An Introduction to EMC Amplifiers

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Broadband amplifiers are necessary for generating the field strengths required for most EMC radiated immunity tests. This whitepaper provides a brief overview of the role of amplifiers in EMC testing as well as a discussion of the parameters and characteristics which have the greatest influence on amplifier performance.

White Paper

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1.2016 - 1

1 An Overview of EMC Testing

1.1 What is EMC Testing?

Figure 1 - Radiated emissions testing

Over the last several decades electronic devices have played an increasingly important role in almost every aspect of everyday life -- they have become virtually indispensable in business, industry, medicine, education and even in the home. All of these devices have the potential to interfere with, or suffer interference from, other electronic devices, either through radiated (over the air) or conducted (via cables) emissions. These interference effects can range from relatively minor disturbances, such as a barely perceptible audible buzz or visible flicker, to device failure and even permanent damage. Given the rapidly growing number of electronic devices, their often close proximity to each other, and their growing importance in our daily lives, it is essential that efforts be made in order to identify, measure, and limit or resolve interference between devices. **Electromagnetic compatibility** (EMC) is the term used to describe the ability of electronic devices to function properly within a defined electromagnetic environment.

The importance of electromagnetic compatibility has given rise to numerous governmental, military, and industrial EMC standards and regulations. In many parts of the world, electronic products cannot be marketed or sold without first demonstrating adherence to the relevant EMC standards, and therefore many companies have incorporated EMC testing into their product development cycle as well.

EMC testing can be subdivided into two general categories: emissions testing and immunity testing. **Emissions testing** (also called **interference testing**) involves measuring electromagnetic signals (unintentionally) emitted by the equipment under test (EUT) to determine if these emissions exceed the permissible limits, potentially causing problems for other nearby devices. The purpose of **immunity testing** (also referred to as **susceptibility testing**) on the other hand, is to verify that a device is capable of functioning properly even when exposed to (often significant) levels of radio frequency energy. There are numerous well-publicized examples of electronic devices that have malfunctioned or failed when exposed to high levels of RF energy -- in some cases malfunctions have even lead to injury and death. Our reliance on electronic technology has significantly increased the importance of effective and efficient EMC testing.

1.2 Amplifiers in EMC Testing

In order to perform immunity testing on an electronic device, we must subject that device to defined levels of radio frequency energy over a wide range of frequencies and verify that the device continues to function properly. This radio frequency energy may be **conducted** into a device via its attached cables or be directly picked up "over-the-air", i.e. from **radiated** signals.

As we will see, radiated emissions represent the greater challenge in immunity testing. The first reason for this is that radiated immunity (or susceptibility) testing often requires the creation of very high electric **field strengths**, with typical values ranging from 3 - 200 V/m. Depending on frequency, distance, and antenna type, this may require an output power of hundreds or thousands of watts -- far higher than most signal generators are capable of creating unassisted. The second reason is that converting conducted output power on a cable into radiated electromagnetic fields using antennas is never 100% efficient, particularly over the wide frequency ranges specified in most EMC standards and regulations. For these reasons, **EMC amplifiers** are an indispensable part of EMC testing.

Figure 2 - Broadband amplifier used in immunity testing

2 Amplifier Fundamentals

2.1 Introduction

In its simplest form, an **amplifier** is an active device that takes an input signal and produces an output signal that is a copy of the input signal, but with increased amplitude.

RF amplifiers can be constructed using a wide variety of devices -- traveling wave tubes (TWTs), klystrons, magnetrons, transistors, etc. For a variety of reasons, almost all modern broadband amplifiers used for EMC immunity testing below 6 GHz use solid state RF transistors. There is, however, some variation is the way in which the transistors are operated (that is, where their bias point has been set), and these have been grouped into **classes of operation**.

2.2 Classes of Operation

Classes of operation are defined in terms of the amplifier's **conduction angle**, or the percentage of the time during which the amplifier is "amplifying" or conducting power. A conduction angle of 360° means that the amplifier conducts over the entire input power cycle, whereas a conduction angle of 180° means that the amplifier only conducts over half of the input power cycle. Higher conduction angles mean higher linearity (i.e. the output is a more precise reproduction of the input) but at the cost of lower efficiency and higher temperatures.

