Emissions measurements on switch-mode power supplies

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Introduction

This article discusses the characterization of the RF emissions of switch-mode power supply units (SMPSUs) and similar products. Other than compliance testing, there are two main application areas in this field; these are diagnosing the emissions from a new design at the prototype stage, and assuring production quality through comparing emissions with an established “golden product” or transfer standard.

In most electronics companies, the measuring instrument used for this purpose is the spectrum analyser. Modern analysers have signal processing features which are well suited to the above tasks, in particular the facility for trace comparison. Test receivers on their own do not give this feature, though it can normally be implemented in their control software. The discussion in this article applies to any kind of spectrum analyser measurement.

1.1. Conducted emission measurements

Measurements of the RF emissions generated by electronic apparatus are nearly always prompted by the need to conform to harmonized standards limiting these emissions. These standards are in turn designed to preserve the useability of the radio spectrum for its legitimate users – broadcasting, communications, navigation and so forth. A list of the most common commercial standards that apply to users and manufacturers of SMPSUs is given in Table 1.

Standard	Scope
CISPR11/EN55011	Industrial, Scientific & Medical
CISPR13/EN55013	Broadcast receivers
CISPR14/EN55014	Household appliances
CISPR22/EN55022	Information Technology equpt
FCC Rules part 15	Unintentional radiators
EN61000-6-3,4	Generic

Table 1 Relevant standards

Those standards whose numbers begin with “EN” have been designated harmonized standards for the purpose of demonstrating compliance with the European EMC Directive. Any electrical or electronic equipment sold within the European Community is subject to this Directive and must comply with one or other of these standards.

The standards all derive to a greater or lesser extent from the publications of CISPR, which is the International Special Committee on Radio Frequency Interference of the IEC. Although different limit values and frequency ranges may be found, the measurement methods are fundamentally the same in all the standards. The mains port of the apparatus is tested in every case, using a 50Ω/50µH artificial mains network or Line Impedance Stabilising Network (LISN), to an upper frequency limit of 30MHz. The general limit values are shown in Figure 1.

SMPSU manufacturers are primarily concerned with the conducted tests up to 30MHz since the harmonics from typical switching frequencies of 50 – 200kHz normally do not exceed this range. Some high performance SMPSUs have harmonic components that extend to higher frequencies and which have to be tested as radiated emissions. This article does not discuss measurements above 30MHz.

1.2. Prototype design checks

It is vital to have an idea of the emissions profile of your new product at the prototype stage, so that the design can be modified as required before it is completed and so that the compliance test is carried out with reasonable confidence in the final result. Compliance testing requires that the equipment under test (EUT) is operated so as to maximize its emissions, and a pre-compliance check will enable you to discover the operating configuration –

