Emission Measurements on Switch-mode Power Supplies

TIM WILLIAMS
Chase EMC

INTRODUCTION

This article discusses the characterization of the RF emissions of switch-mode power supply units (SMPSUs) and similar products. There are two main application areas in this field: diagnosing the emissions from a new design at the prototype stage, and assuring production quality by comparing emissions with an established *golden product* or transfer standard.

In most electronics companies, the measuring instrument used for this purpose is the spectrum analyzer. Modern analyzers have signal processing features which are well suited to these tasks, particularly trace comparison. The concepts in this article can be applied to any kind of spectrum analyzer measurement.

CONDUCTED EMISSIONS MEASUREMENTS

Measurements of the RF emissions generated by electronic apparatus are nearly always

The emissions profile of a new product must be determined at the prototype stage.

prompted by the need to conform to national or international standards limiting these emissions. These standards are in turn designed to preserve 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.

Standards which 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 will have to comply with one or another of these standards.

STANDARD	SCOPE
CISPR11/EN55011	Industrial, Scientific & Medical
CISPR13/EN55013	Broadcast Receivers
CISPR14/EN55014	Household Appliances
CISPR22/EN55022	Information Technology Equipment
VDE0875 (Germany)	Electrical Appliances/Systems
VDE0878 (Germany)	Telecommunication Systems
FCC Rules Part 15 (US)	Unintentional Radiators
EN50081	Generic

TABLE 1. *Relevant 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. The mains port of the apparatus is tested in all cases, using a standard 50 Ω/ 50 μH artificial mains network or Line Impedance Stabilization Network (LISN), to an upper frequency limit of 30 MHz. The actual limit values and lower frequency limits are different for each standard, as shown in Table 2.

SMPSU manufacturers are primarily concerned with the conducted tests up to 30 MHz since the harmonics from typical switching frequencies of 50 to 200 kHz 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 30 MHz.

PROTOTYPE DESIGN CHECKS

It is vital to have an idea of the emissions profile of a 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

Continued on page 74

<table>
<tr><th rowspan="2">STANDARD</th><th colspan="6">LIMIT LEVEL (dBμV) AT FREQUENCY
9 kHz 150 kHz 450 kHz 500 kHz 1.705 MHz 5 MHz 30 MHz</th></tr>
<tr><th>9 kHz – 150 kHz</th><th>150 kHz – 450 kHz</th><th>450 kHz – 500 kHz</th><th>500 kHz – 1.705 MHz</th><th>1.705 MHz – 5 MHz</th><th>5 MHz – 30 MHz</th></tr>
<tr><td>CISPR/EN† Class A</td><td>N/A</td><td colspan="2">79</td><td colspan="3">73</td></tr>
<tr><td>CISPR/EN† Class B</td><td>N/A</td><td colspan="2">66.....56</td><td colspan="2">56</td><td>60</td></tr>
<tr><td>VDE0871 PT 1 Class A</td><td>(91.....69.5)</td><td colspan="2">66</td><td colspan="3">60</td></tr>
<tr><td>VDE0871 PT 1 Class B</td><td>79.....57.5</td><td colspan="2">54</td><td colspan="3">48</td></tr>
<tr><td>FCC PT 15 Class A</td><td colspan="2">N/A</td><td colspan="2">60</td><td colspan="2">69.5</td></tr>
<tr><td>FCC PT 15 Class B</td><td colspan="2">N/A</td><td colspan="4">48</td></tr>
<tr><td colspan="7">†CISPR/EN refers to EN55011, EN55022; EN55013, EN55014, EN50081 PT 1 (Class B only); EN50081 PT 2 (Class A only). All values measured with CISPR 16 quasi-peak (QP) detector, bandwidth 9 kHz above 150 kHz, 200 Hz below 150 kHz; EN standards also require tests with an average detector with limits 13 dB (Class A) and 10 dB (Class B) below the QP limits.</td></tr>
</table>

***TABLE 2.** Limit Levels for Various Standards: Mains Port Conducted Emissions.*

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 identify the operating configuration — 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, a comprehensive and repeatable test setup, and the ability to interpret its results correctly, are necessary.

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 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 a potentially 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, manufacturers must test at least one sample product (they 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 setup is repeatable, the tests are then used to ensure that any changes from the sample are within acceptable margins. The sample can be regarded as the golden product for this purpose.

