App-Note: 001 - VSWR and its Effects on Power Amplifiers

VSWR – Voltage Standing Wave Ratio is a result that happens from having an impedance mismatch between a source (an amplifier) and a load (test application). This mismatch can influence the performance of the source. VSWR is not a hard concept to grasp, but its effects on the instrumentation can be more difficult to realize. For this article, we will focus on RF/Microwave high power amplifiers and how they react to this common physical problem. Amplifiers sometimes need to institute protections to safeguard itself from being damaged. First, let's understand VSWR.

Most RF & Microwave systems are based on a specified impedance which is usually 50 Ω. The instrumentation and components in an RF test system will be designed to maintain this impedance to the extent possible. This allows for a predictable known transfer of power. Ideally, everything would be precisely 50 Ω, but as we all know, living in the real world there are variations. If the instrumentation covers a broad frequency range over many decades, it becomes far more challenging to maintain the ideal 50 Ω impedance. Some level of VSWR is unavoidable.

VSWR is calculated by the following:

$$Z_L > Z_O \quad VSWR = Z_L / Z_O$$

It's a simple ratio of the differences in impedance. The Larger Impedance (Z_L) over, the smaller Impedance (Z_O). 50 Ω/50 Ω = 1 is the ideal result. It can be written on its own and is unitless, or in some cases as a ratio, for example; 2:1, 4:1, or 10:1. The bigger the mismatch of impedance, the larger the VSWR. What is the result of a large VSWR or a small VSWR? The following equation shows a different way to find VSWR knowing the forward and reverse (or reflected) power.

$$VSWR = \left(1+\sqrt{\frac{Watts_{rev}}{Watts_{fwd}}}\right) \Big/ \left(1-\sqrt{\frac{Watts_{rev}}{Watts_{fwd}}}\right)$$

This equation introduces power which allows us to now understand a little more that the mismatch is causing power to reflect back to the amplifier. Reflected power is lost power not transmitted or received by the load. Having a mismatch reduces the delivered power and efficiency of the system. One should try to minimize lost power.

The lost power which is reflected where does it go? We know from Newtons Law of conservation of energy it must go somewhere. It ends up back at the amplifier. Therefore, the amplifier must handle this reflected power coming back into it. This reflected energy creates a standing wave with the output + the reflected. Looking at the worst case of infinite VSWR, this occurs with an open or a short at the amplifier output or load. Infinite VSWR causes a 100% reflection, which can double the voltage thereby putting stress on all the internal components. The stress can manifest as heat dissipation or higher voltages, this higher voltage pushes voltage breakdown limits.

How much reflected power must the amplifier be able to handle? It depends on the size of the mismatch. For this, we need to understand what is typical in most test applications. In most applications, the amplifier, the load, and setup are stable & designed with the lowest VSWR, usually kept to under 2:1. Where 10% of power could be reflected. 10%+100% of intended power = 110% total power that may need to be dissipated.

Examples of these systems are generally narrowband transmitters where designing antennas or transmission lines are a little easier as compared to broadband applications. However, there are applications where more than 2:1 can be seen. High VSWR is often due to testing with very broadband, high-power, and poorly matched loads. It is best to avoid this situation as much as possible, however, sometimes this condition is unavoidable as testing must still be done. Below is a chart showing VSWR vs. reflected power.

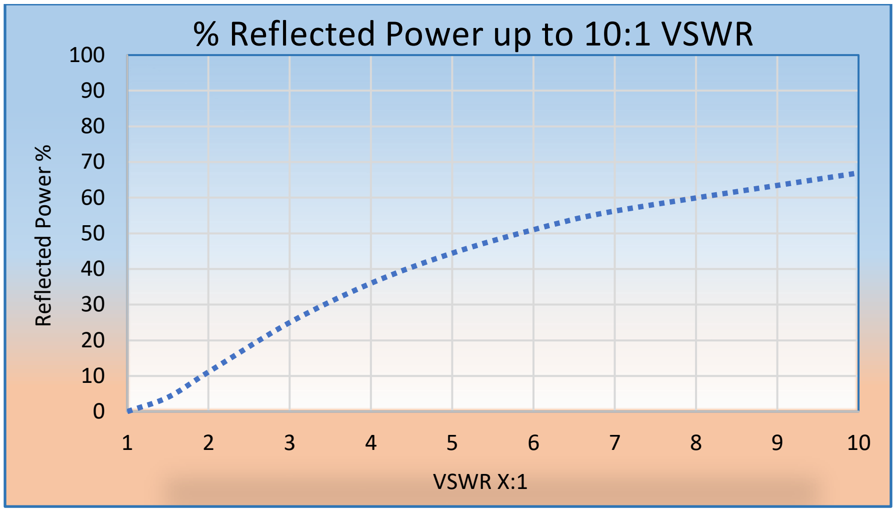

Figure 1: VSWR vs. % Reflected Power

The above chart shows that as VSWR increases so does the amount of lost power. At a 6:1 VSWR, 50% of your power is lost as wasted energy and may require a larger amplifier to overcompensate increasing the cost of your test application.

