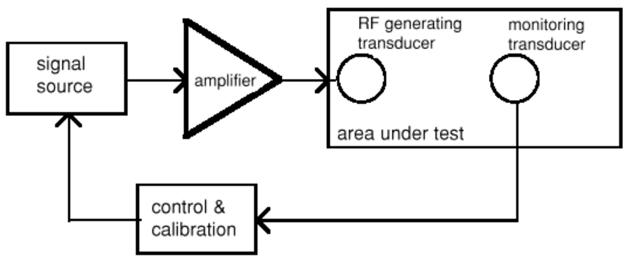
What to look for in an EMC amplifier

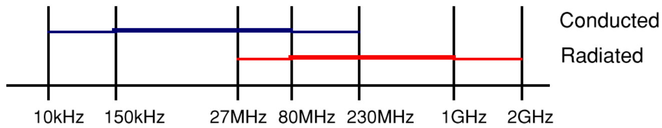
RF immunity testing to IEC1000-4-3 and -4-6 is now an established requirement for an EMC test facility. One of the most important components of an RF immunity test system is the power amplifier since it is the performance of this unit which largely determines the quality and level of RF field that is applied to the equipment under test. Figure 1 shows the basic components of any RF immunity test system. There are many demands on the performance of the amplifier, some of which are obvious but many of which are not. It is very easy to purchase an amplifier on its published specification without appreciating the effect of the lesser-understood demands on the operation of the whole system. This article looks at these demands and discusses the differences in amplifier design and construction which affect the resulting system performance.



You need an amplifier both for radiated testing using antennas, striplines or TEM cells, and for conducted testing using CDNs, current injection probes or the EM-clamp.
The transducer used has a major effect on the specification of the amplifier and the two cannot really be considered separately.

Power output and bandwidth
The most important specifications, those of maximum power output and the bandwidth over which this output is sustained, are interlinked and determined by the required capability of the test facility. They also, to a large extent, decide the cost of the unit. Before beginning to look at amplifiers in detail, you will need to work out what your bandwidth and power needs will be, and this will depend on what standards you intend to test to, and with what test set-up.

Frequency range
The basic standards cover the frequency range 150kHz-80MHz and 80-1000MHz as shown.



However each basic standard may be extended in either direction by the specific requirements of a product standard. For instance the marine equipment standard EN60945 calls for conducted immunity down to 10kHz; the medical standard EN60601-1-2 calls for radiated immunity down to 26MHz. Revisions are in hand to extend radiated immunity testing up to 2GHz. Also, the overlap between conducted and radiated testing is left to the discretion of product committees. Finally, if you are using military, aerospace or automotive standards, your requirements will be different again.
There is a fundamental tradeoff between cost, power and bandwidth. An amplifier of a few watts can be made to cover several decades bandwidth – e.g. 100kHz to 1GHz – but as the power level rises so restrictions in output stage design mean that less bandwidth can be offered. For this reason, be sure to check that the rated output power is available over all the specified bandwidth. The bandwidth may, for instance be specified as a "3dB" bandwidth – which is likely to mean that only half the rated power is available at the band edges.
However, as we will see shortly, the full power capability may not be needed over the whole range. It is therefore quite reasonable to use amplifiers of different power ratings to cover different frequency ranges and to switch bands in mid-sweep. It would of course be helpful to use one amplifier for conducted testing and another for radiated, and this is sometimes possible

depending on the power levels and frequency ranges you need. Be aware that the need to change amplifiers in mid-sweep is an obstacle to fully automated RF immunity testing, although it can be overcome with suitable control hardware and software.

Test level

Assuming that you are working primarily to IEC1000-4-3 and -4-6, a test level of 10V/m radiated or 10V emf conducted will satisfy most requirements. But before fixing on this, consider that you may well want to exceed these levels so that you can over-test your EUT to acquire a margin of confidence. Also, IEC1000-4-3 allows a larger step size (4% of fundamental, which equates to a four-fold reduction in sweep time) if you apply twice the specified field strength. Finally, consider also that there will be system losses in cables and connectors to take into account. These increase with frequency and are usually offset by increasing antenna gain at the higher frequencies; 2dB is a reasonable allowance. All told, aiming for a maximum achievable field strength level of 25-30V/m is a good approach if your spec says 10V/m. Unfortunately, this will call for six times the power capability that you would apparently otherwise need.

Parameters which depend on the test set-up are:

- if using antennas and a screened room: the antenna gain, and the intended test distance;
- if using a TEM or GTEM cell, the plate separation;
- for conducted tests, the transducer factors of the various transducers you will use.

