

Introduction

The measurement of Voltage Standing Wave Ratio (VSWR) has long been considered to be the most universal indicator of the health of transmission systems, and the continuous monitoring of transmission system VSWR, from the output of the transmitter to the input to the antenna is an important component in the maintenance of any wireless communication system. While it is possible to use precision reflection measurement instruments such as vector network analyzers to make high quality measurements on inactive systems, the day to day continuous monitoring of system VSWR under operating conditions typically is performed through the use of in-line directional measurement devices. The best results when using in-line measurement techniques are obtained through the careful management of specific measurement system components and parameters. In this article, we will outline the most important considerations when using in-line VSWR measurement approaches, as well as to provide some recommendations as to the application of these techniques. While we could spend significant time exploring the definition and the supporting mathematics associated with VSWR measurements, the focus of this article will be on the practical details associated with performing continuous measurements on a day to day basis.

VSWR Defined - By way of definition, VSWR is a measurement of the ratio of the maximum voltage of a standing wave pattern on a transmission line to the minimum voltage on the line. The standing wave pattern is developed as a result of the interaction of the forward traveling wave with the reflected traveling wave, where the magnitude of the reflected traveling wave is related to the degree to which the load is mismatched to the characteristic impedance of the transmission system. (see Figure 1)

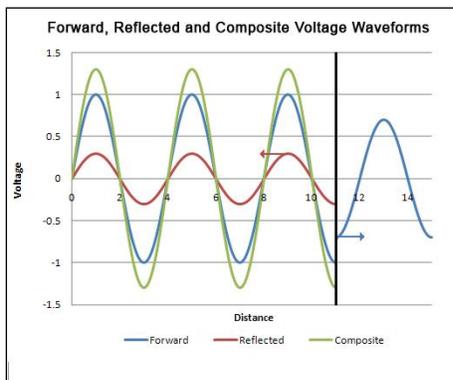


Figure 1

In-Line Measurements- As mentioned above, the most common technique used today for the ongoing maintenance of broadcast communication networks for routine VSWR measurements is to derive VSWR measurements from direct measurement of the forward and reflected traveling wave (forward and reflected power) using in-line directional power meters. This technique has been used for over sixty years with good results, particularly in cases where the directional power meters are carefully selected for specific applications according to signal type, frequency, and power range. While this technique is well established, there are several important considerations when making these measurements that will help to insure high quality measurements. Some of these are:

- 1) **Power Meter Accuracy** - What is the basic accuracy of the directional power meter to be used?
- 2) **Power Meter Dynamic Range** - Over what range of power measurements will the instrument maintain rated accuracy?
- 3) **Power Meter Directivity** - What is the directivity of the directional coupler which forms the heart of the power meter system?
- 4) **Signal Type** - What are the characteristics of the signals that are being measured?
- 5) **Location** - Where is the power meter located within the transmission system?

VSWR Measurements Using In-Line Power Meters

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Power Meter Accuracy - When using a directional power meter (reflectometer) for VSWR measurement, the VSWR value is based upon the values of forward and reflected power according to the following formula:

$$VSWR = \frac{1 + \sqrt{\frac{P_r}{P_f}}}{1 - \sqrt{\frac{P_r}{P_f}}}$$

Where, P_R and P_F are values of forward and reflected power as determined by the power meter. Based upon the above formula, it is clear that the basic accuracy of the power meter will have a direct effect upon the VSWR measurement. In addition, the power meter accuracy must be considered over the entire dynamic range of the instrument, rather than simply the accuracy of the power meter at a single point. It is best to use an example to illustrate this point:

The accuracy statements of most directional power meters are based upon either a percentage of the full scale range of the instrument, or as a percentage of the actual reading as determined by the power meter. For example, if a particular power meter is specified to have a **1 kW** full scale forward power range, and the rated accuracy of the instrument is **+/-5%** of full scale, the possible error of the instrument at full scale would be **+/-50W**, meaning that the instrument could provide a reading between **950W and 1050W** and remain within rated specifications. Using the same approach, if the power meter is operated at **500W** the error would remain at **+/-50W**, and the readings could be anywhere between **450W and 550W**, which translates to an error of **+/-10%**. Since the VSWR measurement is comprised of both forward and reflected readings, the accuracy of the reflected power measurement must also be considered. In our example, our 1kW power meter mentioned above might use a reflected power range of 100W full scale, again with a rated accuracy of **+/-5%** of full scale. As in the case of the 1 kW forward channel, the accuracy of the measurement at full scale is **+/-5%**, but this error expands to a value considerably greater than **+/-5%** for downscale readings.

