EMC Amplifiers for Immunity Testing

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The power amplifier determines the quality and level of the RF field that is applied to the EUT.

INTRODUCTION

RF immunity testing to IEC 1000-4-3 and IEC 1000-4-6 is now an established requirement for an EMC test facility. Figure 1 shows the basic components of any RF immunity test system. One of the most important components of the RF immunity test system is the power amplifier, since it is the performance of this unit which largely determines the quality and level of the RF field that is applied to the equipment under test. 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.

Amplifiers are used both for radiated testing using antennas, striplines or TEM cells, and for conducted testing using CDNs, current injection probes or the EM clamp. It should be understood that the transducer used has a major effect on the specification of the amplifier and the two cannot really be considered separately.

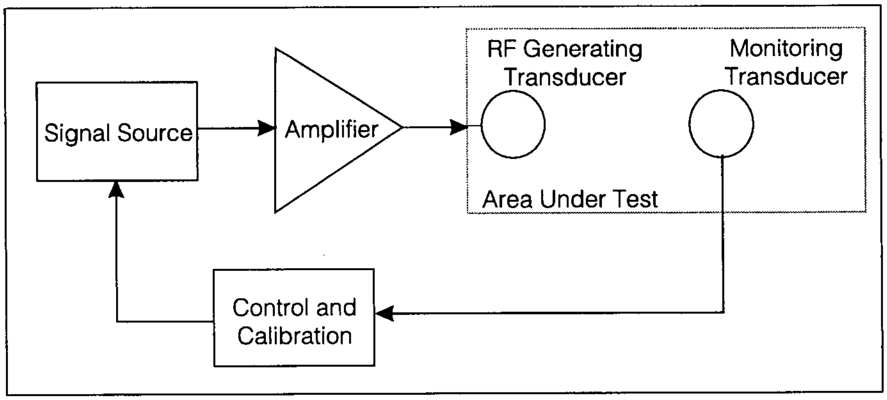

Figure 1. *RF Immunity Test System.*

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, determine the cost of the unit. Before beginning to look at amplifiers in detail, the bandwidth and power needs must be established and these depend on which standards the equipment under test (EUT) will be tested to, and the test setup.

FREQUENCY RANGE

The basic standards cover the frequency range 150 kHz - 80 MHz and 80 MHz-1000 MHz (Figure 2). However each basic standard may be extended in either direction by the specific requirements of a product standard. For instance, the marine equipment standard EN 60945 calls for conducted immunity down to 10 kHz and the medical standard EN 60601-1-2 calls for radiated immunity down to 27 MHz. Revisions are underway which will extend radiated immunity testing up to 2 GHz. Also, the overlap between conducted and radiated testing is left to the discretion of product committees. Finally, if using military, aerospace or automotive standards, 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., 100 kHz to 1 GHz — but as the power level rises, restrictions in output stage design mean that less bandwidth can be offered. For this reason, check that the rated output power is available over the entire specified bandwidth. The bandwidth may, for instance, be specified as a 3 dB bandwidth, which is likely to mean that only half the rated power is available at the band edges.

However, as this article explains, 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,

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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 needed. Technicians should 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 one is working primarily to IEC 1000-4-3 and IEC 1000-4-6, a test level of 10 V/m radiated or 10 Vemf conducted will satisfy most requirements. But before fixing on this, engineers should consider exceeding these levels so that the EUT can be over-tested to achieve a margin of confidence. Also, IEC 1000-4-3 allows a larger step size (4% of fundamental, which equates to a fourfold reduction in sweep time) if twice the specified field strength is applied. Finally, considerations should also be given to the fact that there will be system losses in cables and connectors. These increase with frequency and are usually offset by increasing antenna gain at the higher frequencies; 2 dB is a reasonable allowance. All told, aiming for a maximum achievable field strength level of 25 to 30 V/m is a good approach if the specification says 10 V/m. Unfortunately, this will call for six times the power capability that would otherwise be needed.

