The Effects of VSWR on Transmitted Power

By James G. Lee, W6VAT

No matter how long you have been a ham, sooner of later you will be involved in at least one discussion of something called the Voltage Standing Wave Ratio, or VSWR, of an antenna system. There is a lot of good information available on VSWR as well as a lot misconceptions about what it is and what it signifies. Probably the most often misconception is that your VSWR should be as close to 1:1 as possible, otherwise " you won't get out very well." A 1:1 VSWR implies a perfect match between all elements of the antenna system. The only problem is that it is possible to have a low VSWR and still have some very serious things wrong with your antenna system. Other misconceptions such as a high VSWR causing television interference, or other unwanted problems are often heard and can cause unnecessary worry. The concept of VSWR is easy to grasp and its importance in an antenna system does not require an engineering degree to understand.

WHY VSWR EXISTS

Early in electronics you learned that to get maximum power into a load required that the load impedance match the generator impedance. Any difference, or mismatching, of these impedance would not produce maximum power transfer. This is true of antennas and transmitters as well but, except for handie-talkies, most antennas are not connected directly to a transmitter. The antenna is usually located some difference from the transmitter and requires a feedline to transfer power between the two. If the feedline has no loss, and matches BOTH the transmitter output impedance AND the antenna input impedance, then - and only - then will maximum power be delivered to the antenna. In this case the VSWR will be 1:1 and the voltage and current will be constant over the whole length of the feedline. Any deviation from this situation will cause a "standing wave" of voltage and current to exist on the line.

There are a number of ways VSWR or its effects can be described and measured. Different terms such as reflection coefficient, return loss, reflected power, and transmitted power loss are but a few. They are not difficult concepts to understand, since in most instances the are different ways of saying the same thing. The proportion of incident (or forward) power which is reflected back toward the transmitter by a mismatched antenna is called reflected power and is determined by the reflection coefficient at the antenna. The reflection coefficient "p" is simply a measure of this mismatch seen at the antenna by the feedline and is equal to:

$$\mathbf{P = (Z1 - Z_o)/(Z_1 + Z_o)}$$

Here $\mathbf{Z_1}$ is the antenna impedance and $\mathbf{Z_o}$ is the feedline impedance. Both $\mathbf{Z_1}$ and $\mathbf{Z_o}$ are complex numbers so "p" is also a complex number.

You remember from elementary AC mathematics that a complex number has a "phase angle" associated with it. The phase of the reflected signal will be advanced or delayed depending upon whether the antenna appears inductive or capacitive to the feedline. If the antenna appears inductive the voltage will be advanced in phase, and if the antenna is capacitive, the voltage will be retarded. The reflective signal travels back to the transmitter and adds to the incident signal at that point.

Thus, any mismatch at the antenna gives rise to a second 'travelling wave' which goes in the opposite direction from the incident wave. When $\mathbf{Z_1 = Z_o}$ the reflection coefficient is zero and there is no reflected signal. IN this case all power is accepted by the antenna and this is the ideal situation where VSWR is concerned. The problem is that this condition is rarely, if ever, achieved and so "p" will have a value different from zero. Note that "p" can have negative values, but in calculating VSWR from the reflection coefficient, only the "absolute value" is used - which is a positive value lying between 0 and 1.

As the two travelling waves pass each other in opposite directions, they set up an interference pattern called a "standing wave". At certain places on the feedline the voltages will add producing a voltage maximum, and at others their relative phase difference will cause a voltage minimum to exist on the feedline. These maximum and minimum points occur 1/4 wavelength apart. In the days when open-wire feedlines were used these points could easily be measured with simple indicators. Coax cable however presents another problem since the "inside" of the cable is not readily available for measurements. Consequently, VSWR measurements on coax are usually made at the transmitter end of the feedline. Therefore you are presented with the VSWR of the entire system which includes all losses associated with the entire system.

INTERPRETING WHAT YOU HAVE READ

Many VSWR meters are calibrated to read FORWARD power as well as REFLECTED power. They may actually be measuring voltage, and simply have the scales calibrated in power. The important point is to understand what the meter is actually telling you. Assuming for the moment that the VSWR meter contributes no errors, the FORWARD reading is the SUM of the forward power and the reflected power. As a result, it is greater than your actual power output. The REFLECTED power reading is that amount of power which was not initially absorbed by the antenna and has been sent back down the feedline. At the transmitter end it encounters the transmitter output circuitry and is re-reflected back towards the antenna. This happens because you do, in fact, have a VSWR greater than 1:1 as seen by the transmitter. When the re-reflected power encounters the antenna, a portion of it is absorbed and the whole process starts over again.

