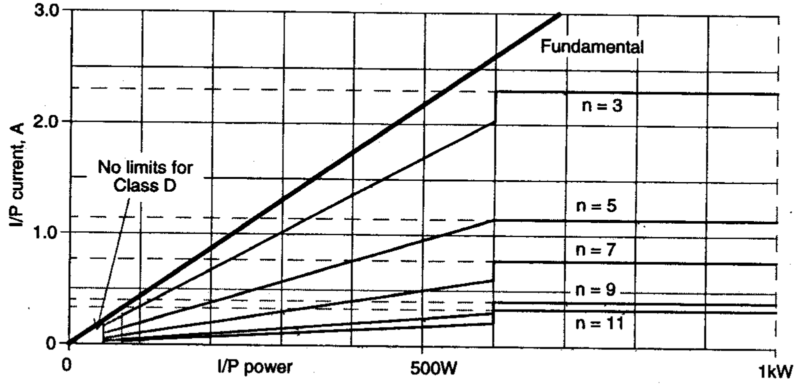


Figure 3.21 Class A and Class D harmonic current limits for n ≤ 11

other aspect. If the EUT is suspected of being Class D, the test equipment must first check the input waveform to confirm whether or not it falls inside the Class D definition, and then decide on its active power, before the limits can be applied. This leads to a fundamental difficulty in deciding what current value to use, especially if the current and/or its harmonic content is fluctuating. This difficulty is decisively addressed in the CENELEC common modification, A14.

The working groups could not agree on an acceptable general method for applying the Class D envelope of Figure 3.20. Since Class D is intended to constrain particular types of equipment which are considered to have the greatest impact on the power network, the new A14 has turned the definition on its head by specifying particular types of product to which the Class D limits must apply. These are:

- personal computers and monitors
- TV receivers

with a *specified* power (see next paragraph) less than or equal to 600W. All other equipment that is not classes B or C is to be regarded as class A. The class D envelope is effectively removed from the discussion, as is the contentious transition of the lower limit from 75W to 50W, which is now postponed indefinitely.

Power basis for class D limits

The class D limits are given in mA per watt, and the basis for the power used for defining the limit value has been hard to pin down. In the new document, *average* emissions are to be compared to limits based upon the *maximum* of the measured values of power in each observation time window over the entire duration of the test. The harmonic currents and active input power are measured under the same test conditions but need not be measured simultaneously.

In order not to arrive at a power at which limits change abruptly (for example, 600W or 75W), the manufacturer is allowed to specify a power level for establishing the limits, but this specified value must be within ±10% of the actual measured value. In other words, if the maximum measured power is close to the class D cut-off point, the manufacturer has the option of specifying a power level within 10% of this value and therefore (potentially) of taking the apparatus outside the level at which severe limits apply. The purpose of this rather tortuous approach is to prevent the situation in which equipment operating near the boundary and tested under slightly different conditions might be subject to widely differing limits. The specified power for this purpose is not necessarily the same as the manufacturer's "rated" power for safety or functional purposes.

3.2.3.2 *Professional equipment*

A significant relaxation, present in the original standard, is that no limits apply (more correctly, limits are "under consideration") for professional equipment with a power of more than 1kW. Professional equipment is defined as "equipment for use in trades, professions or industries and which is not intended for sale to the general public. The designation shall be specified by the manufacturer". A14 relaxes this slightly more, by allowing the connection to "certain types of low voltage supplies" of non-compliant professional equipment, if the instruction manual contains a requirement to ask the supply authority for permission to connect.