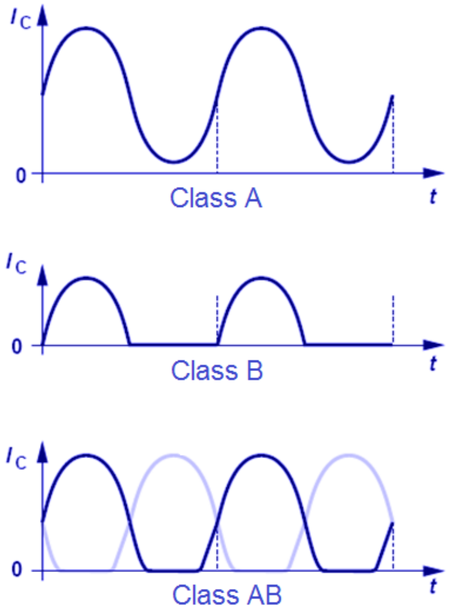


Figure 3 - Amplifier Classes and Conduction Angles

Amplifiers with a 360° conduction angle are called **Class A** amplifiers and amplifiers with a 180° conduction angle are called **Class B** amplifiers. A compromise between the conflicting goals of linearity and efficiency is the **Class AB** amplifier, which has a conduction angle between 180° and 360°. There are numerous other amplifier classes (Class C, Class D, etc.) but these are not used in EMC amplifier designs.

Due to the large amount of distortion they create, Class B amplifiers are generally unsuitable for EMC applications, and thus EMC amplifiers are almost universally either Class A or Class AB amplifiers. At first glance, Class AB amplifiers seem to have several advantages, such as lighter weight, lower cost, increased efficiency, and reasonably linear performance. However, due to their reduced ability to dissipate heat, Class AB amplifiers are much more susceptible to damage resulting from high VSWR levels (see below) than are commonly encountered during the course of normal radiated immunity testing. Although there are various ways to reduce the risk of damage to Class AB amplifiers (such as adding an attenuator at the amplifier output), these protection methods also limit the maximum power output of the amplifier. For these reasons, the use of Class A amplifiers is preferred over Class AB amplifiers in the design of broadband amplifiers used in immunity testing.

2.3 Output power

The most fundamental performance parameter for any amplifier is the level of output power it can produce, usually expressed in watts (or less commonly in dBm). Common immunity testing scenarios typically require output powers in the range of hundreds or thousands of watts in order to generate the necessary field strengths as per the relevant immunity testing standards.

The **gain** of an amplifier is simply the ratio of output power over the input power, usually expressed logarithmically in decibels (dB).

$$gain = 10\log\left(\frac{P_{out}}{P_{in}}\right) dB$$

The amount of output power produced by an amplifier is primarily a function of the drive (amplifier input) power -- for a given input level a corresponding output level is produced. In some cases, amplifier gain may also be adjustable over a given range.

With regards to EMC testing it is important to keep in mind that although amplifiers are specified in terms of their output power, the purpose of amplifiers in radiated immunity testing is to generate a **field strength** of a given intensity at a given distance from the antenna. As described below, field strength is a function of many variables and the amplifier output power needed to create a given field strength is usually highly frequency-dependent. For example, to produce a field strength of 10 V/m in a given test environment may require 100 watts at one frequency and 1000 watts at a different frequency -- the reasons for this are described in more detail later in this paper. We must therefore be sure to use an amplifier that can deliver the power to generate the necessary field strength over the entire frequency range of interest.

As a final note, the losses in lines, couplers, etc. may be non-trivial, especially at higher frequencies. These losses must be carefully considered when calculating the required power output of an EMC amplifier.

2.4 Linearity

As mentioned above, it is very important to use an amplifier that can generate sufficient output power over the entire frequency range used in testing. This can be challenging in that broadband amplifier output power will show some variation over its operating frequency range, even under ideal (matched) load conditions.

An amplifier is said to be operating in its "linear" region when there is a fixed increase in output power for a given increase in input power -- i.e. for every X dB increase in input power there is a X dB increase in output power. **Gain flatness** is a measure of how much the gain varies by frequency, often given in units of ± N dB. Gain flatness variation in the linear region of a well-designed amplifier is normally quite small and can often be ignored in practical applications.

However, eventually all amplifiers will reach a point in which there is no longer a linear relationship between the increase in input power and the increase in output power, and at this point the amplifier is said to be in **compression**.

Amplifier linearity is therefore also specified in terms of a **compression point** at a given power level. An amplifier operated below its compression point should not generate significant harmonics or intermodulation products. At the compression point there is no longer a linear relationship between input and output power. The most commonly used compression point is the so-called 1 dB compression point, which is defined as the point at which the actual output power is 1 dB less than the expected linear output power (for a given input power).