	BiLog (CBL6121)				GTEM 1750		TEM cell	
	1m dist		3m dist		h = 1.5m		h = 80cm	
	3V/m	10V/m	3V/m	10V/m	3V/m	10V/m	3V/m	10V/m
27MHz	25.42	282.5	228.8	2542.1	1.34	14.89	0.38	4.22
80MHz	1.29	14.31	11.59	128.8	1.34	14.89	0.38	4.22
200MHz	0.29	3.23	2.61	29.05	1.34	14.89	0.38	4.22
1GHz	0.33	3.64	2.95	32.75	1.34	14.89		
2GHz					1.34	14.89		

Note: allowances included: +5.2dB for 80% modulation, +6dB for field uniformity (antenna method only)

The table above summarizes the calculated power requirements in watts for radiated testing in the face of these variables. The calculations are based on the following fundamentals.

Radiating antenna method

For an antenna radiating into free space and measured in the far field, i.e. further away than $\lambda/2\pi$, the power required is related to the square of the field strength:

$$P = \frac{(Ed)^2}{30G}$$

where P is the power delivered to the antenna, d is the distance in metres from the antenna, E is the field strength at d in volts per metre, and G is the numerical antenna gain over an isotropic radiator.

This equation assumes only far-field coupling between the antenna and the point at which the field is measured. Clearly the power required is proportional to the square of the distance and therefore a close-in test is to be preferred. But at 30MHz conditions only begin to approach the far field at distances greater than 1.6m, reducing to 0.6m at 80MHz. Mutual coupling between the antenna and EUT exists at substantially greater distances than the near field/far field boundary, and the effect of this is to distort the field structure at the EUT and make it more critical on small changes in position, and to affect the antenna gain and make it dependent on the EUT. Further, with directional antennas such as the log-periodic the Rayleigh range becomes important, reducing the uniformity of field at short distances. It is for these reasons that IEC1000-4-3 prefers the test to remain at 3m distance, although it does allow 1m.

The equation above also assumes free space propagation. This is certainly not the case inside a test chamber, where there are peaks and nulls in the field structure at the EUT position as a result of reflections both from the walls of the chamber and from other included objects such as the EUT itself and the various cables present.

Adding anechoic material to the walls will reduce the amplitude of the reflections but does not eliminate them. The requirement is given by the field uniformity specification of IEC1000-4-3, wherein the measured field strength in a plane area including the front face of the EUT must be within -0,+6dB of the nominal. To cope with possible nulls in the field distribution within the chamber, you will need to allow +6dB on the power output over the theoretical requirement. In an un-lined chamber (that is, screened but not anechoic) much greater amplitude nulls are possible and the field uniformity requirement cannot be met. If you are doing RF immunity tests in such a chamber, either you need a heavily over-rated RF power source or you must accept the likelihood of under-testing at some frequencies (and, it must be said, of over-testing at others). Finally, the power given by the above equation refers only to the power delivered to the antenna. In EMC testing, this is not by any means the same thing as the power rating of the amplifier. More is said about this aspect in the next section.

TEM or GTEM method

Sizing a power amplifier to drive a TEM cell or GTEM is considerably simpler. If the cell termination and the transmission line within provide an accurate 50Ω match, then the field strength within the cell is directly proportional to the applied RF voltage V divided by the distance between the plates h:

$$E = V/h$$

and the power required can be calculated from

$$P = V^2/50$$

For the GTEM, the plate separation increases linearly with distance down the cell and you can choose to take an average separation value at the centrepoint of the EUT position, or to take the widest separation so that parts of the EUT towards the input of the cell are over-tested.

When there is a resonance within the cell, the match at the input to the cell becomes variable and the field structure inside becomes more complex. Resonances do occur with empty cells (even with the GTEM) and are also induced by the inclusion of an EUT. Some over-sizing of the amplifier is needed to deal with them but experience suggests that an allowance of 3-4dB will usually be adequate provided that the maximum allowed dimension of the EUT is not exceeded.

Conducted method

Conducted RF immunity testing is fairly straightforward since only the impedances specified by the calibration method and the required test level define the power that will be needed for a particular transducer. The necessary power is a direct function of the loss through the transducer. With a CDN this loss is fractions of a dB and therefore using a CDN does not need a high-power amplifier. The commonly used alternative method of bulk current injection (BCI) is substantially more power-hungry since the current probe has noticeable loss at the extremes of its frequency range. The conducted power requirements in watts are summarised in the table below.