Parameters which depend on the test setup 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 used

Table 1 summarizes the calculated power requirements for radiated testing in the face of these variables. The calculations are based on the following fundamentals discussed here.

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:

$$P = (d \cdot E)^2/30\,G \qquad (1)$$

where

P = power delivered to the antenna

d = distance in meters from the antenna

E = field strength at d in volts per meter

G = 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 preferred. But at 30 MHz, conditions only begin to approach the far field at distances greater than 1.6 m, reducing to 0.6 m at 80 MHz. Mutual coupling between the antenna and the 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 IEC 1000-4-3 prefers the test to remain at a 3-m distance, although allowing 1 m.

Equation 1 also assumes free space propagation. This is certainly not the case inside a test chamber, where there

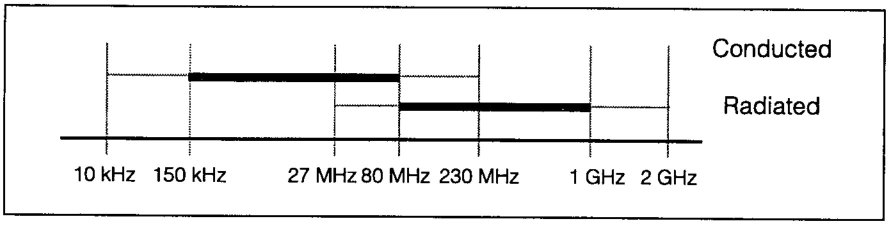

Figure 2. *Application of Basic Standards in the Frequency Range 150 kHz to 80 MHz and 80 MHz to 1000 MHz.*

	BiLog				GTEM		GTEM	
	1 m Distance		3 m Distance		h = 1.5 m		h = 80 cm	
	3 V/m	10 V/m	3 V/m	10 V/ m	3 V/m	10 V/m	3 V/m	10 V/ m
27 MHz	25.42	282.5	228.8	2542.1	1.34	14.89	0.38	4.22
80 MHz	1.29	14.31	11.59	128.8	1.34	14.89	0.38	4.22
200 MHz	0.29	3.23	2.61	29.05	1.34	14.89	0.38	4.22
1 GHz	0.33	3.64	2.95	32.75	1.34	14.89		
2 GHz					1.34	14.89		
Note: Allowances include +5.2 dB for 80% modulation; +3 dB for field uniformity (antenna method only).								

Table 1. *Calculated Power Requirements for Radiated Testing.*

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 IEC 1000-4-3, wherein the measured field strength in a plane area, including the front face of the EUT, must be within 0.6 dB of the nominal. To cope with possible nulls in the field distribution within the chamber, +3 dB must be allowed on the power output over the theoretical requirement. In an unlined chamber (that is, screened but not anechoic) much greater amplitude nulls are possible and the field uniformity requirement cannot be met. For RF immunity tests in such a chamber, a heavily overrated RF power source is needed, or the likelihood of undertesting at some frequencies (and, it must be said, of over-testing at others) must be accepted.

Finally, the power given by Equation 1 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 50-ohm 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 an average separation value at the centerpoint of the EUT position can be selected, or the widest separation can be selected 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 to 4 dB will usually be adequate provided that the maximum allowed dimension of the EUT is not exceeded.

	CDN		EM-Clamp		BCI	
	3 Vemf	10 Vemf	3 Vemf	10 Vemf	3 Vemf	10 Vemf
(10 kHz)					585	(6500)
150 kHz	0.59	6.50	1.46	16.25	29.32	325.78
27 MHz	0.59	6.50	0.94	10.40	4.21	46.80
80 MHz	0.59	6.50	0.59	6.50	4.62	51.35
230 MHz	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 10 kHz are shown for comparison purposes; IEC1000-4-6 does not require this frequency range although other product standards may.

***Table 2.** Conducted Power Requirements.*

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 require 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 are summarized in Table 2.