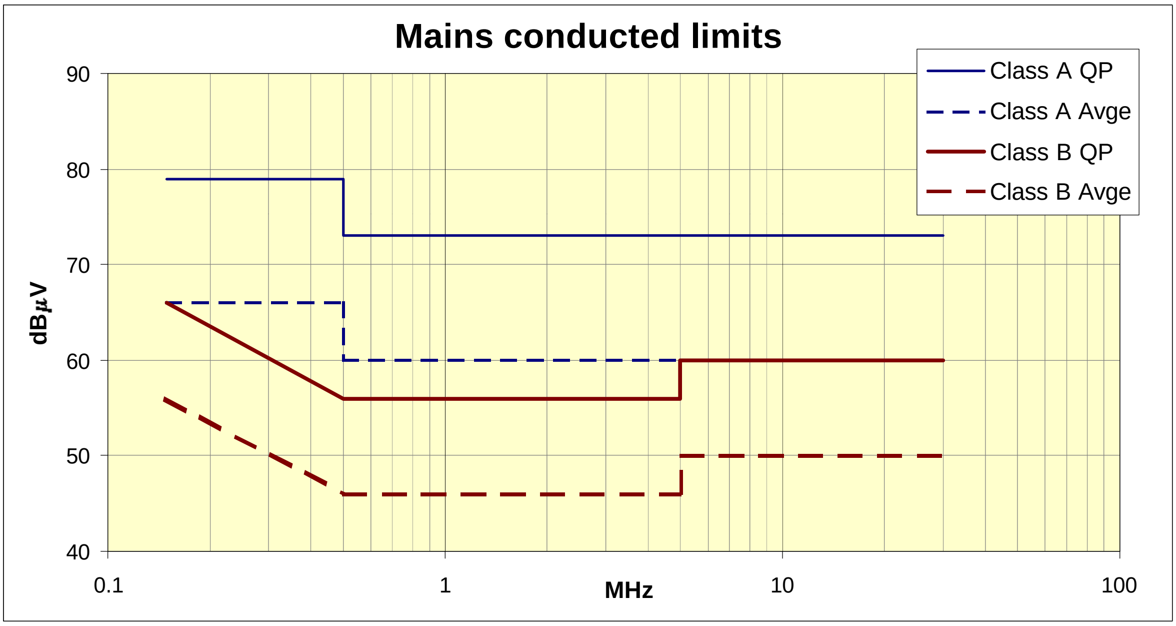

Figure 1 Limit levels for various standards: mains port conducted emissions

type and magnitude of load, input voltage setting, line under test and so on – which does this. Even more important is the ability to make changes to the design and check the results immediately.

In order to do this you need to have a comprehensive yet repeatable test set-up, and to be able to interpret its results correctly.

1.3. Golden product comparison

The European EMC Directive requires manufacturers to take “all measures necessary” to ensure compliance of each manufactured product with the Directive’s essential requirements. Full scale EMC production testing to CISPR standards, covering all the phenomena within the scope of the Directive, is impractical from both a time and cost viewpoint on large samples, especially for products of any complexity. Unfortunately minor changes in a product’s construction can make major differences to its EMC performance. Ignoring re-designs and product variants, a number of factors can affect the emission and immunity profiles:

- engineering design changes
- sourcing of components
- manufacturing process deviations

Clearly a method is needed whereby the critical aspects of EMC performance can be monitored on an ongoing basis without disrupting production and without subjecting each product, or even a sample, to a full suite of EMC tests. Such a method could take its place at the final test stage alongside the functional test procedure. It would need to be as simple as possible and should not assume any detailed knowledge of EMC test methods on the part of the test operator. At the same time it should be sufficiently sensitive to flag any deviations in EMC performance as they occur, so that remedial action can be taken quickly, before possibly non-compliant product is shipped.

This rules out any testing directly to CISPR standards as such testing requires a well specified site, a costly suite of test equipment and considerable expertise on the part of the test engineer. However, the manufacturer must test at least one sample product (he may do this at an external test house) to CISPR standards in order to be able to declare compliance. This sample product can then be used as the basis for comparison of further production units. Provided that the test set-up is repeatable the tests are then used to establish that any changes from the sample are within acceptable margins. The sample can be regarded as the “golden product” for this purpose.

The test set-up

Repeatable results depend on a repeatable and predictable test set-up. This section discusses the test hardware configuration.

2.1. Coupling to the LISN

The Line Impedance Stabilising Network (LISN) performs three functions:

- it couples the signal from the mains port of the EUT to the test instrument;
- it provides a stable, defined RF impedance from each mains line (phase or neutral) to earth;
- it attenuates external RF signals present on the incoming mains supply which could interfere with the measurement.

LISN circuit

CISPR 16-1† defines the LISN's impedance versus frequency and suggests a circuit which can realise this function. The circuit is shown in Figure 2. One of these circuits is inserted in series with each of the live and neutral lines or, in the case of a three phase supply, in series with each of L1, L2 and L3.

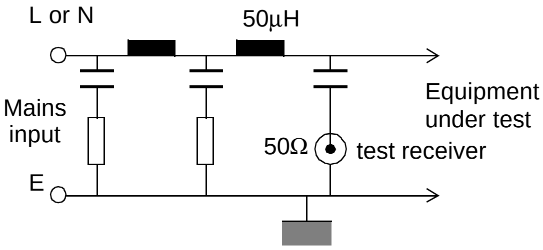

Figure 2 CISPR 16-1 50Ω/50µH LISN circuit

The 50Ω impedance, defined by the input impedance of the test receiver, together with the 50µH inductor determine the impedance presented by the LISN at RF. Careful construction of the LISN can ensure a predictable impedance to beyond 30MHz. The impedance is defined with respect to the **ground terminal** of the LISN. This ground terminal is therefore the reference for the whole test set-up and there must be a low impedance at RF between the components of the test set-up. This can only satisfactorily be achieved with a ground plane, which is discussed in section 2.2.

Safety

The value of the parallel combination of the capacitors in the LISN circuit is around 12µF. For the circuit which is connected in series with the live line, the full supply voltage appears across this capacitance which is connected to earth, and hence a current of around 0.75A will flow in the earth connection. If the LISN's earth connection is not reliably bonded to the safety earth of the incoming mains supply, the case of the LISN and anything connected to it will be live and will present a serious risk of electric shock. Always ensure that the LISN case is properly bonded to the mains safety earth before connecting the mains supply.