When comparing amplifier linearity, it's important to use the same power levels and compression points: the 1 dB compression point is by far the most widely accepted measure of amplifier linearity. However, some amplifiers are specified using 2 dB or 3 dB compression points, even though there will be significantly higher levels of harmonics and intermodulation products at these points compared to the standard 1 dB compression point. Furthermore, compression points should always be specified at full nominal output power -- for example, it is impossible for a user to know the performance of a 1000W amplifier whose 1dB compression point is specified at 700W.

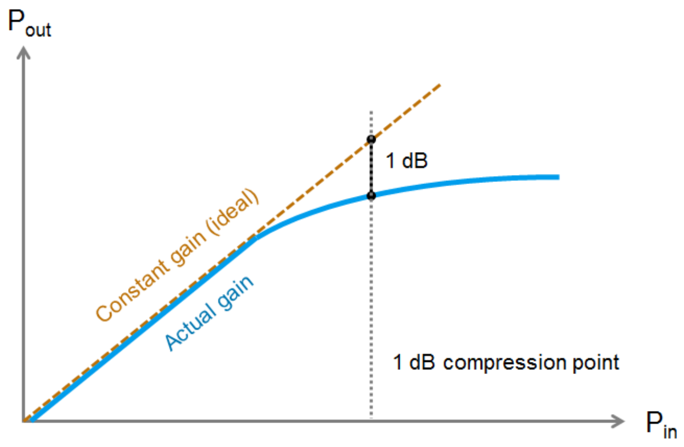


Figure 4 - Gain compression and 1dB compression point

When an amplifier is in compression, there are two consequences. The first is somewhat obvious: additional increases in input power no longer result in the same increase in output power, and eventually the maximum amplifier output power will be reached regardless of input power - we simply can't get any more power out of the amplifier because the amplifier has been driven into saturation. This problem is relatively easy to avoid if one choose an amplifier whose nominal maximum output power is sufficiently large.

The second consequence of being in compression is much more important with regards to radiated immunity testing. We know that amplifiers in compression can produce harmonics and intermodulation products at frequencies other than the fundamental frequency. These undesired products can increase rapidly and unpredictably as the amplifier goes further into compression. The power in these undesired products is power taken away from power at the desired frequency.

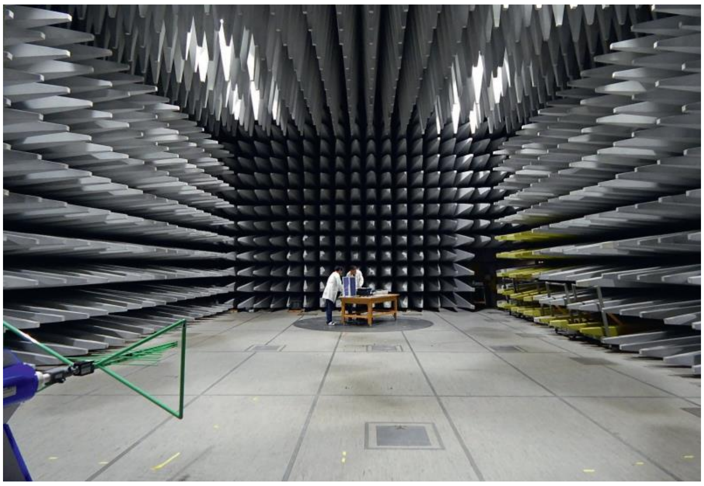


Figure 5 - Chamber used in radiated immunity testing

Recall that in radiated immunity testing we are trying to determine the frequencies and levels which adversely affect the functioning of an EUT. If an amplifier is in compression and generating intermodulation products, the possibility arises that the EUT may be reacting to the energy in these harmonics and intermodulation products rather than reacting (exclusively) to energy at the fundamental (intended) frequency. The presence of harmonics and intermodulation products can therefore make it very difficult to determine which frequency components are responsible for undesirable EUT behavior. Note too that while harmonics usually have lower power than the fundamental, the harmonic may actually yield a higher field strength due to the frequency response of the antenna. For these reasons, EMC standards often define the maximum harmonic levels at various power levels for a given test scenario.