Ultimately then, most of your signal is eventually absorbed by the antenna. You might be tempted to think that all of this bouncing back and forth would cause "smearing or blurring " of your signal but this is not so. The average transmitted signal appears as a "steady-state" signal to the feedline and antenna. Remember your signal is travelling at a significant fraction of the speed of light. For instance, the velocity of propagation of RG-8/A is 0.66 or 2/3 the speed of light. The speed of light is close to 1000 feet per microsecond, and a dot or voice peak takes milliseconds to complete. If the speed of light were 20 miles-per-hour then the situation would be completely different and we probably wouldn't have radio transmission at all. (Ed. Note, it would be as fast as the mail then.)

Given the reality then that almost all power launched down a feedline reaches and absorbed by the antenna, one has to wonder why VSWR is all that important. The importance is due to the fact that feedlines have losses and, antennas have something called radiation efficiency. They are what make proper interpretation of VSWR important. Power is lost due to feedline attenuation and this loss goes up as the VSWR goes up. The efficiency of an antenna is determined by the ratio of its "radiation resistance" to its "loss resistance". Antenna efficiency can simply described by the following equation:

$$\mathbf{\%\ Efficiency=[R_a/(R_a+R_{loss})]\ X\ 100}$$

The radiation resistance is $\mathbf{R_a}$, and $\mathbf{R_{loss}}$ is made up of any associated losses of the antenna such as loading coils and ground systems. How well you "get out" therefore depends more on low losses and efficient antennas than on what your actual VSWR is as the following example will show.

THE EFFECTS OF ATTENUATION ON VSWR

Early in this discussion the statement was made that your VSWR may appear to be very low and yet there could be serious things wrong with your antenna system. Figure 1 shows how this can happen. The curves in the figure represent the forward and the reflected voltage on an antenna which has a feedline loss of 3 dB. and a reflection coefficient of p=0.5. In this example the actual value of voltage is inconsequential and can be considered to be "E". We are only interested in relative values of "E" in any case. The length of the feedline is also arbitrary since we are only concerned with its total loss between transmitter and antenna.