Because of the continuous safety earth current a LISN cannot be used directly on a mains supply circuit which is protected by a residual current device (RCD, or earth leakage circuit breaker, ELCB). The continuous earth current will ensure that the circuit breaker stays permanently tripped. If an unprotected supply circuit cannot be found, use a suitably rated isolation transformer between the supply and the LISN as shown in Figure 3.

For those supplies where a LISN would be impractical or unsuitable, CISPR 16-1 suggests the use of a voltage probe incorporating a 1500Ω resistor and blocking capacitor. This does not provide the impedance stabilising or filtering function of a proper LISN but does serve to couple the signal to the test instrument. Because you are making a mains connection directly through to the measuring instrument, safety precautions are even more important with this probe.

Transient protection

Transients from the EUT, especially when switching it on or off, and also transients coupled down the supply mains, may have sufficient energy to destroy the input of the spectrum analyser and therefore it is recommended that you keep an attenuator setting of at least 20dB when the LISN is connected. If you need to make use of the more sensitive ranges, connect a transient limiter between the LISN and the test instrument input. This inserts

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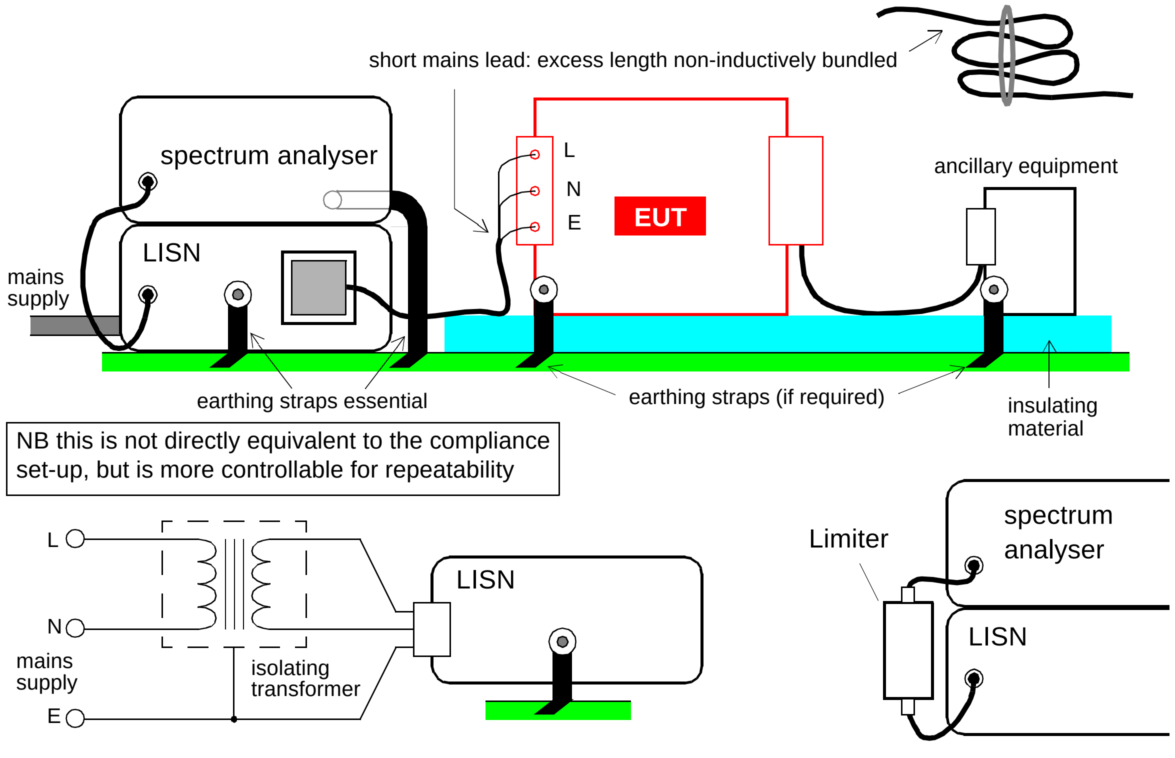
† CISPR 16-1:1999 *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity measuring apparatus*



Using an isolating transformer on an RCD-protected mains supply

Using an external limiter

Figure 3 The test set-up – mains port testing

10dB attenuation in the signal line at the same time as limiting transient signals to safe levels. In fact, since the operator may inadvertently switch out the input attenuation from the analyser’s front panel, habitual use of a limiter at all times is recommended.

2.2. The ground plane

Any voltage measurement must be made against a circuit node which can be referred to as the “zero volt reference”. This is as true at radio frequencies as it is at DC or low frequencies. Providing such a zero volt reference is more critical at RF because the impedance of even short lengths of wire becomes significant, so that the voltage at one end of the wire differs from that at the other. At 30MHz, two pieces of equipment connected together by more than a few inches of wire cannot be said to be at the same potential.