Although field strength probes can be used to measure the field strength applied to the EUT, most field strength probes are not frequency-specific and therefore cannot (easily) be used to determine whether harmonics and intermodulation products are being generated. Frequency-selective devices such as EMI receivers or spectrum analyzers can be used to detect and measure any harmonics and intermodulation products present in the transmitted signal. While this is useful from a diagnostics point of view, it does not solve the problem of amplifier nonlinearities. The simple (and only) solution to the issue of nonlinearities is to choose an amplifier with good linearity and to operate that amplifier within its linear region. Harmonic specifications should always been given at full output power, never at a lower power output level.

Using an amplifier with a 1 dB compression point (well) above the maximum output power level is a simple way to help avoid nonlinearities and potential issues with the EUT responding to spurious frequencies. However, with regards to obtaining the necessary field strength, there is another important factor to consider: voltage standing wave ratio (VSWR).

3 Voltage Standing Wave Ratio (VSWR)

3.1 VSWR Overview

Maximum power transfer of radio frequency energy to a load occurs when the impedance of the load is the same as the impedance of the source. In this case, these two impedances are said to be "matched", and given a lossless transmission line, all of the output power generated by the amplifier will be absorbed by the load. This represents the ideal situation and provides maximum power transfer to the load -- something that is clearly desirable in radiated immunity testing.

What happens if the load impedance is not the same as the source impedance? In this case, some of the power transmitted towards the load (the **forward power**) is returned back to the source (the **reflected power**). This results in so-called standing waves on the transmission line between source and load - an undesirable, inefficient, and even potentially hazardous situation.

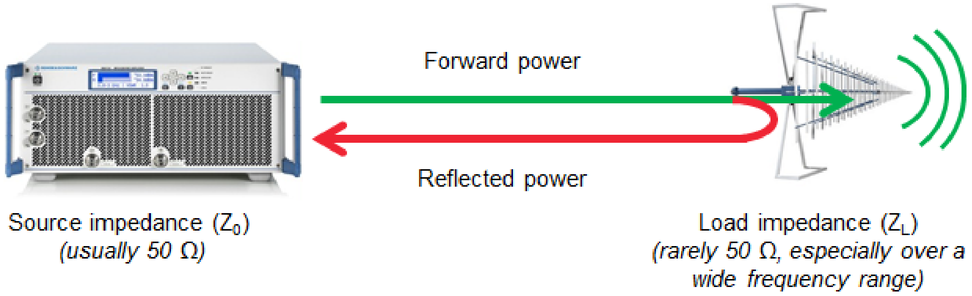


Figure 6 - Forward and Reflected Power

Reflection is quantified by means of a **reflection coefficient**, Γ, which is a function of the load impedance (Z_L) and the source impedance (Z_0).

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

As we will see, the fact that these impedances are complex, frequency-dependent values (R ± jX) has a tremendous impact on the selection and use of amplifiers for radiated immunity testing.

As mentioned above, the combination of the forward and reflected waves leads to standing waves on the transmission line. The ratio of the peak voltage to minimum voltage on a transmission line is called the **voltage standing wave ratio** (VSWR - often pronounced "viz-war"). VSWR can be derived from the reflection coefficient Γ as follows.

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

VSWR is most often specified either as a ratio (2:1) or as a normalized value (2). A VSWR of 1:1 (1.0) indicates a perfectly matched load with no reflected power. Although obtaining a perfect or near-perfect match is highly desirable (again, since it maximizes power transfer and minimizes reflected power), it is rarely obtainable in radiated immunity testing.

3.2 Antennas and VSWR

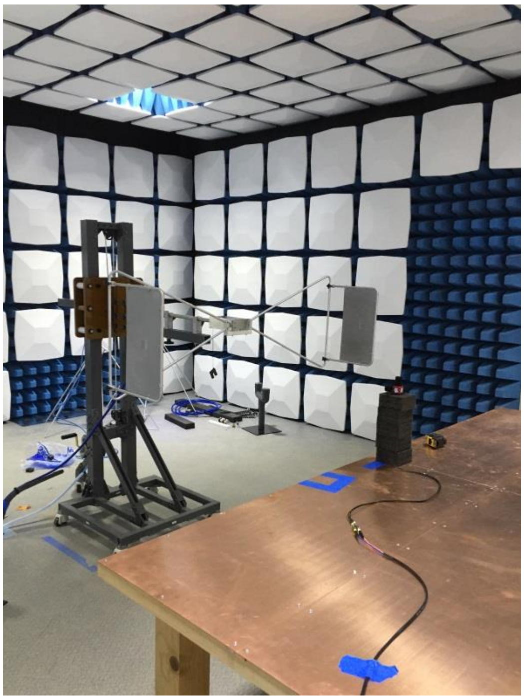


Figure 7- Antenna in a radiated immunity test setup

EMC amplifiers are normally designed to have fixed, non-reactive source impedance, typically with a nominal value of 50 (or 75) Ω over their operating frequency range. In most cases, this is an achievable objective that does not pose any issues for radiated immunity testing.