Figure 1

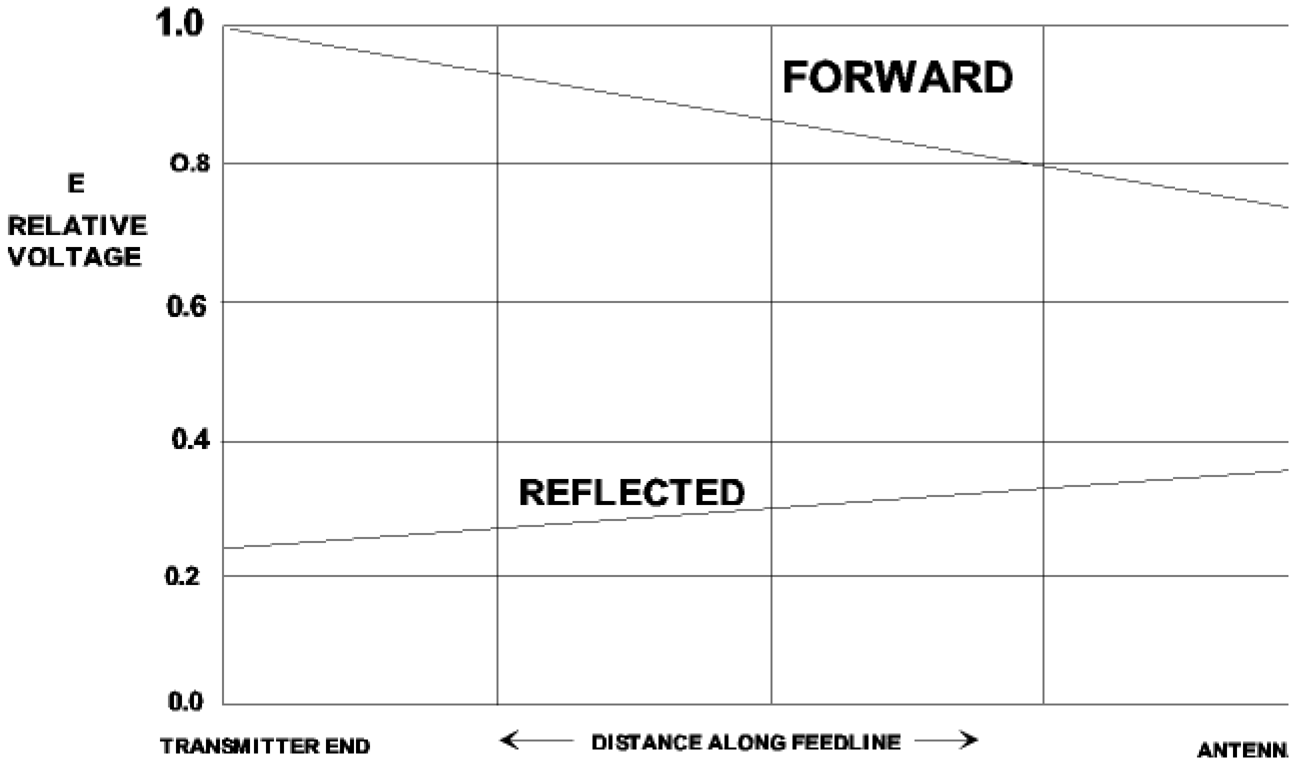

FIGURE 1: EFFECT OF LINE LOSS ON SIGNAL AMPLITUDE

The signal voltage "E" starts out at full value -1.0 E - on the feed line and is attenuated at a 3-db rate. This means that the voltage will only be 71% - or 0.707E - when it reaches the antenna terminals. Remember that while 3-db is a factor of two for power considerations, power is proportional to E-squared, consequently E will be only 0.71e when it arrives at the antenna input. The top curve in Figure 1 shows the FORWARD voltage decay as it travels down the feedline to the antenna input.

Since the antenna in this example has a reflection coefficient of 0.5, this means that 1/2 of the incident voltage will be reflected back down the feedline. This value is (0.5 X o.71E) or 0.35E volts. The feedline has no way of knowing which way signals are traveling, so this reflected voltage will suffer the same 3-db attenuation on the return trip. When it arrives back at the transmitter end of the feedline its value is only (0.71 X 0.35E) or 0.25 volts. The VSWR meter sees this value and since

$$\mathbf{VSWR=(E_{fwd} + E_{ref})/(E_{fwd} - E_{ref})}$$

the VSWR meter will read 1.67:1

That value of VSWR is guaranteed is to make almost everyone happy, but your antenna system is not very good. The 3-db loss down the feedline means only 1/2 of your output power reaches the antenna, and if your antenna has significant losses, something less than 1/2 of your power will be radiated depending upon how bad the losses really are. If for instance, the loss resistance equals your radiation resistance, the antenna is only 50% efficient meaning only 1/4 of your output power is actually radiated. Yet that reading of 1.67:1 looks fine. A reflection coefficient of p =0.5 means your antenna is not well matched to the feedline. VSWR can be calculated from the reflection coefficient by the following:

$$\mathbf{VSWR = (1+p)/(1-p)}$$

Using this formula shows your VSWR at the antenna is 3:1, quite a different value than your VSWR meter reads. The difference in the input and output VSWR values is due to the loss introduced by the feedline. Figure 2 shows how this loss can cause you to get a different VSWR depending upon where you measure VSWR in a feedline. You can measure VSWR at the antenna end of the feedline, but it is usually impractical to do.

Figure 2

FIGURE 2 EFFECT OF LINE LOSS ON VSWR

You can use 1/2 wavelengths of coax between your VSWR meter and the antenna because a 1/2 wavelength of cable repeats the impedance it sees. The only problem is that you are introducing other possible elements into your measurements. But let's assume that your VSWR measurement at the feedline is reasonably close to what is actually occurring on the feed line, and that your feedline losses are not great. The burning question still is "how good or bad is the VSWR reading?"

