Understanding SWR by Example

Take the mystery and mystique out of standing wave ratio.

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It sometimes seems that one of the most mysterious creatures in the world of Amateur Radio is standing wave ratio (SWR). I often hear on-air discussion of guys bragging about and comparing their SWR numbers as if it were a contest. There seems to be a relentless drive to achieve the most coveted 1:1 SWR at any cost. But why? This article is written to help explain what SWR actually is, what makes it bad and when to worry about it.

What is SWR?

SWR is sometimes called VSWR, for voltage standing wave ratio, by the technical folks. Okay, but what does it really mean? The best way to easily understand SWR is by example. In the typical ham station setup, a transmitter is connected to a feed line, which is then connected to the antenna. When you key the transmitter, it develops a radio frequency (RF) voltage on the transmission line input. The voltage travels down the feed line to the antenna at the other end and is called the forward wave. In some cases, part of the voltage is reflected at the antenna and propagates back down the line in the reverse direction toward the transmitter, much like a voice echoing off a distant cliff. SWR is a measure of what is happening to the forward and reverse voltage waveforms and how they compare in size.

Let's look at what happens when a transmitter is connected to 50 Ω coax and a 50 Ω antenna. For now, pretend that the coax cable doesn't have any losses and the transmitter is producing a 1 W CW signal. If you were to look at the signal on the output of the transmitter with an oscilloscope, what you would see is a sine wave. The amplitude of the sine wave would be related to how much power the transmitter is producing. A larger amplitude waves means more power. This wave of energy travels down the transmission line and reaches the antenna. If the antenna impedance is 50 Ω, just like the cable, then all of the energy is transferred to the antenna system to be radiated. Anywhere on the transmission line you measured, the voltage waveform would measure exactly the same as the sine wave coming from the transmitter. This is called a matched condition and is what happens with a 1:1 SWR.

Table 1
SWR vs Reflected Voltage or Power

VSWR	*Voltage Reflected (%)*	*Power Reflected (%)*
1.0:1	0	0
1.1:1	5	0.2
1.2:1	9	0.8
1.3:1	13	1.7
1.4:1	17	2.8
1.5:1	20	4
1.6:1	23	5.3
1.7:1	26	6.7
1.8:1	29	8.2
1.9:1	31	9.6
2.0:1	33	11
2.5:1	43	18.4
3.0:1	50	25
4.0:1	56	36
5.0:1	67	44.4
10.0:1	82	67

For the case of resistive loads (see sidebar), the SWR can be easily calculated as equal to the (Load R)/Z_0 or Z_0/(Load R), whichever gives a result greater than or equal to 1.0.

The load or terminating resistance is the RF resistance of whatever is on the end of the transmission line. It could be an antenna, amplifier or dummy load. The line impedance is the characteristic impedance of the transmission line and is related to the physical construction of the line. Conductor size, space between conductors, what plastic was used in the insulation — all affect line impedance. Generally, the cable manufacturer will list the line impedance and there's nothing you, as a user, can do to change it.