For this reason the zero volt reference for RF measurements must be provided by a **ground plane**. The ground plane is to a first order non-inductive and its impedance at RF is orders of magnitude less than that of a wire of equivalent length, being determined only by the surface conductivity of the material and by its skin depth. The test instrument and the LISN should be bonded to this ground plane by short, wide straps of copper braid or tape, connected to the case terminal of each. Whether or not you also bond the EUT to it depends on whether the EUT has a dedicated earth terminal, but the chosen method must be consistently maintained during testing.

Ground plane characteristics

The ground plane material can be copper, aluminium or steel. Aluminium is the best compromise between conductivity, cost and ease of handling, but the other materials are perfectly acceptable if they are available. Thick material is not necessary for RF purposes since the skin effect tends to confine circulating currents to within a fraction of a millimetre of the surface, and a bench clad with 0.25mm or thicker copper or aluminium sheet is adequate.

The size of the ground plane should be large enough to encompass the test equipment, the EUT, its interconnecting cables and any ancillary equipment which is connected for test purposes (the presence of such ancillary equipment, such as loads on the power outputs, may well modify the RF coupling characteristics). A border of at least 10cm around the equipment should be provided. Typically for small EUTs you can use a conductively clad benchtop; for larger items a covered floor area will be needed. The ground plane may be

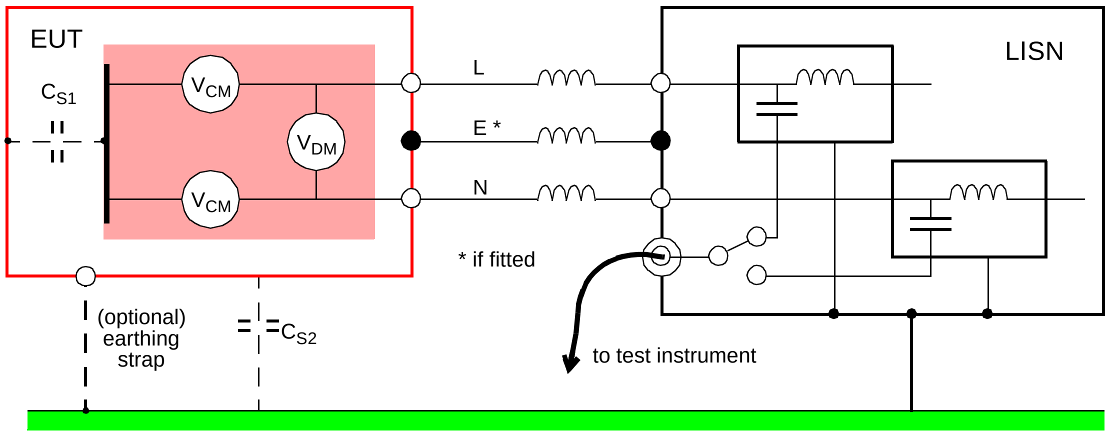


Figure 4 Equivalent circuit for conducted emissions

extended vertically if necessary provided that electrical continuity is maintained along the seam.

2.3. The equipment under test

The equivalent circuit for interference emissions conducted along the mains lead is shown in Figure 4. Noise sources V_{CM} generate common mode noise (between L/N and E) and V_{DM} generates differential mode noise (between L and N). The LISN connection measures noise between either phase and earth, thus it sees a mixture of common mode and differential mode voltages.

A critical component in the coupling path is the stray capacitance between the EUT and the ground plane. If the case is non-conductive then C_S exists directly between the internal circuits and the ground plane; otherwise, C_S has two components, C_{S1} from the internal circuits to the case and C_{S2} from the case to the ground plane.

Connecting the case to the ground plane via the mains lead’s green-and-yellow earth wire modifies but does not eliminate the capacitive coupling path. In fact a resonance is set up between C_S and the mains lead inductance which may amplify the coupling at certain frequencies. C_S may be bypassed by strapping the case directly to the ground plane with a short braid or tape as shown in Figure 3. Except for large values of C_S or large EUTs, the resonance introduced by this earth connection should be above the 30MHz range. Because of the unpredictable effect of resonances, making an earth connection in this way could either increase or decrease the measured emissions, depending on the quality of screening of the case.

