RF Power Amplifiers – Just How Do They Rate?

Abstract

RF power amplifiers have many different aspects that can be measured and, accordingly, specified. The obvious parameters are: frequency range, output power, and gain. Depending on the application, other parameters may be important such as bandwidth, harmonic output, gain compression, intermodulation distortion, etc.

1. Frequency Range and Bandwidth

For a broadband amplifier, bandwidth is the operating frequency range. For a narrowband amplifier, the bandwidth is generally defined as the difference of the -3 dB gain response frequencies, and the range is specified by the amplifier manufacturer. In some services, such as television, the amplifier must amplify the signal with minimum change in the amplitude and phase response over the bandwidth of the input signal and that defines the bandwidth. For fast pulse signals, wide instantaneous bandwidth is required to faithfully reproduce the pulse. The amplifier application determines both the range of operating frequencies and the instantaneous bandwidth required.

2. Gain

The gain of an amplifier is the ratio of output power to input power, usually expressed in dB. Amplifiers do not have a constant gain. Above the point where gain compression starts the gain decreases with increasing output power. Temperature affects the effective transistor gain. Varying load impedances affect the output stage gain, etc. Manufacturers usually measure the amplifier gain on the linear part of the input-output gain curve while operated into the specified load impedance. For linear amplifiers, measurement of the gain at one half the amplifier rated power allows measurement on the linear part of the curve. Due to the highly non-linear input-output curve of a class C amplifier, the measurement is usually made at rated power. See Figure 1.

3. Output Power and Gain Compression

The output power rating would at first seem obvious; however, there are many ways of specifying the output power of an RF amplifier. An amplifier used in an application where gain linearity is not important, such as FM, would generally be operated in Class C with the output stage saturated. The rated output power in this case would be the saturated output power.   For a linear amplifier, the power rating is determined and specified by the manufacturer and can be anywhere from fully saturated and just below the point of destruction to well down into the linear portion of the input-output curve. One unambiguous measurement is the 1 dB gain

compression point. This is the power level where the gain of the amplifier has decreased by 1 dB. Amplifiers may generally be operated at power levels above the 1 dB compression level; however, distortion of the signal increases rapidly. Linearity and low distortion are important when an amplifier is used for amplification of envelope modulated signals such as SSB, AM, and multicarrier. In these applications, the amplifier peak power should be below the 1-dB compression point in order to prevent clipping of the envelope peaks with subsequent high levels of intermodulation distortion.

4. Peak Envelope Power

An amplifier designed to provide a specified rated power will severely distort two simultaneously different frequency input signals that would each generate one half the amplifier rated power. A half power signal will have 0.707 times the full power voltage. When the two signals are applied to the input, both sine waves add, the total required voltage will now be twice the voltage for half power or 1.414 times the full power voltage. The amplifier would need to deliver two times the rated power at the voltage peaks. For two-tone operation without clipping the envelope peaks, each tone will need to be one-fourth the rated power. For linear amplifiers, the peak envelope power of the amplifier is also the rated power and for reasonable distortion levels, this should not be higher than the 1 dB compression power level. The voltage of multiple input signals add resulting in peak power requirements that are the square of the number of input signals.

5. Other Gain Compression Measurements

There are two other common gain compression power level measurements. In one case, the amplifier is operated at rated power then the input level is decreased 10 dB. The difference between 10 dB and the decrease in the output power is the full power gain compression. The other common gain compression measurement is the reverse of the full power measurement. In this case, the amplifier is operated at 10% rated power then the input level is increased 10 dB. The difference between 10 dB and the actual output power increase is the gain compression. Note that these measurements are not the same. In the latter measurement, the amplifier does not reach rated power by the amount of gain compression where in the first case the amplifier measurement is started at rated power. In both of these cases, it is the manufacturer's rated power that is the reference whereas the 1 dB compression power level is a function of the amplifier.

6. Harmonics

If an amplifier had a perfectly straight input output curve, there would be no harmonic output. Deviation from the straight input-output line results in squared, cubed, and higher order terms to describe the curve. When these terms are applied to an input sine wave, outputs at two, three, and higher multiples of the input frequency appear at the output. Measurement of the harmonic levels is usually done

at rated power. Measurement of the harmonics at lower than rated power will usually provide lower harmonic levels referenced to the output level as the amplifier is operated in a more linear part of the input-output line. Measurement of harmonics at higher than rated power will conversely have higher harmonic levels due to compression and flattening of the sine wave peaks. Meaningful harmonic measurements should be made at the rated power of the amplifier unless the amplifier is to be normally operated at lower than rated power.