But, what if the antenna wasn't 50 Ω? Suppose that the antenna is 100 Ω and the

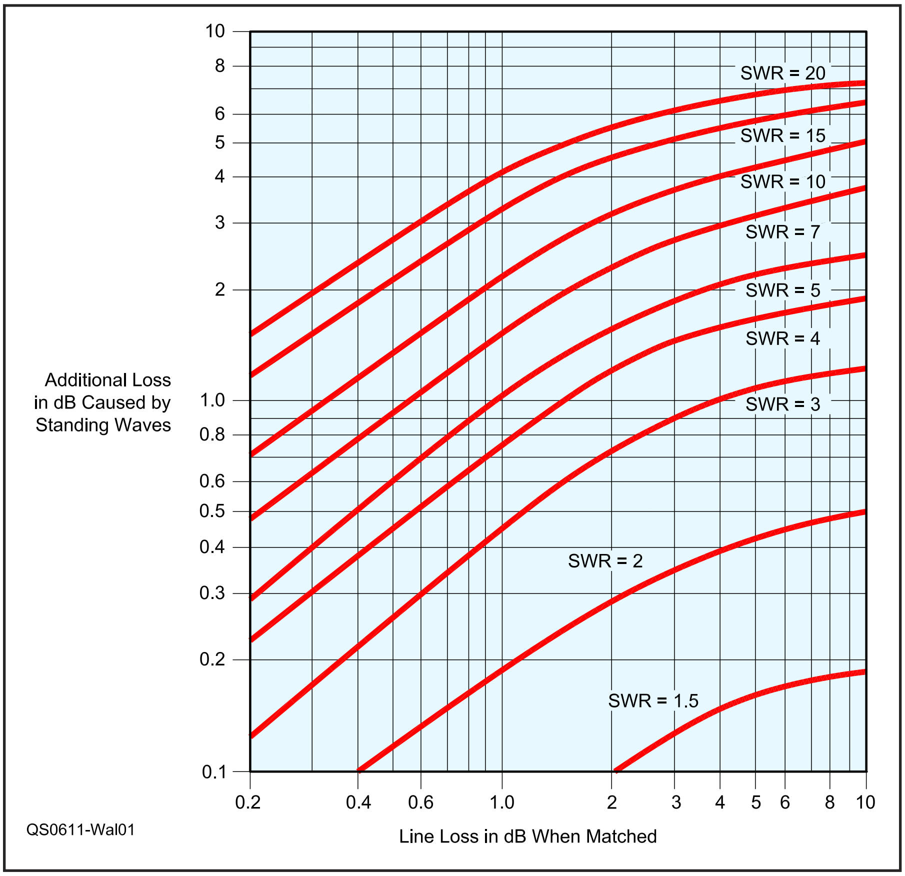

Figure 1— A graph showing the additional loss in a transmission line due to SWR higher than 1:1.

Adding Reactance to the Picture

In the main article I used several examples of SWR based on a resistive load. A resistive load is the easiest to visualize, calculate and understand, but it's not the most common type of load. In most cases, loads have some reactive impedance as well. That is, they contain a resistive part and an inductive or capacitive part in combination. For instance, your antenna might appear as a 50 Ω resistor with a 100 nH inductor in series, or perhaps some capacitance to ground. In this situation, the SWR is not 1:1 because of the reactance. Even antennas that show a perfect 1:1 SWR in mid-band will typically have some larger SWR at the band edges, often due to the reactance of the antenna changing with frequency. Fortunately, a given SWR behaves the same on a transmission line whether it's reactive or resistive. If you have a handle on understanding the resistive case, the concept will get you pretty far.

To explore SWR further, it's useful to look at the reactive load case, or what happens under the condition that loads are not simply resistive. Complex imaginary number math is the routine way to analyze the SWR of complex loads and can be done if you have access to a calculator or computer program that will handle it. Even so, the math gets tedious in a hurry. Fortunately, there's a very easy way to analyze complex loads using graphical methods and it's called the Smith Chart. See Figure A.

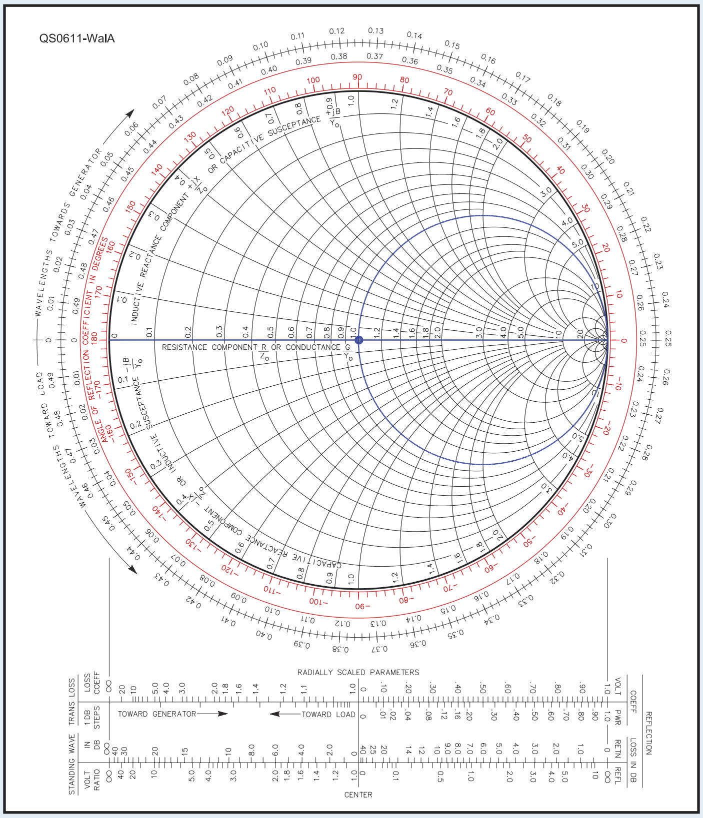

Figure A — The normalized Smith Chart, ready to simplify transmission line analysis.