For a repeatable measurement it is essential to control C_S. If the case is intended to be separately earthed then it is best to do this as shown in the test set-up with an earth strap. If not, or if the case is insulating, then the EUT must be positioned a fixed distance from the ground plane, and at a fixed orientation to it. This can be achieved with a block of dielectric insulating material (e.g. plastic foam) as in Figure 3. The thickness of the block is unimportant provided that it stays constant; 10cm is a convenient dimension for table top apparatus, or a thin insulating sheet can be used for floor standing equipment. The compliance test requires 40cm distance through air, but does not control the orientation explicitly.

Connecting cables

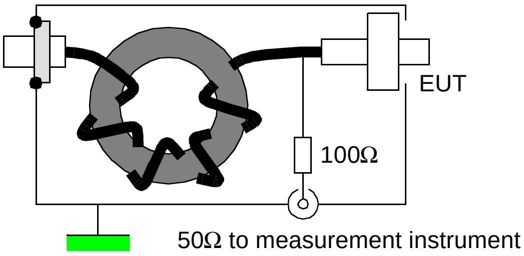
For the same reason the inductance of the mains lead, and its stray capacitance to the ground plane, must also be regularized. The cable should be as short as practicable. If excess length is unavoidable, bundle it zig-zag fashion to ensure that extra inductance is not created. CISPR standards specify 1m as the default length, but for comparative tests the shortest possible length is preferable.

The cable should be stood off from the ground plane by a fixed distance. A convenient way to do this is to run it along the top of the block of insulating material.

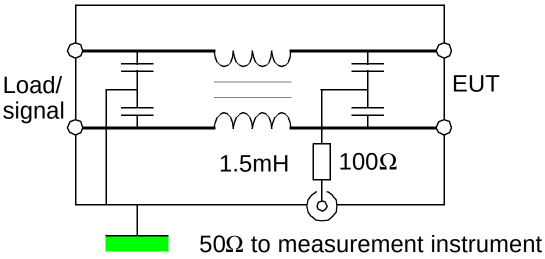
The same considerations apply to other cables that may be connected to the EUT, and their terminations to the ground plane at the far end, as these can affect the coupling even though they are not being directly measured.

2.4. Testing DC output ports

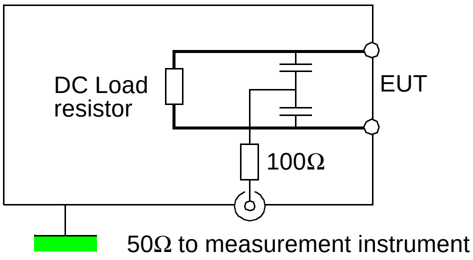
You may want to test other EUT connections for RF emissions as well as the mains port, particularly the DC output. This could be for instance to check the effectiveness of output filters in a golden product comparison, or to determine whether other terminals are contributing to the overall emissions in the prototype tests. To do this you need to stabilize the RF impedance of the connected cables in a similar way to that of the mains port. The measurement that is made is of the common mode voltage that is present on the overall cable bundle, i.e. on all individual wires together, or on the screen if the cable is screened.



for screened cables



for unscreened power cables with remote loads



for local, floating DC loads

Figure 5 ISNs for DC outputs

The conventionally accepted common mode impedance for such tests is 150Ω. This is representative of the average figure demonstrated by typical cables in typical environments. Therefore an impedance stabilising network (ISN) is needed for each cable port that will define a 150Ω common mode RF impedance and at the same time allow coupling of the RF signal out to the test instrument. Suggested circuits for ISNs for different situations are shown in Figure 5. The first two are widely used for conducted immunity tests to IEC 61000-4-6.

All ISNs have a common mode choke that ensures a high impedance beyond the signal pick-off point, unless the load is floating and has no significant stray capacitance to ground. The 150Ω impedance is then determined by the 50Ω input of the test instrument in series with a 100Ω resistor and a low frequency/DC blocking capacitor. This arrangement attenuates the measured signal by 9.5dB.

Screened cables are easily handled by winding the entire cable on a suitable ferrite core and taking the signal from the screen. The core size and characteristics must enable it to offer an impedance substantially greater than 150Ω. If the cable is unscreened, a connection must be made to each line via a coupling/blocking capacitor. For power cables, where the line-to-line capacitance is immaterial, this simple arrangement is adequate. Where some line-to-line isolation is needed then individual resistors can be placed in series with each coupling capacitor such that the overall parallel combination of resistors is equivalent to 100Ω. If you need greater isolation – not usually the case for power supply outputs – a separate common mode choke must be included in the pick-off paths. The in-line common mode choke can be produced by winding the entire cable on a single core, or for a small number of wires, use a discrete common mode choke with multiple windings.