Instead, the challenge in immunity testing is the extreme variability of the **load** impedance. Unlike a purely resistive dummy load, the impedance of antennas used in radiated immunity testing normally varies tremendously as a function of frequency. It is difficult, if not impossible, to design antennas that have a low (< 2:0) VSWR over even moderately large frequency ranges. Many radiated immunity tests span a frequency range of several megahertz to several gigahertz, and even over much smaller frequency ranges, antenna impedance will vary widely. Even for well-designed and properly maintained antennas used in radiated immunity testing, VSWR can easily exceed 6:1 over their nominal operating range.

One potential solution for achieving "reasonable" VSWR values over these wide frequency ranges is to separate the total frequency range into smaller subranges and use a different antenna over each of these ranges. Based on practical considerations, the number of subranges is usually limited to six or less, depending on the standard. This method is quite common in radiated immunity testing, although it does require either manual or electronic switching between antennas (with a corresponding impact on test time and efficiency). Nevertheless, even it can still be difficult to obtain a "good" VSWR over even a single subrange, especially when VSWR is due to factors external to the antenna (see below).

Another potential solution is to alter the (apparent) impedance of the load. Since high VSWR is caused by a significant impedance mismatch, so-called **matching networks** are sometimes used in an attempt to make the load impedance "match" the source (or amplifier output) impedance. Although matching networks are used successfully in many applications, it is difficult to design matching networks that are effective and/or efficient over very wide frequency ranges.

3.3 Other factors affecting VSWR

Although the antenna has by far the greatest influence on VSWR, there are numerous other factors that can affect the VSWR during radiated immunity testing, and these must also be taken into consideration when selecting a broadband amplifier.

In an ideal testing environment, there would be no interaction or coupling between the EUT and the radiating antenna: field strength and VSWR would be the same whether the EUT were present or not. In reality, there is often some coupling between the antenna and the EUT, and this coupling can have a non-trivial impact on VSWR. The degree of coupling is a function of many factors, such as the distance between the EUT and the antenna, the aspect angle, and the composition / construction of the EUT itself -- all of these also being (highly) frequency-dependent.

Similarly, VSWR is often affected by the dimension of the chamber itself. Generally speaking, the smaller the chamber, the greater the effect on VSWR. For example, there may be a sharp increase in VSWR when the wavelength of the transmitted signal becomes close to one or more linear internal dimensions of the chamber. Factors such as the size, location, and electrical characteristics of the ground plane can also affect VSWR.

Although the nominal VSWR curve of a given antenna may be known, it can be difficult to predict or model external effects on VSWR, especially when these effects are frequency-dependent. In other words, we may not know how much a given EUT will affect VSWR until we actually put the device into the chamber and begin testing it. Note that coupling between the antenna and the EUT almost always results in an **increase** (rather than a decrease) in VSWR. Thus, it is prudent to allow for potentially higher-than-expected VSWR when planning for radiated emissions testing, and we will see how this in turn has implications with regards to choosing an EMC amplifier.

Note that although we've been discussing antennas and chambers as separate entities in terms of their contributions to VSWR and/or gain, in actuality there are complex interactions between them, with the degree of interaction being highly dependent on frequency, antenna placement and orientation, etc.

Figure 8 - Large metallic EUT with the potential for affecting VSWR

3.4 Effects of VSWR in immunity testing

It is sometimes easy to overlook the fact that in radiated immunity testing, we are not interested in RF **power** so much as in RF **field strength**. Antennas are used as transducers which convert conducted power into radiated fields, and this is where VSWR becomes a very important consideration: the higher the VSWR at a given frequency, the lower the percentage of amplifier power that is successfully delivered to the load (i.e. the antenna), and hence the lower the resulting field strength.

Therefore as VSWR increases, the level of amplifier output power must also be increased in order to maintain a given field strength. Problems can arise when a broadband amplifier faced with high VSWR is unable to produce the necessary output power to generate the desired field strength. When specifying a broadband amplifier, careful calculations must be made to ensure that the amplifier can deliver enough forward power to create the desired field strength over the entire frequency range and at all probable VSWR values. Poor linearity, uneven performance (especially at band edges), and unexpectedly high VSWR due to antenna-EUT coupling can all create a situation in which the necessary field strength is not achievable due to an underpowered or underperforming amplifier.