The concept behind the Smith Chart is simple. There is a resistive axis that is down the middle of the chart, left to right, and a reactive axis along the outer edge of the chart's circumference. Inductive loads are plotted in the top half of the graph, and capacitive loads in the bottom. Any value of resistance and reactance in a series combination can be plotted on the chart. Then, with a ruler and compass the SWR can be determined. Advanced users of the chart can plot a load and use graphic techniques to design a matching structure or impedance transformer without rigorous math or computer. It's a very powerful tool. Here's a simple example showing how to determine SWR from a known load using the chart.

Suppose you have just measured a new antenna with an impedance bridge and you know that the input impedance is 35 Ω in series with 12 Ω reactive. The coax cable feeding it has a Z_0 of 50 Ω. What is the SWR at the antenna end of the coax?

This impedance can be written as the complex number Z=35 +*j*12.5 Ω. The "*j*" is used to indicate the reactive part from the real part and they can't simply add together. To use a "normalized" Smith Chart we divide the impedance by 50 Ω, to normalize the impedance. [Smith Charts are also available designed for 50 Ω with 50 at the center instead of the 1.0 that we show for the normalized chart. — *Ed.*] We now have Z=0.7 +*j*0.25. Smith Chart numbers are normalized, which means that they have been divided by the system impedance before being plotted. In most cases, the system impedance is the transmission line impedance and is represented on the chart by the dot in the center. Now plot Z on the chart. Along the horizontal line find the 0.7 marker and move upward (inductors or positive reactances are upward, capacitors or negative reactances are down-

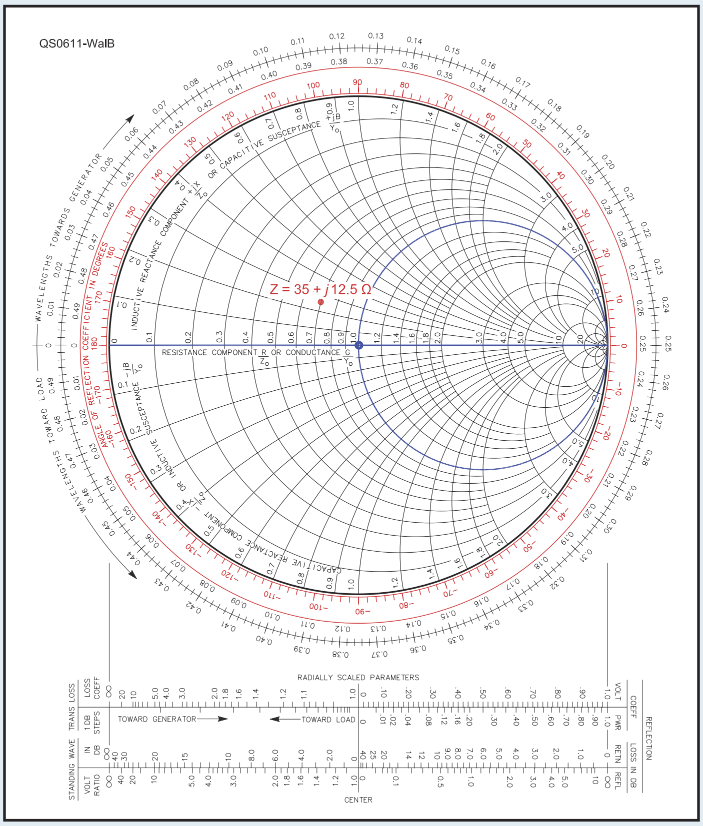

Figure B — An impedance of 35 +*j*12.5 Ω normalized to 0.7 +*j*0.25 Ω to use on the normalized chart.