2.5. Probe measurements

For golden product comparison, the frequency range up to 30MHz can best be covered by conducted measurements. Occasionally, though, you may want to check for near field emissions around the EUT, especially during product development. This can be useful for locating points of insufficient screening or abnormally high interference currents. A near field probe set is suitable for this purpose. Separate probes are used to sense the magnetic and electric components of the field around an emitting source, and the magnetic probe is preferable for most diagnostic work. This will detect regions of high magnetic field strength, responsible for inductive coupling of interference. The electric field probe will detect locations of high electric field strength, which will be responsible for capacitive coupling of interference.

Electric fields are more susceptible to variability due to environmental factors, and the electric field probe is not recommended for product comparison. If you are going to use the magnetic field probe, ensure that the probe is mounted in a jig which accurately determines its distance and orientation from the EUT, as these factors markedly affect the amplitude of fields measured with the probe.

Test procedures and interpretation

3.1. Identifying ambient and spurious signals

The test instrument will display any signals at its input regardless of their source. Always ensure that you have characterized the displayed spectrum with the EUT powered off before making any measurements. The LISN will attenuate signals conducted in from the mains supply by a factor of 30–60 dB but there will still be a number of sources of external interference which will appear on the display:

a) strong RF interference present on the incoming mains which is insufficiently attenuated by the LISN;

b) interference picked up by the EUT and its mains cable, acting as a passive antenna;

c) low-frequency interference due to other instruments or computers coupled through the local supply network.

a) and b) are normally most noticeable in the 2–20MHz range where the cables act as efficient antennas for HF signals. b) can be identified by disconnecting the EUT power cable at the LISN output. This interference can be eliminated by performing the tests in a screened room and pre-filtering the mains supply. To minimize c), ensure that you have as few as possible other instruments operating on the same supply, and that they are specified for low EMI emissions.

Until you are familiar with the ambient signals in your own environment, you can use the comparison facility of the test instrument to compare the ambient signature with the signature from the EUT to distinguish the EUT's own emissions. Figure 6 shows typical emissions from a SMPS with an oscillator frequency of around 70kHz; in

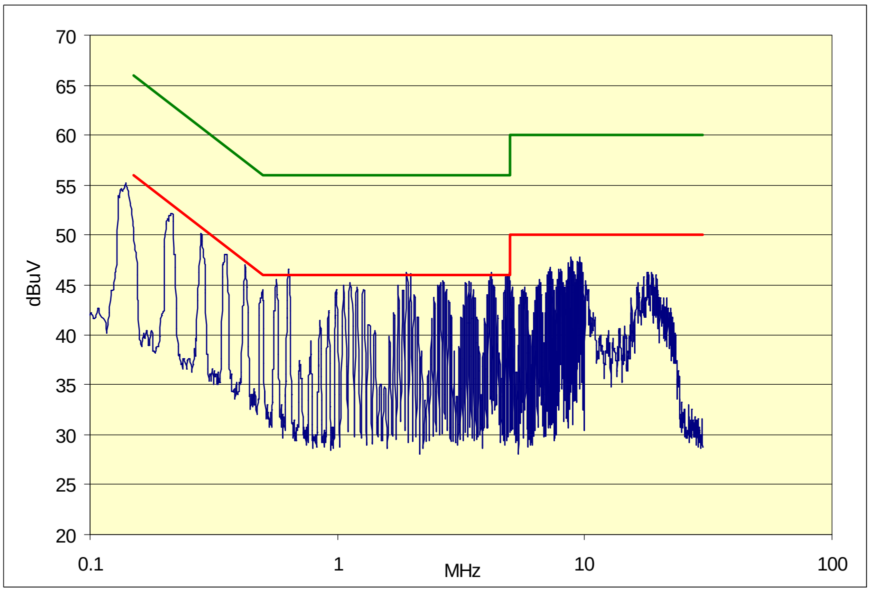


Figure 6 Typical SMPS display

this case, one that is carefully tailored to just meet the Class B average limit line.

3.2. Frequency bands and bandwidth

Provided that you appreciate the effect of bandwidth on the measurement, it is not necessary to use the true CISPR bandwidths for comparative tests; this applies to any spectrum analyser measurement. Many spectrum analysers do not have the fully compliant CISPR bandwidths of 9kHz above 150kHz measurement frequency and 200Hz below it, but this by no means prohibits them from making comparative measurements.

For broadband interference, the change in indicated level in dB is proportional to the change in bandwidth. Broadband noise power is directly related to the bandwidth it is measured in. Thus a 10 times increase in bandwidth at a given frequency will show a 10dB increase in signal level, all other factors being constant. This explains the apparent step changes in level that can occur when switching between bandwidths.