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 (150 ohm) impedance, this impedance will not be seen during testing. 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, power should be fed from the amplifier to the transducer through a buffering attenuator pad. In IEC 1000-4-6 this is specified to be 6 dB, and its effect is to decouple the EUT from variations in amplifier impedance and vice versa. A 6 dB 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. IEC 1000-4-6, para 6.1, specifies an output VSWR of $\leq$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 speci-

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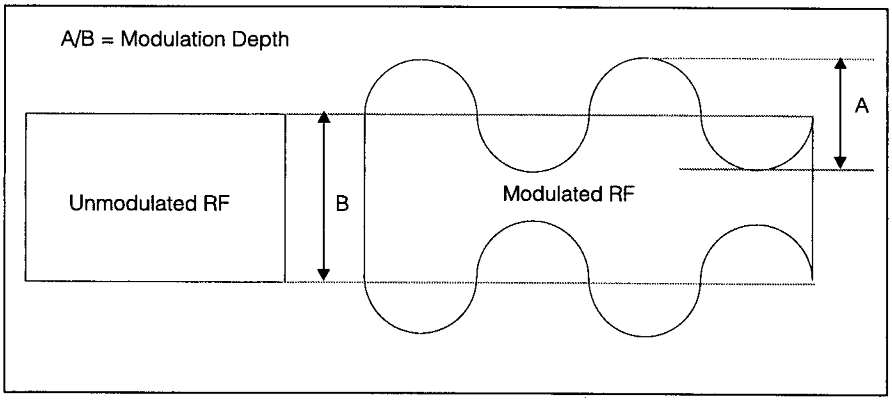

Figure 3. *Relationship between Modulation Depth and Amplitude Envelope.*

fication than this will not meet IEC 1000-4-6 even with a 6 dB pad in place. The disadvantage of the pad is that an associated +6 dB increase in output power is needed from the amplifier, but a repeatable and reliable test is impossible without it.

MODULATION

Another factor which affects the power requirement is the need for amplitude modulation. In both the relevant parts of IEC 1000-4, and in the product and generic standards which reference them, the test level is defined in terms of an unmodulated signal, and consequently, 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 1 kHz sinusoid at 80% depth. The relationship between modulation depth and the amplitude envelope of the signal is shown in Figure 3. The rms power in the signal is increased by 1 dB but the peak power is increased by 5.2 dB, and the amplifier rating must reflect this. Note that the 1 dB increase will show up on any monitors which are checking the applied signal. The drive to the amplifier must not be reduced to compensate for this.

VSWR TOLERANCE

VSWR (voltage standing wave ratio) is a measure of the match to a resistive 50 ohms that is presented at the terminals of an amplifier or a transducer. Unless the impedance is exactly 50 ohms, 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 $= (1 + |\rho|)/(1 - |\rho|)$
$= Z_0/Z_L$ or Z_L/Z_0
Reflection Coefficient ρ
$= (K-1)/(K+1)$

A VSWR of 1:1 implies a perfect match and $\rho = 0$. An open or short circuit implies $\rho = 1$ 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 30 MHz. 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 unheard of 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.

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 objective facing amplifier designers is to minimize cost and weight and maximize output power capability. The most fundamental design decision is whether to bias the amplifier in Class A or Class AB.

CLASS A OR AB?

The definitions of Classes A and AB, originally used for valve amplifiers are not strictly applicable to solid state amplifiers. An ideal Class A valve amplifier has an operating current that does not vary with output power. It can be either single-ended or push-pull. In push-pull operation, each valve still conducts through 360°. The advantage of push-pull is that the departures from linearity of the transfer characteristic of the valves should cancel. Class A has the lowest efficiency, and therefore the highest cost, but, as it is designed to dissipate all the DC power supplied to it when no input signal is present, it can also tolerate total reflection of the output power. The excellent small signal linearity of Class A is not a great advantage for EMC applications, but the ruggedness (load tolerance) is an advantage. Class A is also the only class of amplifier that will operate with very fast (e.g., pulse) modulation signals. In the other classes the amplifier operating current needs to vary with the modulating signal and the intrinsic parasitics of the amplifier circuits will not allow sufficiently rapid variation of the operating current.