3.2.4 Flicker

A companion requirement to IEC 61000-3-2 on harmonics is that provided by IEC 61000-3-3 on flicker. Flicker is defined as the "impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time". The problem with respect to EMC is that varying loads on a power supply network can result in voltage changes at common points of connection which are of sufficient amplitude to induce flicker in connected luminaires. The affected luminaires may have nothing to do with the load equipment that is causing the variations. Therefore, IEC 61000-3-3 – which applies to the same wide range of apparatus as does IEC 61000-3-2 – regulates the degree to which a given item of equipment can cause perceptible flicker. It does so by limiting the voltage variations that are generated across a reference load, and it places limits on three factors:

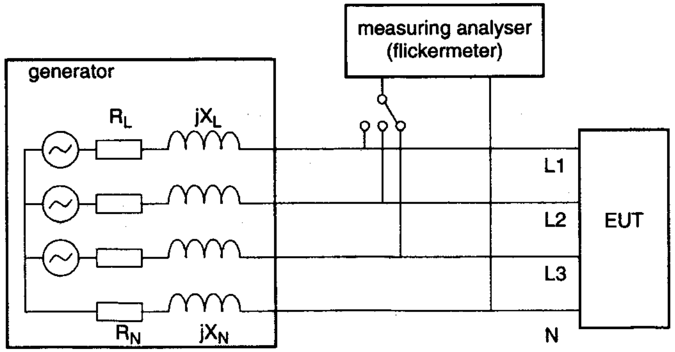
- the relative voltage change
- the short-term flicker value P_{st}
- the long-term flicker value P_{lt}

These limits do not apply to emergency switching or interruptions, and the P_{st} and P_{lt} limits do not apply to manual switching or voltage changes occurring less frequently than once per hour. The voltage change limits do apply to such occasional events, however, and this effectively places a limit on allowable switch-on inrush current for any apparatus. It has not been clear that this particular effect of the flicker standard was intended by its authoring committee. The standard also states that "tests shall not be made on equipment which is unlikely to produce significant voltage fluctuations or flicker", and since the restriction on inrush current has up till now not been made explicit, this statement has been widely interpreted as meaning that most typical electronic apparatus whose steady-state load current changes only slightly can be excused testing. As a result, few manufacturers of equipment with electronic power supplies – many of which will exceed the voltage change limit on switch on – are aware that they are in breach of the standard. An amendment to the standard that is undergoing voting at the time of writing does make it slightly clearer that inrush current limitation is intended, and does in fact change the limits in this context, but it will be some time before manufacturers really become aware of this obligation.

Equipment that typically *will* produce flicker includes any device which switches varying loads during its operating cycle; many household appliances fall into this category, and particular offenders are products which have heaters whose temperatures are controlled by burst firing, i.e. power is provided to the heater for a few cycles of the mains supply at a time, and the on/off ratio of the bursts controls the temperature. If the heating load is at all substantial this kind of equipment easily falls foul of the flicker limits.

3.2.4.1 *Measuring instrumentation*

The basic instrumentation used to measure flicker has essentially the same block diagram and characteristics as the harmonics analyser shown in Figure 3.19, and for this reason harmonics and flicker analysers are often packaged together. The difference can be seen in Figure 3.22, which gives the circuit for a three-phase supply, and which shows that the measured variable is now the voltage across the point of supply rather than the current drawn from it. The source impedance of the supply generator is more carefully defined so that load current changes in the EUT produce a defined voltage change which is then analysed to compare it with the various limits.



$R_N = 0.16\Omega$, $X_N = 0.1\Omega$ at 50Hz
$R_L = 0.24\Omega$, $X_L = 0.15\Omega$ at 50Hz

For a single phase supply the impedances can be lumped together to give $0.4 + j\,0.25\Omega$

Figure 3.22 Flicker measurement circuit

The accuracy of this set-up is required to be such that the relative voltage change can be measured with a total accuracy of better than ±8% of the maximum allowed value. The measurement errors can be distributed between the reference impedance and the analyser as long as the total remains within this limit.

3.2.4.2 *Relative voltage change*

The RMS voltage is evaluated (typically by direct measurement, but it is also possible to calculate it given the active and reactive parts of the current waveform) over successive half-periods (each 10ms) to build up a time dependent view of the voltage changes. The voltages are normalized to the nominal value to give d(t) and two characteristics are derived:

- the relative steady-state voltage change d_c, which is the difference between two adjacent steady-state voltages separated by at least one change (steady state is defined as persisting for at least 1 second);
- the maximum relative voltage change d_{max}, which is the difference between maximum and minimum values of the voltage change characteristics.