VSWR AND TRANSMITTED POWER

Let's assume you have an efficient antenna, fed with a low-loss feedline so that the VSWR meter at the transmitter gives you a true reading of 1.65:1. There is no real reason to try to lower it, in fact the same would hold true if the reading were 2:1. Figure 3 is a chart showing the equivalence of VSWR to RETURN LOSS(dB), REFLECTED POWER(%) and TRANSMISSION LOSS(dB). Return loss is related to reflection coefficient by the equation:

$$\textbf{Return Loss} = -20\log_{10}(p)$$

It is just another way of measuring VSWR. For example, with a perfect 1:1 VSWR there would be no reflected power consequently the return loss on the feedline would appear to be infinite. A short or open circuit at the antenna is the worst case scenario since the reflection coefficient would be p =1.0. All incident power would be reflected, and with a lossless feedline the return loss would be 0-dB. this is what the RETURN LOSS (dB) column refers to

The most informative columns in Figure 3 are the REFLECTED POWER(%) and the TRANSMISSION LOSS(dB) columns since they provide an answer to our question of whether further reduction of VSWR is worthwhile. Figure 3 shows that for a VSWR of 1.65:1 the reflected power is only 6.2% of the incident power, and the transmission loss is only 0.27 dB. In more familiar terms, if you count an S-unit as 6 dB, then the 0.27 dB loss is only 1/22 of an S-unit. A reduction of the VSWR to 1.5:1 would provide only a 0.09 dB reduction in transmission loss. This is not worth the effort it would take to achieve such a miniscule increase in power.

Figure 3

VSWR	Return Loss (dB)	Reflected Power (%)	Transmiss. Loss (dB)	VSWR	Return Loss (dB)	Reflected Power (%)	Transmiss. Loss (dB)
1.00	oo	0.000	0.000	1.38	15.9	2.55	0.112
1.01	46.1	0.005	0.0002	1.39	15.7	2.67	0.118
1.02	40.1	0.010	0.0005	1.40	15.55	2.78	0.122
1.03	36.6	0.022	0.0011	1.41	15.38	2.90	0.126
1.04	34.1	0.040	0.0018	1.42	15.2	3.03	0.132
1.05	32.3	0.060	0.0028	1.43	15.03	3.14	0.137
1.06	30.7	0.082	0.0039	1.44	14.88	3.28	0.142
1.07	29.4	0.116	0.0051	1.45	14.7	3.38	0.147
1.08	28.3	0.144	0.0066	1.46	14.6	3.50	0.152
1.09	27.3	0.184	0.0083	1.47	14.45	3.62	0.157
1.10	26.4	0.228	0.0100	1.48	14.3	3.74	0.164
1.11	25.6	0.276	0.0118	1.49	14.16	3.87	0.172
1.12	24.9	0.324	0.0139	1.50	14.0	4.00	0.18
1.13	24.3	0.375	0.0160	1.55	13.3	4.8	0.21
1.14	23.7	0.426	0.0185	1.60	12.6	5.5	0.24
1.15	23.1	0.488	0.0205	1.65	12.2	6.2	0.27
1.16	22.6	0.550	0.0235	1.70	11.7	6.8	0.31
1.17	22.1	0.615	0.0260	1.75	11.3	7.4	0.34
1.18	21.6	0.682	0.0285	1.80	10.9	8.2	0.37
1.19	21.2	0.750	0.0318	1.85	10.5	8.9	0.40
1.20	20.8	0.816	0.0353	1.90	10.2	9.6	0.44
1.21	20.4	0.90	0.0391	1.95	09.8	10.2	0.47
1.22	20.1	0.98	0.0426	2.00	09.5	11.0	0.50
1.23	19.7	1.08	0.0455	2.10	09.0	12.4	0.57
1.24	19.4	1.15	0.049	2.20	08.6	13.8	0.65
1.25	19.1	1.23	0.053	2.30	08.2	15.3	0.73
1.26	18.8	1.34	0.056	2.40	07.7	16.6	0.80
1.27	18.5	1.43	0.060	2.50	07.3	18.0	0.88
1.28	18.2	1.52	0.064	2.60	07.0	19.5	0.95
1.29	17.9	1.62	0.068	2.70	06.7	20.8	1.03

1.30	**17.68**	**1.71**	**0.073**	**2.80**	**06.5**	**22.3**	**1.10**
1.31	**17.4**	**1.81**	**0.078**	**2.90**	**06.2**	**23.7**	**1.17**
1.32	**17.2**	**1.91**	**0.083**	**3.00**	**06.0**	**24.9**	**1.25**
1.33	**17.0**	**2.02**	**0.087**	**3.50**	**05.1**	**31.0**	**1.61**
1.34	**16.8**	**2.13**	**0.092**	**4.00**	**04.4**	**36.0**	**1.93**
1.35	**16.53**	**2.23**	**0.096**	**4.50**	**03.9**	**40.6**	**2.27**
1.36	**16.3**	**2.33**	**0.101**	**5.00**	**03.5**	**44.4**	**2.56**
1.37	**16.1**	**2.44**	**0.106**	**6.00**	**02.9**	**50.8**	**3.08**

Further examination of the chart shows that a VSWR of 2.6:1 results in only about 1 dB of transmission loss. A high VSWR of 6:1 shows just a 3 dB transmission loss, but this is 1/2 an S-unit. You will still be getting out but this is becoming a significant loss. Your feedline will be dissipating more power than it should, and there may be other serious things wrong with your antenna system.