THE TEST SETUP

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

COUPLING TO THE LISN

The Line Impedance Stabilization 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 measurements.

LISN Circuit. CISPR 16 (1987 CISPR specification for radio interference measuring apparatus

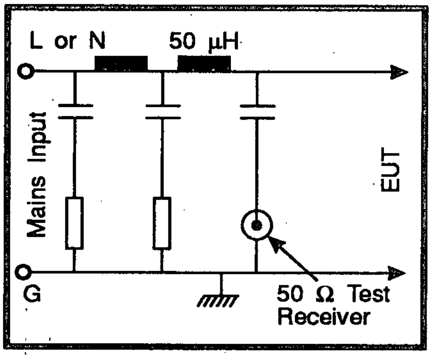

FIGURE 1. *CISPR 16, 50 Ω/50 µH LISN Circuit.*

can ensure a predictable impedance to beyond 30 MHz. The impedance is defined with respect to the ground terminal of the LISN. This ground terminal is therefore the reference for the whole test setup and there must be a low impedance at RF between the components of the test setup. This can only satisfactorily be achieved with a ground plane, which is discussed later.

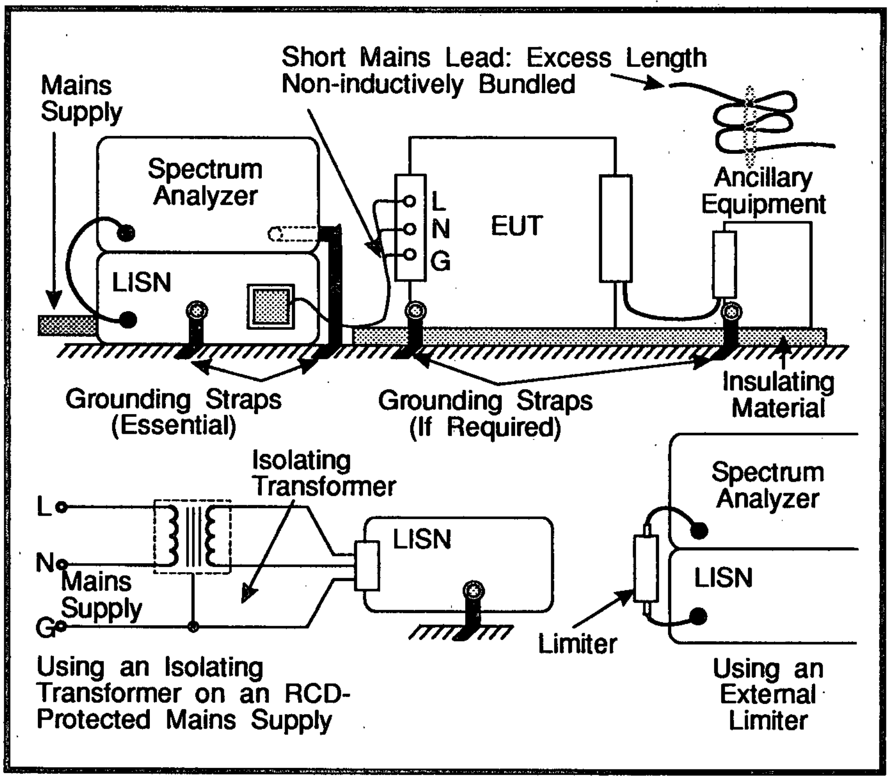

FIGURE 2. *The Test Setup — Mains Port Testing.*

and measurement method) defines the LISN's impedance function versus frequency and suggests a circuit which can realize this function. The circuit is shown in Figure 1. 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.

The 50 Ω impedance, defined by the input impedance of the test receiver, together with the 50 µH inductor, determine the impedance presented by the LISN at RF. Careful construction of the LISN

Safety. The value of the parallel combination of the capacitors in the LISN circuit approaches 10 µF. For the circuit which is connected in series with the live line, the full supply voltage (240 V ac rms in the UK) appears across this capacitance which is connected to ground, and hence a current of around 0.75 A will flow in the ground connection. A greater current will flow through the ground connection of a three-phase LISN. If the LISN's ground connection is not reliably bonded to the safety ground 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. The LISN case must always be properly bonded to the mains safety ground before connecting the mains supply.