The standard requires that d_c does not exceed 3% and d_{max} does not exceed 4%, and that the value of d(t) during a voltage change does not exceed 3% for more than 200ms. These values are multiplied by 1.33 for manual switching or events occurring less often than once an hour.

3.2.4.3 *Short-term flicker*

Voltage changes by themselves do not adequately characterize the flicker perceptibility. The human eye-brain combination varies in sensitivity to flicker as the flicker frequency changes. To account for this, the voltage changes must themselves be processed over a period of a few minutes to take account of the frequency of changes, the shape of the voltage change characteristic, and the cumulative irritating effect of repeated changes. Whilst in some special cases this can be done analytically, and in one case by direct comparison to a graph (see below), in general the voltage changes are passed to a "flickermeter", whose specifications are given in a separate standard, IEC 868 (in the process of being replaced by IEC 61000-4-15). The flickermeter applies a weighting to the voltage change characteristic depending on its waveform, and is the reference method.

The output of the flickermeter gives the short-term flicker indicator P_{st}. P_{st} is observed over a period of 10 minutes, to include that part of the operating cycle in which the EUT produces the least favourable sequence of voltage changes. P_{st} is not allowed to exceed a value of 1.

For the special case of rectangular voltage changes of the same amplitude separated by equal time intervals, the P_{st} value can be derived from a graph published in the standard and reproduced in Figure 3.23. This shows the value of d(t) versus frequency which gives a P_{st} of 1, and illustrates the maximum physiological sensitivity at around 8Hz or 1000 changes per minute.

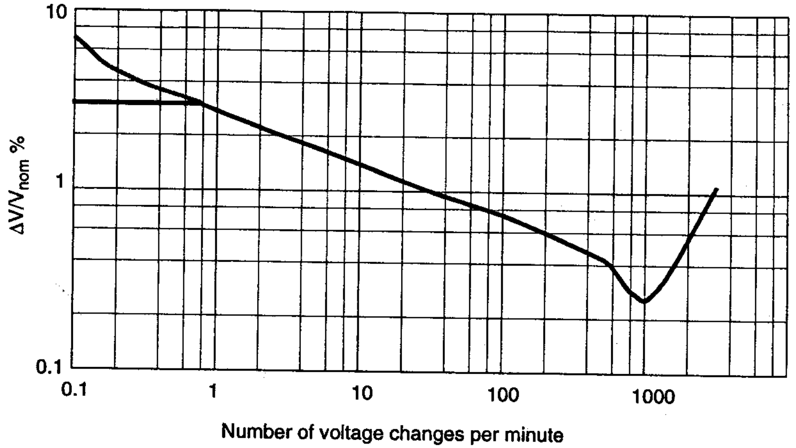


Figure 3.23 Curve for $P_{st} = 1$ for rectangular equidistant voltage changes

3.2.4.4 *Long-term flicker*

In some cases flicker must be evaluated over a longer period, using successive values of P_{st} to give P_{lt}. The P_{st} values are averaged on a root-sum-of cubes basis:

$$P_{lt} = \sqrt[3]{\left(\sum_{1}^{N} P_{st}^3\right) / 12}$$

The standard suggests that this is necessary for equipment which is normally operated for more than 30 minutes at a time. The observation period is 2 hours, that is, 12 successive P_{st} values are recorded. P_{lt} is not allowed to exceed a value of 0.65. The justification for this, in effect, is that whereas the average human can cope with a P_{st} value of up to 1 for ten minutes, if the flicker continues for a longer time, the threshold of irritability lowers.

Annex A of the standard gives operating conditions and application of the limits for certain types of equipment, particularly white goods and consumer products. In several cases, P_{lt} does not need to be evaluated.