The broadband/narrowband distinction

Interference is defined as broadband when the separation of its spectral components is less than the bandwidth of the measuring instrument; conversely, it is narrowband when the spectral components have a greater separation than the measuring bandwidth. So a harmonic spectrum with a 20kHz spacing will appear as broadband when measured in a 30kHz resolution bandwidth (RBW) but as narrowband when measured in 10kHz. Individual harmonic spectrum lines will be distinguishable with the narrower RBW but not with the higher.

For diagnostic purposes, knowing the frequency of the interference is crucial since this identifies a particular oscillator and its harmonics, particularly valuable if there are several switch mode circuits in the same power supply. The separation between individual harmonic lines gives the oscillation frequency directly: assuming all harmonics are present, for instance two adjacent frequencies of 5.00 and 5.10MHz will indicate a fundamental of 100kHz. Bear in mind that the frequency readout of many lower-cost analysers is only accurate near the centre of the display, and improves as the span is reduced. To get a good idea of the actual frequency, always operate on the narrowest span that gives an adequate picture of the spectrum.

3.3. Attenuator settings

Initial observations of an unknown EUT should always start with maximum attenuation to prevent overload of the input and possible damage.

High input levels, even those at frequencies which appear off-screen, such as below a few tens of kHz, may cause spurious signals to appear on the display. These are generated by distortion at the analyser input. Their level is non-linearly related to that of the input signal. To establish if a particular signal of interest is spurious, momentarily switch in a +20dB or +10dB attenuator. All true signals should drop in amplitude equally by the amount of attenuation you have inserted. Any which drop more than this are spurious. Since mains conducted signals may well carry high levels of mains frequency harmonics, a high-pass filter which cuts out signals below 9kHz can helpfully be applied at the input.

3.4. Sweep rate and detector time constant

An accurate display will only be obtained on narrowband signals if the sweep rate is slow enough for the selected bandwidth and detector time constant. If the sweep speed is too fast, the instrument will not dwell on any particular signal for long enough for the bandwidth-determining filter to respond fully. This will mean that the displayed signal level will be less than the true level, and that the displayed signal will be shifted slightly to the right (higher in frequency). Too fast a sweep speed will also mean that modulated or pulsed signals may not be accurately detected on each sweep, causing the displayed level to vary between sweeps. The sweep speed should therefore always be set as slow as possible consistent with a repeatable display. Especially at the low frequencies, this may mean a tradeoff between fast updating for diagnostic purposes, and accuracy for comparison purposes.

Detector time constant

The peak detector gives the fastest response. For comparison and diagnostic purposes, the quasi-peak detector, which is an artificial construct used only for compliance tests, is unnecessarily cumbersome. When the detector time constant is slow this means that the post-detector bandwidth (or video bandwidth, VBW) is less than the measuring bandwidth, and this time constant becomes the limiting factor on sweep speed for accurate measurement. For most measurement purposes, select the detector time constant such that the displayed levels are just unaffected at the sweep speed you have selected.

One difficulty with switched-mode power supplies is that the fundamental switching frequency is not well controlled and may vary from unit to unit, or with varying loads. This makes it very difficult to compare traces

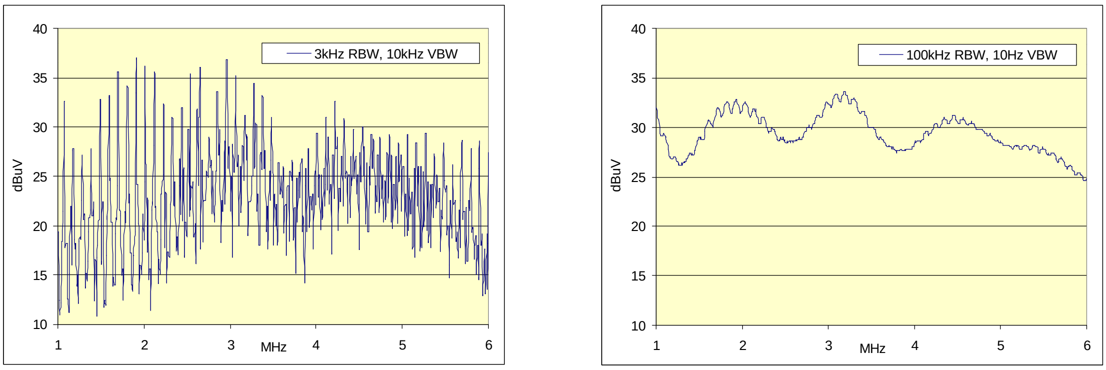


Figure 7 a) Short time constant, narrow RBW b) Long time constant, wide RBW

between units when the fundamental frequency is high enough for its harmonics to appear as narrowband spectral components. To get around this problem, you can either increase the detector time constant (by reducing VBW), or widen the resolution bandwidth, so that the trace becomes smoothed, blurring the individual harmonics and creating a "signature" which is independent of the actual switching frequency. Comparing Figure 7 (a) and (b) shows this effect, both traces being of the same signal.