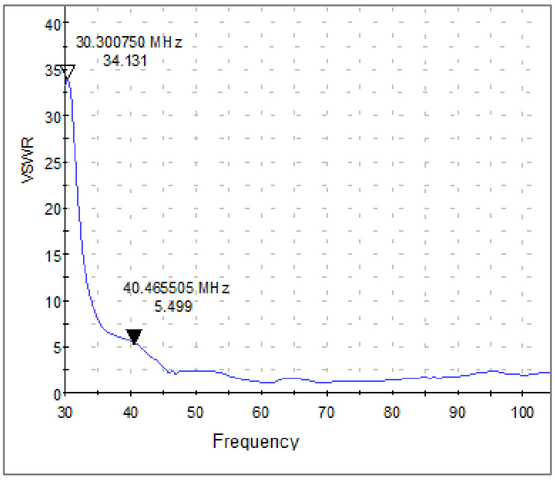
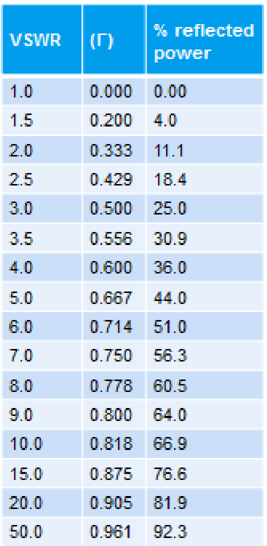


Figure 9 - Typical VSWR range (MIL-STD application)

The other complication of higher VSWR is the effect of the reflected power on the amplifier itself. A VSWR of 6:1 corresponds to 50% reflected power, and once VSWR reaches 15:1, more than 75% of transmitted power is reflected back towards the amplifier. High levels of reflected power can be very harmful to an amplifier: immediate damage to the amplifier can be caused by internal arcing or transistor breakdown. Damage or degradation of amplifier performance may also occur more gradually when reflected energy generates excessive heat within the amplifier itself.

The simplest way to protect an amplifier from reflected power is to put a fixed attenuator in the path. While this does reduce the level of reflected power seen at the amplifier, it obviously reduces the transmitted power as well.

A more sophisticated method of preventing damage from high reflected power levels is known as **foldback** -- as the reflected power level increases, the amplifier automatically decreases its output power until the magnitude of the reflected power falls to safe levels. Assuming the foldback circuitry can quickly sense and react to excessive reflected power, this approach is fairly straightforward and reliable. Foldback does however have one severe drawback: it reduces the power supplied to the load, and thus reduces the radiated field strength as well. Foldback can protect an amplifier from degradation or damage, but at the cost of (often significantly) reduced performance and the inability to achieve the target field strength.



VSWR	(Γ)	% reflected power
1.0	0.000	0.00
1.5	0.200	4.0
2.0	0.333	11.1
2.5	0.429	18.4
3.0	0.500	25.0
3.5	0.556	30.9
4.0	0.600	36.0
5.0	0.667	44.0
6.0	0.714	51.0
7.0	0.750	56.3
8.0	0.778	60.5
9.0	0.800	64.0
10.0	0.818	66.9
15.0	0.875	76.6
20.0	0.905	81.9
50.0	0.961	92.3