Because of the continuous safety ground current, a LISN cannot be used directly on a mains supply circuit which is protected by a residual current device (RCD), or ground leakage circuit breaker. The continuous ground current will ensure that the circuit breaker stays permanently tripped. If an unprotected supply circuit cannot be found, a suitably rated isolation transformer can be used between the supply and the LISN, as shown in Figure 2.

For those supplies where a LISN would be impractical or unsuitable, CISPR 16 suggests the use of a voltage probe incorporating a 1500 Ω resistor and blocking capacitor. This does not provide the impedance stabilization or filtering function of a proper LISN but does serve to couple the signal to the test instrument.

Transient Protection. Transients from the EUT, especially when switching it on or off, and transients coupled down the supply mains, may have sufficient energy to destroy the input of the spectrum analyzer and therefore an attenuator setting of at least 20 dB is recommended when the LISN is connected. If the more sensitive ranges are needed, a transient limiter between the LISN and the test instrument input can be connected. This inserts 10 dB attenuation in the signal line at the same time as it limits transient signals to safe levels. In fact, since the operator may inadvertently switch out the input attenuation from the analyzer's front panel, habitual use of a limiter is always recommended.

Continued on page 276

Electric fields are more susceptible to variability due to environmental factors; electric field probes are not recommended for product comparison. If the magnetic field probe is used for this purpose, the probe should be 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

IDENTIFYING AMBIENT AND SPURIOUS SIGNALS

The test instrument displays any signals at its input, regardless of their source. The displayed spectrum should be characterized 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 to 60 dB but there will still be a number of sources of external interference which will appear on the display:

- Strong RF interference present on the incoming mains which is insufficiently attenuated by the LISN
- Interference picked up by the EUT and its mains cable, acting as a passive antenna
- Low frequency interference due to other instruments or computers coupled through the local supply network

Interference on the incoming mains and interference picked up by the EUT are normally most noticeable in the 2 to 20 MHz range where the cables act as efficient antennas for HF signals. Interference picked up by the EUT and its mains cable 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 low frequency interference due to other instruments, as few as possible other instruments should operate on the same supply, and they should be specified for low EMI emissions.

Until familiar with the ambient signals in their own environment, test personnel can use the comparison facility of the test instrument to compare the ambient signature with the EUT's signature to distinguish the EUT's own emissions.

FREQUENCY BANDS AND BANDWIDTH

Provided that the effect of bandwidth on the measurement is understood, it is not necessary to use the true CISPR bandwidths for comparative tests; this applies to any spectrum analyzer measurement.

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

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. Hence a harmonic spectrum with a 20 kHz spacing will appear as broadband over the range 300 kHz to 3 MHz (with a 40 kHz bandwidth) but as narrowband over the range 30 kHz to 300 kHz (4 kHz bandwidth). Individual spectral lines will be distinguishable over the lower range but not over the higher range.

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 may cause spurious signals to appear on the display. These are generated by distortion within the input circuitry. Their level is non-linearly related to that of the input signal. To determine whether a particular signal is spurious, momentarily switch in a ±20 dB or +10 dB attenuator. All true signals should drop in amplitude equally by the amount of attenuation inserted. Any signals which drop more than this are spurious.

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 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. Therefore, the sweep speed should 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 is always used for the fastest response. When the detector time constant is such that the post-detector bandwidth is less than the measuring bandwidth, this time constant becomes the limiting factor on sweep speed for accurate measurement. For most measurement purposes, the detector time constant is selected so that the displayed levels are unaffected at the selected sweep speed.

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 between units when the fundamental frequency is high enough for its harmonics to appear as narrowband spectral components. To bypass this problem, the detector time constant can be deliberately increased so that the trace becomes smoothed, blurring the individual harmonics and creating a "signature" which is independent of the actual switching frequency.

Average Detector and Video Filter. The average detector responds to the average value of pulsed or modulated signals and therefore exhibits a longer time constant than the peak detector. The major function of the average detector is to discriminate continuous, narrowband signals within an emissions signature which is predominately made up of pulsed signals, such as motor or phase control emissions. For an EUT with a complex emission signature, both average and peak detectors can be used.