Average detection

Average detection responds to the average value of pulsed or modulated signals and is implemented in spectrum analysers simply by reducing the VBW while using the peak detector. The major function of averaging is to discriminate continuous, narrowband signals within an emissions signature which is predominantly made up of pulsed signals, such as motor or phase control emissions. For an EUT with a complex emission signature you may want to use both average and peak detection.

The video bandwidth filter affects only the graininess of the display and makes no difference to the resolution of the instrument. If the noise consists of especially sharp pulses, such as DC motor interference, then the peak level may actually overload the analyser while still displaying a low value through averaging, and you will have an inaccurate reading; extra attenuation as discussed in section 3.3. may be needed.

3.5. Making comparisons

It is essential that "golden product" comparisons are only made between different EUTs using the **same** settings of the test instrument. As discussed above, the controls can markedly affect the accuracy and interpretation of the measurement. It is advisable to record all the control settings for each test – most easily in the analyser's configuration memory, or in control software – along with a description of the test set-up, where this may vary.

At the beginning of each batch of tests, perform and store a measurement of the golden sample for use with that batch. As well as confirming that you are using the same settings for the comparison, you can compare the golden sample measurement on a daily basis to a record of its original tests so that any discrepancies, which may be caused by faults in the test jig or procedural errors, can be flagged and corrected.

Comparisons with stored samples are facilitated by a "difference" facility. This subtracts the stored trace from the measurement trace and displays only the difference between them, in the form of deviations from the centre line. For this to work effectively, both traces should be free of random fluctuations. This requires that they should be captured on a slow sweep with the detector time constant set fairly high.

3.6. Margins

A display line facility is useful for indicating whenever a particular emission signal is greater than a level which you have chosen. This is particularly helpful in conjunction with a difference option. Decide what error margin in dB is acceptable for the EUT you are testing and set the display line to this value above the display centreline. Then, whenever the measured value exceeds this margin above the golden sample the displayed signal will exceed the display line.

Rather than set a margin at a fixed value from the golden sample's measurements, you may simply wish to set a margin at a particular level regardless of the golden sample, in which case the difference facility is not selected.

Calculating the margin

The error margin you choose for these purposes will depend on the golden sample's margin compared to the specification limit, the measurement uncertainty of the production test set-up and the measurement uncertainty of the original tests on the golden sample, together with the required degree of confidence that any tested product will be within the limit.†

Measurement uncertainties of the tests done to CISPR standards on the golden sample will normally be expressed at a confidence level of 95% – that is, a probability of 0.95 that the test result is true within the declared uncertainty. For conducted emissions measurements, an uncertainty of 2dB would be typical (though you should of course establish from the test laboratory what figure applies to your particular tests). This value should also be typical of the test jig for the tests as described in section 2 of this note. The accuracy of the test instrument might be up to ±3dB. These uncertainties can then be added on a root-sum-of-squares basis to determine the overall uncertainty (at 95% confidence level) that should be attributed to the golden product comparison procedure, i.e.

$$U_{tot} = \sqrt{(U_1^2 + U_2^2 + \ldots + U_n^2)}$$

where $U_{1..n}$ are the magnitudes of the individual uncertainty contributions

So that in this case,

$$U_{tot} = \sqrt{([2dB]^2 + [2dB]^2 + [3dB]^2)}$$

$$= 4.1dB$$

This uncertainty should be subtracted from the margin available between the golden product's maximum emission level and the specification limit value to give the margin that can be allowed for comparison purposes (Figure 8). This will give a 95% confidence level of compliance assuming that all uncertainties were expressed at this level and that you are testing each production item. For a different confidence level, or if you are sample testing, then you will need to derive different margins.

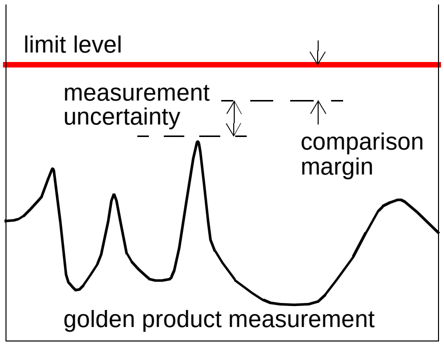


Figure 8 Derivation of margin

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† See UKAS publication LAB34, *The Expression of Uncertainty in EMC Testing*, for a general discussion of measurement uncertainty (www.ukas.com)