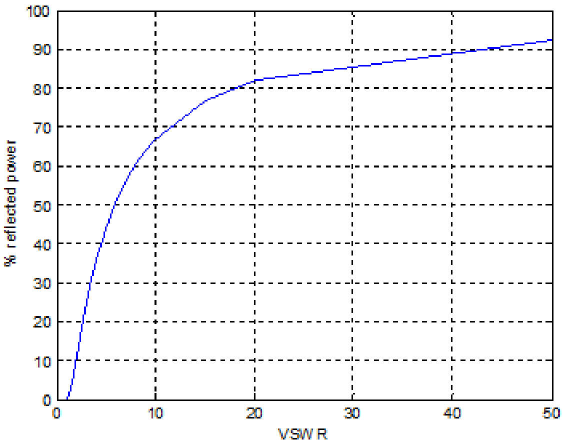


Figure 10- VSWR and % Reflected Power

While VSWR is used to describe the percentage of power that is reflected, it is the absolute **level** of the reflected power that triggers the foldback mechanism. For example, at a 6:1 VSWR, 50% of the power is reflected, but the amount of reflected power presented to the amplifier depends on the output level: 50% of 100 watts is far less damaging than 50% of 1000 watts. Therefore it is not enough to simply specify at which VSWR value foldback occurs -- we must also know at what power levels foldback occurs for a given VSWR. A 1000W amplifier that folds back to 500W at a VSWR of 6:1 is clearly superior to an amplifier that folds back to 500W at only a 3:1 VSWR. A clear understanding of how and when foldback is implemented in a given amplifier design is important in selecting an amplifier capable of generating the required field strength over the frequency range of interest, even under adverse VSWR conditions.

Obviously creating a uniform field strength across a wide range of frequencies can be very challenging. Fortunately, so-called "power leveling algorithms" are often included as part of EMC test automation environments, although the speed and efficiency of these proprietary algorithms can vary tremendously between platforms.

3.5 VSWR for open / short circuits

High VSWR values are often unavoidable during normal radiated immunity testing. However, we also have to consider VSWR in two abnormal (and potentially dangerous) situations -- namely, when the transmission line ends in either a short or in an open circuit. It goes without saying that neither of these situations should ever occur during normal immunity testing, but unfortunately shorted and open loads can and do occur as the result of both equipment failure and/or human error.

In the case of a short , the load impedance Z_L will be zero (since there is no load). An open corresponds to an infinite resistance (no current flow) and therefore Z_L will be infinity. Both cases (Γ= -1 and Γ = 1, respectively), result in a VSWR of infinity, and in both cases all of the transmitted power is reflected back towards the source.

The practical consequences of 100% reflected power (due to either a short or an open) can be dramatic, to say the least. Broadband amplifiers vary tremendously in terms of how long they can continue to operate without damage when connected to a large mismatch such as an open or short. Unfortunately, some broadband amplifiers are not well equipped to deal with these extreme (but sadly not uncommon) situations, and damage or complete destruction often follow within minutes of an open or short condition.

Excessive VSWR may be encountered either continuously or temporarily (such as during a frequency sweep). Although some amplifiers may be able to deal with short periods of high VSWR, amplifiers that are capable of running for extended periods (hours) into an open, shorted, or high VSWR loads provide an extra level of protection against potentially catastrophic failures. This is especially true in automated testing, when quick manual intervention may not be possible.

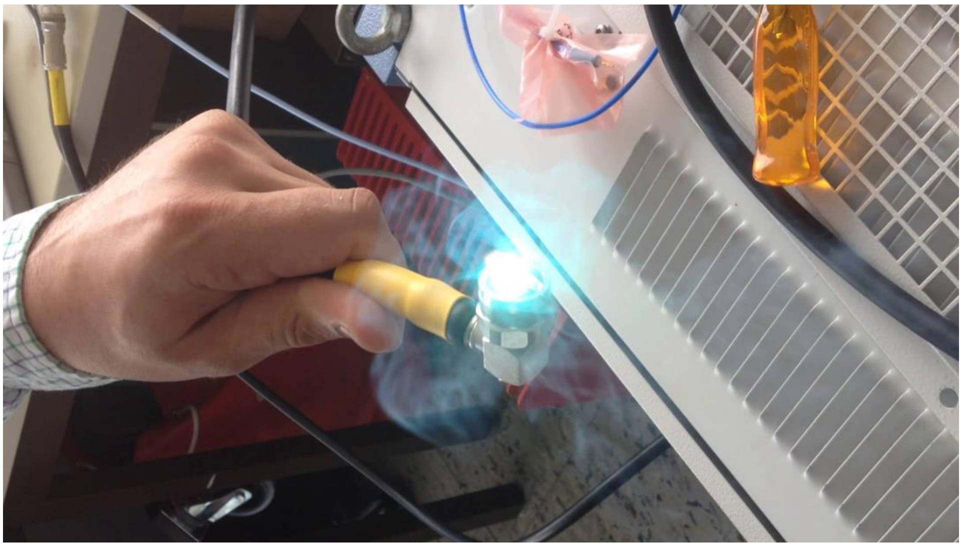


Figure 11 - Amplifier continuing to deliver power to an open load

4 Additional amplifier considerations

4.1 Heat dissipation

All amplifiers generate non-trivial amounts of heat, usually in proportion to both their output gain and to VSWR / reflected power level. Heat can temporarily degrade amplifier performance, reduce the operational life of an amplifier, and lead to permanent amplifier damage. Excessive heat generated by an amplifier can also adversely affect nearby external devices. Efficient heat dissipation creates a safer and more efficient (not to mention more comfortable) working environment.