7. Intermodulation Distortion (IMD)

The same mechanism that results in harmonic distortion, non-linearity of the input output curve, also causes an amplifier to function as a mixer as well as an amplifier. The third and higher order non-linearities of the gain curve causes mixer products of two or more input signals to fall in the pass band of the amplifier. If the input frequencies of the two input signals are f1 and f2, products such as 2f1-f2 and 2f2-f1 are close to the original two frequencies, separated by only the difference of the input frequencies. This particular intermodulation pair is the third order products. Fifth and higher order products are also generated but usually at much smaller levels than the third order products. To measure the third order products, two sine wave inputs that each produce no more than one-fourth the amplifier rated power are applied to the input. The third order products are measured with a spectrum analyzer relative to the power in one of the output signals. This measurement is indicated in dBc where the c indicates reference to one of the two tones. Typical values in a linear amplifier range from –25 to –40 dBc. Another specification of the same measurement that provides a number 6 dB higher has as the reference the peak envelope power and should be written dBpep. As this number is bigger by 6 dB than the same measurement referenced to the power in one of the signals, it makes the amplifier appear better. Frequently there is no reference indication in the intermodulation specification and one can usually expect that the peak envelope power was used. The spectrum analyzer used to make this measurement will be subjected to the peak envelope power of the input signal. In order to avoid overdriving the spectrum analyzer, the two input signals should be no higher than 6 dB below the highest analyzer graticule. Overdriving a spectrum analyzer can make both the harmonics and IMD appear much worse than they really are due to harmonic generation in the analyzer.

Another term, the third order intercept (TOI) point is related to the measurement of the third order IMD. See Figure 2. The third order intercept point is the intersection of the continuation of the linear part of the input-output curve and the continuation of the third order intermodulation output versus power level. The third order intercept point is above the output power capabilities of the amplifier. The measurement also requires an amplifier with reasonable linearity for the TOI point to have meaning. If an amplifier has poor linearity, the extension of the IMD line is poorly defined, as would be the TOI point. In a linear amplifier, the slope of the input output curve, if plotted in dB, will be one and the slope of the third order IMD will be three.

8. Input Impedance

The input impedance of an amplifier is simply the complex ratio of voltage and current. It is generally easy to measure, reasonably constant with input level and usually a small function of frequency. Nominal values of 50 or 75 ohms are typical.

9. Output Impedance

The output impedance of an amplifier can have several different definitions. The most often used is the design load impedance, usually 50 ohms. This is the impedance that the amplifier is designed to drive not the source impedance or the output impedance of the amplifier.

For power amplifiers, the source impedance is rarely 50 ohms as that would limit the efficiency of the amplifier to 50% before other losses reduce this value further. Generally, an amplifier design starts with a set of specifications such as frequency range, bandwidth, power, gain, etc. Active devices are then chosen that will meet the specifications and the design is started. The voltage swing and current that the active devices can safely withstand determine the output power level of an output module. Modules are then combined to achieve the required power. Nowhere is the device output impedance considered. Note that transistor manufacturers provide load impedance tables for their devices. These tables are not the transistor source impedance (or complex conjugate). To generate these tables, the output network is tuned for rated output power. The device is then removed and the device load impedance is measured at the input of the output network. Tuned vacuum tube amplifier design differs from solid state but the tube source impedance is generally not a consideration.

The source impedance of a solid state amplifier is generally lower than 50 ohms, 10 to 25 ohms is typical and tuned tube amplifiers generally have higher than 50 ohm source impedances, typically in the 125 ohm region. These non-50 ohm ohm values allow better efficiency than would a 50 ohm source impedance. To further complicate the issue of source impedance, the value is dependent on signal level, and for broadband amplifiers, the value is dependent on frequency. There are two values of source impedance that would result in 100% efficiency: zero (a voltage source) and infinite (a current source), both impossible in real devices.

Amplifiers that use quadrature combiners in the output will have close to a 50-ohm impedance measured from the amplifier output connector but this is a measurement of the combiner termination, not the source impedance of the amplifier. In other words this amplifier will have an S_{22} measurement of 50 ohms but can have any source impedance.