To illustrate the effect that power meter accuracy has upon VSWR measurement, consider the following example:

Again considering our 1 kW transmitter system, if we desire to measure a load **VSWR of 1.1** with the power meter described above, this would mean that the reflected power associated with this VSWR value would be **2.26W** if the forward power is 1 kW. If our power meter has a specified accuracy of **+/-5%** of full scale, the actual VSWR reading will range from **1.09** on the low side, to **1.19** on the high side based upon instrument accuracy alone. This condition improves considerably with later generation power meters, where the accuracy of the power meter is specified as a percentage of reading, rather than a percentage of full scale. In large part, this has been made possible through the use of square law diode detector techniques, which behave linearly with respect to power. (see Table 1)

VSWR RANGE FOR POWER METER TYPES VSWR = 1.1		
Instrument Specifications	Reflected Power Range (W)	VSWR Range
% Full Scale	0 to 7.26	1.00-1.19
% Reading	2.15 to 2.37	1.09-1.10

Table 1



Power Meter Dynamic Range - The dynamic range of a directional power meter is defined as the range of power values over which the instrument is capable of resolving measurements, while maintaining full rated accuracy. It is important to note that in most cases, power meters used for broadcast applications are configured as full two channel instruments, with separate channels for incident and reflected measurements. Often, the full scale power ranges of each channel are tailored to specific measurement conditions. For the forward channel, the power range is selected based upon 80 to 90% of the transmitter operating power. The reflected channel full scale power is normally based upon the anticipated reflected power as it applies to the expected VSWR of the antenna system. There is however, a limitation to this approach based upon the maximum power handling capability of the directional coupler / detector circuit. For example, if a power meter is to be selected for a 20kW transmitter application and the expected antenna VSWR is 1.1, this would imply that the anticipated reflected power would have a value of approximately 46W. For this reason, it would make sense to set the full scale range of the reflected channel to 100W, so that the expected reflected power could be easily resolved.

Directional Power Meter Directivity - At the heart of every in-line, directional power meter is a directional coupler for the purpose of providing a sample of the transmission line voltage, while discerning between the forward and reflected traveling wave.

The directivity parameter for the couplers is a measure of how well the coupler is capable of discerning between the energy traveling toward the load, and the energy that is being reflected due to mismatch of the characteristic impedance of the transmission system with the impedance of the load. The directional characteristics of these couplers are a result of the fact that the coupler extracts two samples of the energy in the transmission line. One sample is derived from the electric field within the line, and the other is derived from the magnetic field. The directional nature of the magnetic field provides directionality, but the electrical balance between the magnetic field and the electric field samples serves as an indicator of the coupler directivity. The more balanced these samples are, the higher the intrinsic directivity of the coupler. Generally, directional couplers that are not fitted with frequency compensation networks have higher directivity, as the compensation networks are always reactive in nature, and will tend to alter the phase response of the coupler. These couplers will of course have a narrower operating frequency range.

As a first order approximation, the directivity value of a coupler may be used to determine the lower limit of the reflected power that a particular directional power meter is able to resolve. This is based upon the fact that although the reflected directional coupler is oriented such that it will respond only to the reflected traveling wave, it will also be affected by the forward traveling wave, in accordance with its directivity. For example, using our 20 kW transmitter example, if we are using a reflected directional coupler with 30dB directivity, this would mean that the reflected coupler would see about 20W of additional energy due to less than perfect directivity. (see Table 2)

DIRECTIVITY ERROR FIRST ORDER APPROXIMATION 1.1 VSWR	
Coupler Directivity	30 dB
Forward Power	20 kW
Reflected Power (Expected)	45.3 W
Max Reflected Power	65.3 W
Min Reflected Power	25.3 W
Max VSWR	1.12
Min VSWR	1.07

Table 2

While the above discussion will serve well as a first order approximation, it is important to understand that the samples of energy collected by a directional coupler will appear as voltages at the coupler sidearm, and thus must be treated as vector quantities. Further, both the magnitude and angle of the load impedance is also important in a complete analysis of the effects of directivity upon directional power measurements. Since the angle of the load impedance is rarely known, and any transmission line between the load and the directional coupler location will

transform the impedance seen at the coupler, the easiest approach to completely understand the effects of directivity is to calculate the change in reflected power appearing at the sidearm of the reflected directional coupler as both the contribution due to directivity and the actual voltage due to the reflected energy appearing at the coupler sidearm are treated as phasors. (see Fig.2) Returning to our example:

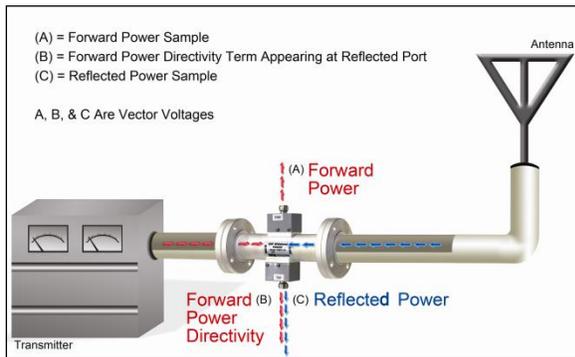


Figure 2

a) **Calculate Voltage Due to Reflected Power** - This may be determined from the following formula:

$$\text{Reflected Power (\%)} = \left(\frac{VSWR - 1}{VSWR + 1} \right)^2 \times 100$$

$$\text{Reflected Voltage} = \sqrt{P_R / R} = \boxed{V_R}$$

b) **Calculate Voltage Contribution Due to Directivity** - First, calculate the directivity power after converting the directivity value to a ratio, and then applying this to the forward power value. Based upon 30dB directivity, and 20 kW forward power, the directivity contribution would be:

$$\text{Directivity Power Ratio} = 10 \text{ (Directivity/10)}$$

$$\text{Directivity Power} = \frac{\text{Forward Power}}{\text{Directivity Ratio}} = \boxed{P_D}$$

$$\text{Directivity Voltage} = \sqrt{P_D / R} = \boxed{V_D}$$

c) **Find the Maximum and Minimum Reflected Power Limits** - These are found by simply adding and subtracting the voltages obtained in "a" and "b", and then converting these values back to power.

$$\text{Maximum Reflected Power} = \frac{(V_D + V_R)^2}{50}$$

$$\text{Minimum Reflected Power} = \frac{(V_D - V_R)^2}{50}$$

Based upon the above reflected power values, the VSWR measured at the power meter in this example (1.1 VSWR) will range from a low of **1.03** to a high of **1.17**. Keep in mind that this represents the change in VSWR over any condition of load phase angle. It is extremely rare that these conditions would be observed in practice. (see Table 3)

VSWR RANGE BASED UPON DIRECTIVITY ERROR (PHASOR ANALYSIS) 1.1 VSWR	
Coupler Directivity	30 dB
Forward Power	20 kW
Reflected Power (Expected)	45.3 W
Max Reflected Power	125 W
Min Reflected Power	5.12 W
Max VSWR	1.17
Min VSWR	1.03

Table 3

Finally, the directivity of a directional coupler will also serve as an indicator of the degree of immunity to line position under conditions of high standing wave. In other words, the higher the coupler directivity, the less immune to line position the coupler will be.

Signal Type - In-Line RF power meters are affected by the nature of the signals that they measure. The extent to which the power meter is affected depends upon the power meter type, as well as the modulation characteristics of the signals being measured. Conventional in line instruments that have been in use since the 1950's use point contact diode detectors, configured as peak detectors. These instruments are typically connected to analog meters with scales **calibrated** to read average power. Under conditions where modulation is not present (CW), or the crest factor of the signals to be measured is low, these instruments perform very well. As the crest factor of the signal is increased, these instruments tend to follow the envelope of the modulation waveform, resulting in greater inaccuracy. Later generation diode type power meters use detectors operated in the diode square law region, where the diode voltage output is proportional to the square of the input voltage. These detectors will provide detected voltages proportional to true power, as long as the signal applied to the detector is bounded within the diode square law region.

In-Line Power Meter Location - The location of the directional power meter within the transmission system may have a significant effect upon the ability of the instrument to resolve antenna VSWR. The prime consideration related to the location of the power meter is that the losses associated with the transmission line, as well as the insertion loss values of any other system components will have the effect of isolating (masking) the power meter from the measurement point. The best way to illustrate this point is with an example:

We are operating a 10 kW transmitter, connected to an antenna located **730'** up the tower, using 1-5/8" Heliac transmission line. The VSWR, measured with a directional power meter located at the output of the transmitter is **1.08**. The question is: what is the VSWR at the antenna?

The loss of 1-5/8" Heliac is specified at **0.2 dB per 100'** of length, this means that the one way loss due to the feedline is **1.46 dB**. Since a VSWR or Return Loss measurement is comprised of both incident and reflected parameters, the one way loss must be doubled to arrive at the isolation. A 1.08 VSWR corresponds to a return loss of **28.3 dB**. When the feedline isolation is subtracted from this value, the new return loss, at the antenna is **25.3 dB**, which corresponds to a VSWR of **1.12**. (see Table 4)

VSWR MASKING DUE TO TRANSMISSION LINE LOSS	
VSWR Measures at Transmitter	1.08
1-5/8 Heliac Loss	0.2 dB / 100'
Total Line Loss	1.46 dB
VSWR at Antenna	1.12

Table 4

If the path between the in-line power meter and the antenna includes components such as switches, adapters, or other items, the insertion losses of these components will also have the effect of further isolating the power meter from the antenna.

Conclusion - VSWR measurements using in-line power meters are important components in the day to day operation of broadcast transmission systems. Following the above guidelines will help to insure that the highest quality measurements are obtained using this approach.