For many low- to mid-sized amplifiers, air cooling is often sufficient, although the effectiveness of air cooling is highly dependent on the design and placement of heat sinks and fans. For larger amplifiers, liquid-based cooling systems are preferred due to their greater heat-dissipation capabilities. In some cases, liquid-cooled amplifiers may be equipped with external or remotely-mountable heat exchangers that allow the heat to be dissipated in another room or even outdoors. This can substantially reduce the amount of ambient heat as well as increase the reliability and longevity of the amplifier itself.

4.2 Noise level

Closely related to heat dissipation in air-cooled systems is the level of (audio) noise generated by the amplifier. High speed and high power fans are often used to cool broadband amplifiers, but these fans can create noise that is both continuous and substantial. Although the RF performance of an amplifier itself is typically unaffected by the level of audio noise it generates, serious workplace health and safety issues may result from an environment in which fan noise exceeds the levels recommended for normal human exposure. A properly designed and efficient air cooling system should not require extremely loud and/or bulky fans.

4.3 Additional considerations

In terms of control and operation, broadband amplifiers may be operated as standalone, manually-adjusted devices or as part of a larger test automation environment. In both cases, it is important that the amplifier have clear, easy-to-understand controls, preferably with visual indications of such parameters as output power and VSWR.

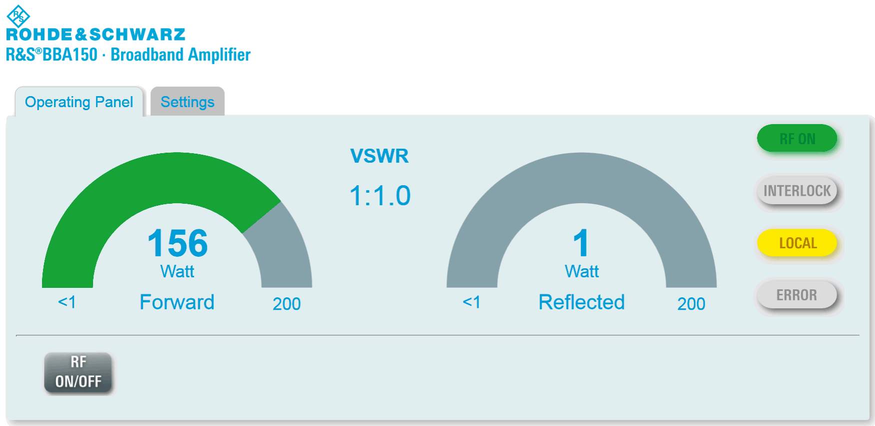


Figure 12 - Display of Forward / Reflected Power and VSWR

Although directional power meters can be used in-line to make direct measurements of forward and reflected power, built-in sample ports on an amplifier make this task both simpler and safer. Here also there can be differences between amplifiers, particularly with regards to the coupler's directivity and degree of isolation between ports.

Safety features such as interlocks (to automatically turn off power when a chamber door is opened, for example) are standard on most amplifiers, although multiple independent interlocks can be a useful feature for amplifier systems having multiple paths to different chambers. Modular amplifiers that can be configured for different (or multiple) frequency bands provide advantages both in terms of flexibility as well as ease of replacement / upgrade. One should not overlook the physical dimensions of the amplifier itself, such as size and weight. Ideally we would like an amplifier that produces maximum power output with minimum physical volume. And lastly, the ability to remotely access and diagnose an amplifier can be very helpful, especially in the case of geographically-distributed teams and test labs.

5 Summary / conclusion

EMC immunity testing uses broadband amplifiers in combination with one or more antennas to generate high levels of RF field strength. While the most important functional parameter of an amplifier is its output level, we have seen how this output level must be chosen based on performance-affecting considerations such as linearity and VSWR. In particular, the difficulty in achieving a good impedance match over wide frequency ranges means that amplifiers must be able to provide sufficient output power under widely varying VSWR conditions. Furthermore, amplifiers must be able to deliver this power with good linearity (i.e. without going into compression). An amplifier that can handle high levels of reflected power is also necessary for both performance and safety reasons. Careful consideration and accurate comparison of a wide range of parameters is the essential first step when evaluating amplifiers for immunity testing.

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