Class AB allows for a slight overlap as crossover. Each valve conducts over more than 180°; thus reducing crossover distortion. A distinction between classes AB_1 and AB_2 indicates the presence or absence of positive grid current. Class AB has better efficiency than Class A, but the amplifier needs to be protected against excess reflected power if its thermal design takes advantage of this.

These classifications must be applied with caution to solid state amplifiers. The great majority of recent designs use field effect rather than bipolar transistors. A typical FET amplifier will operate in Class A, but the quiescent current can be lowered in order to lower dissipation when operating at low power. This does not reduce ruggedness at high power levels, provided that the cooling provision is not also reduced, so Class AB can be more reliable than Class A, depending upon the design margins allowed by the amplifier manufacturer. Note also that what one manufacturer calls Class AB another may call Class A. Many MOSFET amplifiers operate in a mode between Class A and Class AB whereas some GaAsFET amplifiers operate in Class A. These operating modes are considered to offer the best reliability, performance and cost tradeoff.

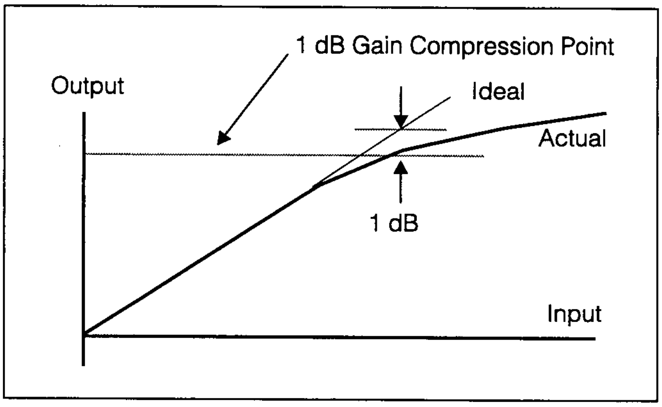

Figure 4. *Amplifier Linearity.*

LINEARITY

When using a power amplifier for EMC immunity testing with modulation applied to the signal source, a crucial assumption is made: the amplifier remains linear over its whole frequency range up to the maximum power it is delivering. If it does not, there are two consequences:

- The peak of the modulated RF envelope will be flattened. This creates harmonics of the modulation frequency (2 kHz, 3 kHz, etc.) which may excite susceptibilities in the EUT that would otherwise be unaffected. It will also reduce the actual peak applied field strength applied and therefore under-test the EUT. This will not be detectable since calibration is performed with an unmodulated signal, unless a wideband oscilloscope is used to check the modulated RF envelope continuously.
- Harmonics of the applied frequency will be generated (e.g., if one is applying 100 MHz, there will be components at 200 MHz, 300 MHz 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. IEC 1000-4-6 specifies harmonics and distortion more than 15 dB below the carrier level (-15 dBc). This can be checked while running the test by using a spectrum analyzer with a directional coupler on the power amplifier output.

A simple linearity check can be performed at any time by manually reducing the signal source level by 1 or 3 dB and confirming that the output level changes by the same amount. Amplifier linearity is normally quoted in terms of power output at the 1 dB gain compression point and the specified performance of harmonic generation (in -dBc) is only obtained up to this level. Above it, the distortion rises rapidly (Figure 4).

POWER GAIN

It is usual for amplifiers to be specified to deliver their maximum power output for a given input level, typically 0 dBm. 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 +10 dBm — 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, repair and recalibration should be swift and effective. It is unusual to have backup 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.

CONCLUSION

Choosing a power amplifier for EMC testing is not a simple matter of deciding on the power and bandwidth requirement and then comparing prices from different vendors. Many more subtle aspects are involved in determining the overall performance of the system in which the amplifier is embedded. This article has reviewed those features of a power amplifier which should be considered before making a final choice for an immunity testing system.

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