Examples of applications where loads can have high VSWR: low frequency (<100MHz) broadband, EMC testing for radiated immunity and conducted immunity, experimentation where the load might not be known, or instances where the load has failed or been damaged. Care should be taken to match the impedances better, and all the instrumentation can handle the VSWR. Keep in mind the VSWR is different across the frequency range. Higher VSWR levels are a sign of a poor setup. Steps should be taken to improve the impedance matching.

Improving VSWR

It is good to start with good quality components, interconnects, coax cables, and loads/transducers that have low VSWR ratings. If you have to use a load/transducer with high VSWR and need to improve the VSWR seen by the amplifier, what can you do? The most common way to improve VSWR is to use an attenuator, sometimes referred to as a PAD. A 3dB PAD added to the input of the load/transducer improves the match. This method is used many times when testing with (BCI) Bulk Current Injection probes and (Bi-Con) Biconical antennas. The negative aspect of this is that 3dB or ½ the power is delivered; 500 watts now becomes 250 watts. An alternative is to have a matching network which transforms the change in impedance. Thus losing less power than an attenuator would. Matching networks are more complex in design, they match only the load it is designed for and may be limited in frequency range. For this reason, matching networks are not readily available.

How do amplifiers handle VSWR?

Some techniques can be implemented in the design of amplifiers to handle higher levels of VSWR. Most amps can handle a 2:1 VSWR as this is a very common mismatch. Many amplifier specifications have a worst-case output rating of 2:1, so it must be able to protect itself from connecting to a 50Ω load. Solid-State amplifiers typically have far better robustness then this, possibly working without damage into shorts and opens while maintaining full forward power. Driving full power into the load can propose an unsafe test setup as typically a high VSWR is a sign of damage or an error in the test setup. As power levels increase above 100 watts to 1kW and further it is increasingly difficult to build an amplifier to handle infinite VSWR or 100% reflected power. It is sometimes thought that a Class A amplifier can inherently handle VSWR better than a Class AB amplifier. This is not necessarily the case. Robustness goes beyond what Class the amplifiers are biased at and has more to do with circuit design. But if the design cannot handle the high VSWR, other protections can be implemented.

Amplifier Protection

Active protection – comes in different forms. Many amplifiers will have basic circuitry protections such as over-temperature and current. These aid in protecting the amplifier from high VSWR but are not the main reason for their use. To safeguard from VSWR the output power and reflected power are usually monitored, and a protection loop is tied in. Two different methods are instituted:

> Shutdown – if a high reverse power (or VSWR) is measured, the amplifier will shut down with an error indicating the Fault. The manufacturer sets this to what is a safe reflected power level for the amp. Once the fault condition is cleared, the amp can then be used again.
>
> Foldback – if high reverse power is monitored, the amplifier reduces its internal gain, thereby lowering the output. This limits the reverse power from exceeding a threshold keeping the amp active but protected from failure.

Non-active protection – may be implemented to lower the amplifier cost since the setup has little or no chance of high VSWR. Or in cases where the amplifier is robust enough to handle high VSWR and therefore not need active protection. An example of this would be Circulator protection. Circulators prevent reflected power from returning to the source and are available for some frequency ranges and power levels. These are not typically available for broadband application <100MHz.

Conclusion

Knowledge of the VSWR levels in the RF setup is essential to know and understand to predict performance. High VSWR is a relative term depending on the application. In a vast majority of amplifier applications, a 2:1 is normal. Greater than 6:1 or even above 4:1 should be considered high. High VSWR is stress on all amplifiers becoming very concerning as powers increase to 500+ watts. Although specifications of an amplifier may state; "it can withstand all VSWR levels without damage" does not mean it is not stressful on the instrument. Prolonged exposure in this high VSWR condition can have damaging effects. Care should be taken to use the amplifier correctly and maintain a well-matched test setup. This will extend the life of the instrument and the equipment investment.