	CDN		EM-clamp		BCI(CIP9136)	
	3Vemf	10Vemf	3Vemf	10Vemf	3Vemf	10Vemf
(10kHz)					585	(6500)
150kHz	0.59	6.50	1.46	16.25	29.32	325.78
27MHz	0.59	6.50	0.94	10.40	4.21	46.80
80MHz	0.59	6.50	0.59	6.50	4.62	51.35
230MHz	0.59	6.50	0.59	6.50	5.85	65.00

Note: figures for the BCI method are shown as volts emf according to IEC1000-4-6. The figures for 10kHz are shown for comparison purposes; IEC1000-4-6 does not require this frequency range although other product standards may.

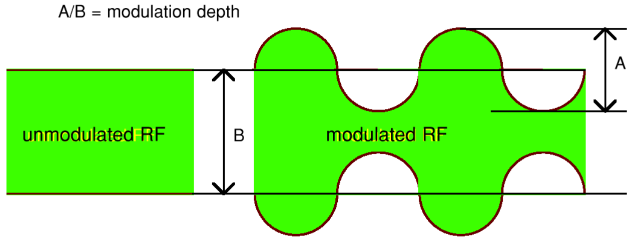
Still, the conducted method does present a different set of problems. In this case there is close coupling (through the CDN or current probe) between the amplifier output and the EUT cable port's common-mode impedance to the ground plane. Although the transducer and amplifier system is calibrated into a constant (150Ω) impedance, when testing you will see anything but a constant impedance.

If the EUT presents a low or a high common-mode impedance at various frequencies across the test range at its cable port, this varying impedance appears directly at the amplifier output unless precautions are taken. Since the amplifier impedance is not guaranteed to be constant and known, the effect is to create a test level that is uncontrolled and will vary from one amplifier to another even though the test calibration is the same. Also, the amplifier itself

can be quite severely stressed by the power reflected from the varying load.
To deal with this you should feed the power from amplifier to transducer through a buffering attenuator pad. In IEC1000-4-6 this is specified to be 6dB, and its effect is to decouple the EUT from variations in amplifier impedance and vice versa. A 6dB pad will give a maximum VSWR of 1.67:1 at one port when the other port is either an open circuit or a short circuit load.
IEC1000-4-6 para 6.1 specifies an output VSWR of 1.2:1 with the pad in place, which means that the amplifier's own output VSWR may then be up to 2.14:1. An amplifier with a worse specification than this will not meet IEC1000-4-6 even with a 6dB pad in place. The disadvantage of the pad is that an associated +6dB increase in output power is needed from the amplifier, but a repeatable and reliable test is impossible without it.

Modulation

A further factor which affects the power requirement is the need for amplitude modulation. In both the relevant parts of IEC1000-4, and in the product and generic standards which reference them, the test level is defined in terms of an unmodulated signal, and in consequence the calibration method uses an unmodulated signal. But when the test is actually run, modulation is applied.



The default modulation (certain product standards may change this) is a 1kHz sinusoid at 80% depth. The relationship between modulation depth and the amplitude envelope of the signal is shown above. The rms power in the signal is increased by 1dB but the peak power is increased by 5.2dB, and the amplifier rating must reflect this.
Note that the 1dB increase will show up on any monitors which are checking the applied signal. You must not reduce the drive to the amplifier to compensate for this!

VSWR tolerance

VSWR (Voltage standing wave ratio) is a measure of the match to a resistive 50Ω that is presented at the terminals of an amplifier or a transducer. Unless the impedance is exactly 50 Ω, some power is reflected from the terminals and travels back down the cable (which is assumed to present a good match). Matching is also defined in terms of reflection coefficient and the two parameters are related as follows:

VSWR $K = (1 + |r|) / (1 - |r|) = Z_0 / Z_L$ or Z_L/Z_0
Reflection coefficient $r = (K-1) / (K+1)$

A VSWR of 1:1 implies a perfect match and r = 0. An open or short circuit implies r = 1 or -1 and an infinite VSWR.

No transducer presents a perfect 50 ohm match to the amplifier output. A biconical antenna can show a VSWR > 30:1 at 30MHz. Even at the higher frequencies, where the manufacturer's curves show a VSWR of better than 2:1 (in free space), coupling with the screened room and the EUT can markedly worsen this figure. If closely coupled to a current probe or CDN for conducted injection, VSWRs greater than 60:1 can result. It is also not unknown for the amplifier to be powered-up when its output connector is open circuit, or through a fault, short-circuit. Under these conditions all the applied RF power is reflected back to the amplifier output.

Power amplifier biasing

A power amplifier for EMC immunity testing must, first of all, be able to withstand repeated abuse of this nature without damage, and second, deliver as much as possible of its rated power into mismatched loads. The problem facing amplifier designers is to minimize cost and weight and maximized output power capability. The most fundamental design decision is whether to bias the amplifier in class A or class AB.