The video filter affects only the noise present on the display and makes no difference to the resolution of the instrument.

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. Wherever possible, the preset positions of the variable controls should be used as these will be repeatable from one test to the next. It is also advisable to record all the control settings for each test, and in cases where this may vary, to record a description of the test setup.

At the beginning of each batch of tests, a measurement of the golden sample is made and stored for use with that batch. As well as ensuring that the same settings are used for the comparison, the golden sample measurement can be compared daily to a record of its original tests so that any discrepancies, which may be caused by faults in the test jig or by 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 center line. For this to work effectively, both traces should be as noise-free as possible. This requires that they be captured on a slow sweep with the detector time constant set fairly high.

MARGINS

A display line facility is useful for indicating whenever a particular emission signal is greater than the chosen level. This is particularly useful in conjunction with a difference option. The display line is set to the acceptable error margin above the display centerline. Then, whenever the measured value exceeds this margin above the golden sample, the displayed signal will exceed the display line. An audible alarm can be activated to reinforce the operator's awareness of this event.

Calculating the Margin. The error margin chosen for these purposes will depend on the golden sample's margin compared to the specification limit, the measurement uncertainty of the production test setup, and the measurement uncertainty of the tests on the golden sample. The required degree of confidence that any tested product will be within the limit also affects the choice of error margin.

Measurement uncertainties of the tests performed to CISPR standards on the golden sample will normally be expressed at a confidence level of 95 percent — that is, a probability of 0.95 that the test result is true within the declared uncertainty. For conducted emissions measurements, an uncertainty of 2 dB would be typical. This value should also be typical of the test jig for the tests described earlier in this article. The accuracy of the test instrument might be up to 4 dB. These uncertainties can then be added on a root-sum-of-squares basis to determine the overall uncertainty (at 95 percent confidence level) that should be attributed to the golden product comparison procedure, ie.,

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

where $U_{1..n}$ are the magnitudes of the individual uncertainty contributions. So that in this case,

$$U_{tot} = \sqrt{([2\text{ dB}]^2 + [2\text{ dB}]^2 + [4\text{ dB}]^2)}$$
$$= \sqrt{(1.26^2 + 1.26^2 + 1.585^2)}$$
$$= 2.38 \qquad = 7.5\text{ dB}$$

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 5). This will give a 95-percent confi-

Continued on page 286

 . . . Continued from page 283

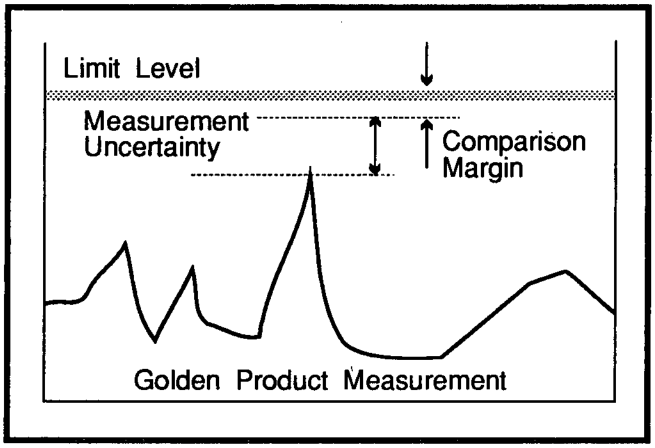

***FIGURE 5.** Derivation of Margin.*

dence level of compliance assuming that all uncertainties were expressed at this level and that each production item is being tested. For a different confidence level, or if sample testing, different margins will need derivations.

CONCLUSION

The spectrum analyzer is the most widely used measuring instrument for characterizing the RF emissions of switch-mode power supply units and similar products. A repeatable test is required, both to measure emissions from new designs at the prototype stage, and to monitor production of equipment and ensure that EMC criteria are met. Quality control standards are assured by comparing emissions with an established golden product.

***TIM WILLIAMS** received a B.Sc. degree in electronic engineering from the University of Southampton, UK, in 1976, and is a member of the Institution of Electrical Engineers (IEE). He has worked as an electronics design engineer in various industry sectors, and for the last few years has been specializing in EMC with particular interests in product design, testing, and the implementation of the European EMC Directive. He now offers consulting and training in these areas. +44 (243) 533361.*