Signal generators are designed to have a 50 ohm source impedance but the power levels are so low that efficiency is not a consideration.

RF power amplifiers are designed to provide rated power into a specified load impedance, and only in special circumstances have a specified source impedance.

10. Load Impedance and Power Output

Tuned and untuned RF power amplifiers differ in their ability to produce power into other than the design load impedance. Tuned amplifiers usually have an adjustable output network that can compensate for a wide range of load impedances yet provide the design load to the amplifier device. This results in full rated power to the load over a wide range of load impedances.

Untuned amplifiers have been designed for a specific RF voltage swing and current capability, usually with some reserve for device safety reasons. The result is that as the load impedance moves away from the design value, the amplifier cannot provide much more than the design load voltage into higher impedance loads and conversely, not much more than the design current into lower impedance loads.

A VSWR of 2:1 causes a reflected power of only 11% per cent leaving 89% to be dissipated (or radiated) in the load. The VSWR information alone leaves out an important consideration which is the power that the amplifier can deliver to the mismatched load. If the amplifier were designed for maximum power into the specified load impedance of 50 ohms, the voltage across a 100-ohm load would be the same as across a 50-ohm load resulting in half power dissipated in the load. The same would apply to the current in a low impedance load. For a 3:1 VSWR, the power dissipated in the load would be 1/3 rated power, etc. This is not quite the actual case as amplifiers are generally designed to provide more than rated power and there are some other factors, such as device saturation voltage being a function of current, that allow higher than the rated power divided by the VSWR available to the load. One must also be careful about interpreting directional wattmeters. The power dissipated in the load is the forward power minus the reflected power. The forward reading alone is meaningless unless the load impedance is a 50 ohms.

11. Amplifier Class

The most common classes of operation of RF amplifiers are class C, class B, class AB and class A. There are also a number of switch mode amplifiers that are generally designed for specific applications.

Class C
Class C amplifiers are very non-linear and are used for constant envelope applications such as FM. They can have very high efficiency and because the conduction cycle is much less than 180 degrees, they require tuned circuits for energy storage and harmonic suppression.

Class B

True class B amplifiers have a 180-degree conduction cycle. Single ended amplifiers require tuned circuits for energy storage. A push pull amplifier could theoretically use untuned class B, but transistor and tube transfer curves are not really sufficiently linear at low levels to permit true class B operation in linear applications.

Class AB

Class AB operation has a conduction cycle of greater than 180 and less than 360 degrees. It is by far the most common mode for RF amplifier output stages used for linear operation. AB has good linearity and efficiency.

Class A

In a true class A amplifier, the DC supply current would remain constant under all levels of output power, from zero to full rated output. Amplifiers are usually not operated in true class A as the efficiency is very poor and compression also generally not as good as the same number of devices operating class AB. Due to the low efficiency, class A amplifiers generate a lot of waste heat and therefore require substantial cooling.

The class of operation chosen by the designer depends on the application. Amplifiers that operate above 500 MHz are generally operated with high bias current to help maintain the device gain. Many broadband amplifiers are also operated in the same mode but are not truly class A as there is a small change in supply current between quiescent and full output. Class AB is frequently used in HF and low VHF applications as it provides comparatively high efficiency with good linearity. The ability of an amplifier to withstand high VSWR loads is independent of the class of operation. It is more related to good heat removal and conservative operation of the output devices from the standpoint of device voltage and current limits and reasonable die temperatures.

12. Summary

RF power amplifiers are not perfect. There are limitations to linearity, harmonics power output, etc. An understanding of these limitations will help in specifying an amplifier for your application. For example: Do not specify full rated power to be delivered to a 3:1 VSWR if you don't really need it as that amplifier will cost three times one rated for 1:1. Power delivered to the load is that dissipated in or radiated by the load, not the forward reading on a wattmeter. Values of IMD better than 40 dB will be expensive. The source impedance of an RF power amplifier will generally not be 50 ohms. Be aware of the peak envelope power requirements when using multiple input signals. For linear amplifiers, the class of operation is relatively unimportant. The class is usually dictated by design requirements. Comparison of amplifiers of different manufacturers should be done very carefully as measurement conditions can be utilized to conceal deficiencies. Some examples

are measurement of harmonics at less than rated power and rated power specifications.