Throughout this article you've noticed the use of the term "antenna system". The word "system" means you must pay attention to other things besides just the VSWR and your power output. Each component of your antenna system must be optimized to get the best results. Many factors must be considered such as operating frequencies, bandwidth requirements of the antenna system, heights, and directivity, all of which affect its efficiency. Since the height of your antenna, and your operating frequency determine both the length of the feedline and its losses the interfaces become very important. So there are a number of trade-offs which must be considered when you contemplate putting up a good antenna system, but these are tales for other times.

You can build or buy your own VSWR meter, but make sure that you understand what it is measuring and what it is really telling you. Then once you are satisfied that you have put up a really efficient antenna, fed with a low loss feedline, you can sleep well knowing that to try to reach the ultimate 1:1 VSWR is only an ego trip. As a rule of thumb, any accurate VSWR reading under 2:1 is probably not worth the effort to achieve if the other elements of your antenna system are the best you can make them. In fact you might be surprised to find that you really do have a low VSWR when you put up the best antenna and feedline you can. There is an old saying in ham radio that "a dime in the antenna is worth a dollar in the transmitter any day". Try it and see if you don't agree. **-30-**

Editors note:
W6VAT has a lot of good points, and careful attention should be paid to what is covered in his article, as it can make a difference in your signal. A case in point involves a ham club that I belonged to many years ago. They had just gotten the license for their repeater, and the only antenna that was available was a commercial antenna fed with ancient heliax. The antenna had only a small amount of reflected power and it seemed to get out well. Everyone was happy, and all was well with the world.

Until my boss who was a ham and I took the liberty of checking out the repeater with the equipment from the two-way shop. When I disconnected the RG-8A pigtail, water poured from the heliax for about 5 minutes. But the Bird showed no reflected power with a 10 watt element and 50 watts forward. This was met with extreme disbelief when the club members were told of the water cooled coax. No one wanted to spend the money to replace the antenna and coax. However, since we had a very heavy rain just before the meeting, duplication of the waterfall was easily achieved.

To the extreme displeasure of the older members who wanted to "patch the feedline and connections" a motion to spend the money to replace the old antenna and coax with new everything. After the purchase of a Ringo and some 1" heliax and the installation of same, the repeater range was tripled. The grumblers did not like the Ringo, as "it was not good enough". And, after I had left the area, they spent nearly two hundred dollars for a commercial antenna cut for the frequency, which they purchased from a club member who ran a two way shop and was adamant that the Ringo was no good. They were totally destroyed to find out that the high dollar antenna gave them no more range than the Ringo.

The moral to this story is things are not always as they seem, especially when it comes to VSWR, coax, and antennas that seem to work on frequencies that they shouldn't. Never take anything for granted, especially when it is your RF going up the flue. **-30-** ***K5CNF***.

A Reader's Different Opinion

Editor's Update:
Jim Lee's article came out originally in a 1989 issue of antenneX and below is the first time our attention has been drawn to this... and he's right! Thanks George!
I read the article "The Effects of VSWR on Transmitted Power" by James G. Lee, W6VAT posted on your web site. While generally very good, it is in need of a correction and/or qualification. Mr. Lee states that, on a VSWR meter, "the FORWARD reading is the SUM of the forward power and the reflected power." This is only true if 100% of reflected power is re-reflected at the transmitter.While this can be true, it generally is not. It is probably more likely that no power is re-reflected at the transmitter than total power. Consider the case of a transmitter with a 50 ohm output impedance feeding a 50 ohm transmission line and a mismatched (not 50 ohm) antenna. Reflected power from the antenna impinges on the transmitter and, at 50 ohms, it is terminated.

Mr. Lee downplays the relevance of an antenna mismatch and it is no wonder -- he has overlooked the single biggest loss
due to a mismatch: the reflected power that is never seen again. By falsely claiming "the reality then that almost all power launched down a feedline reaches and absorbed by the antenna," he incorrectly concludes that an imperfect SWR is no
big deal. George Warner

Send mail to webmaster@antennex.com with questions or comments.

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