Class AB biasing reduces the quiescent power dissipation to well below the rated power. When the maximum power is being delivered then there is also the greatest dissipation in the amplifier. Any mismatch will reflect some (and perhaps all) of the delivered power back to the amplifier, and this will over-stress the output stage if it is rated for this dissipation only with a matched load. In order not to destroy the output, some form of protection is implemented which limits the power drive and hence that which can be delivered.

This is quite a difficult task and does not always work with all phases of reflected power. Even so, the amplifier must of necessity be unable to reach its power rating when even a moderate mismatch is presented. Since conditions of high VSWR (maximum reflected power) are precisely those conditions when highest forward power is needed – typically, a biconical at the bottom of its frequency range – this limits the usefulness of the class AB amplifier.

Class A biasing sets the output stage operating point such that the RF output voltage swings equally about the DC quiescent level, thus giving very good linearity up to the specified 1dB compression point. The disadvantage of this scheme is that the amplifier dissipates maximum power when it is quiescent, and its efficiency is low. Any RF delivered to the load subtracts from this dissipation. This means that a class A amplifier will be larger, heavier, and inevitably more costly than its class AB equivalent for a given rated matched power, to cope with this continuous dissipation.

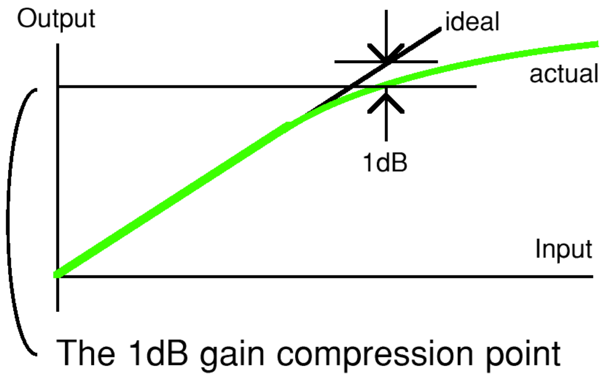
Its advantage though is that any reflected power does not raise the output stage dissipation above that for which it has been designed. No out-of-limits output protection is necessary, and the unit can comfortably supply its rated forward power whatever the load conditions. (Note that no power will actually be delivered to the load if it is an open or short circuit – all the power gets reflected back to the amplifier under such conditions.) For typical EMC immunity testing applications, this means in turn that the specified power rating is exactly what you get, even at the extremes of load that are characteristic of biconical antennas and current probes.

Linearity

When you are using a power amplifier for EMC immunity testing with modulation applied to the signal source, you are having to make a crucial assumption: this is that the amplifier remains linear over its whole frequency range up to the maximum power it is delivering. If it doesn't, there are two consequences:

- the peak of the modulated RF envelope will be flattened. This creates harmonics of the modulation frequency (2kHz, 3kHz etc) which may excite susceptibilities in the EUT that would otherwise be unaffected. It will also reduce the actual peak applied field strength and therefore under-test the EUT. You will not be able to detect this – since calibration is performed with an unmodulated signal – unless you use a wideband oscilloscope to check the modulated RF envelope continuously.
- harmonics of the applied frequency will be generated (e.g. if you are applying 100MHz, there will be components at 200MHz, 300MHz etc.). If the non-linearity is severe the harmonic amplitudes can approach the fundamental, and this can excite susceptibilities at apparently the "wrong" frequency, as well as reducing the applied field strength at the right frequency. IEC1000-4-6 specifies harmonics and distortion more than 15dB below the carrier level (-15dBc).

You can check for this while running the test by using a spectrum analyser with a directional coupler on the power amplifier output.



The 1dB gain compression point

You can perform a simple linearity check at any time by manually reducing the signal source level by say 1 or 3dB and confirming that the output level changes by the same amount. Amplifier linearity is normally quoted in terms of power output at the 1dB gain compression point (see figure above) and the specified performance of harmonic generation (in -dBc) is only obtained up to this level. Above it, the distortion rises rapidly.

Power gain

It is usual for amplifiers to be specified to deliver their maximum power output for a given input level, typically 0dBm. The power gain from input to output should be maintained over the whole operational frequency range. If it is not, then a higher level of drive signal is needed, typically at the edges of band coverage. This may place an extra demand on the output of the chosen signal source. Provided that there is some leeway in hand – for instance the maximum source output may be +10dBm – there is not necessarily a problem, but the total system requirement should be checked before committing to purchase.

Reliability and maintainability

Despite the best efforts to improve reliability of equipment, power amplifiers do still occasionally fail.

When this happens, you need to be sure that repair and re-calibration are swift and effective. It is unusual to have back-up units available, and an amplifier that is out of commission will hold up a large part of the expensive test facility, not to mention product development and testing schedules. Always check with your supplier what their policy is on repair.