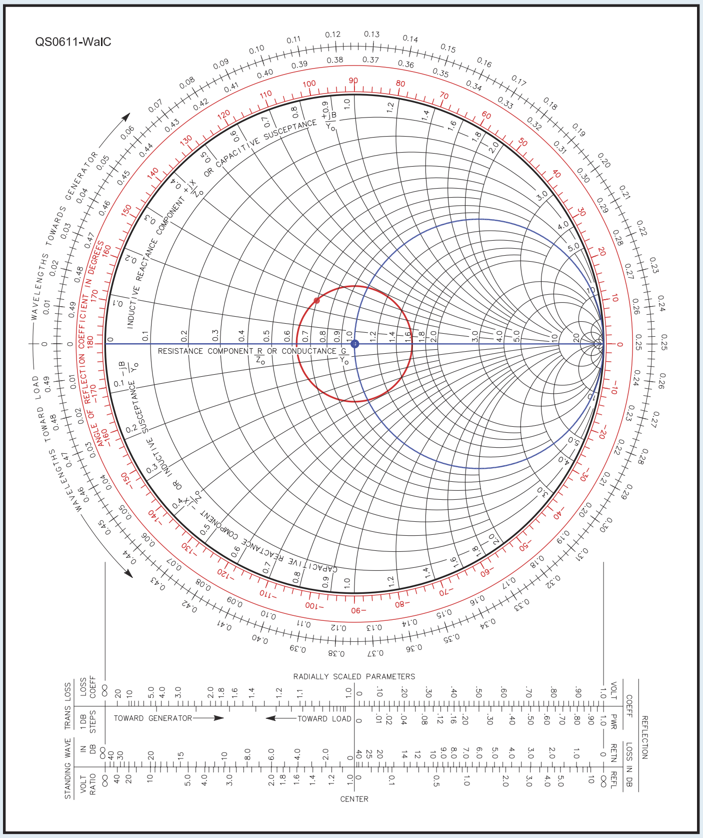

Figure C — A circle of constant SWR drawn through the impedance of Figure B. The SWR is 1.6.

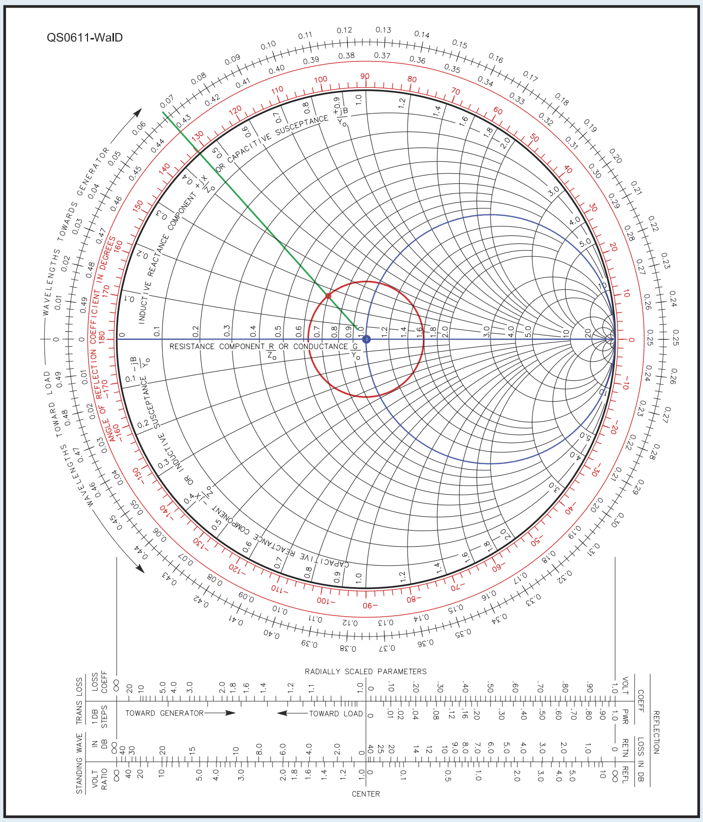

Figure D — A line drawn from the chart center through the impedance of Figure B to the edge showing the distance from the pure resistive points on the line.

ward from center) until you cross the 0.25 reactance line (see Figure B). Draw a point here that notes your impedance of 35 +*j*12.5 Ω. Next draw a line from the center dot of the chart to your Z point. Measure the distance of that line, then draw the same length line along the bottom SWR scale. From here you can read the SWR for this load. The SWR is 1.6:1.

Another useful attribute of the Smith Chart is called a constant SWR circle. The SWR circle contains all the possible combinations of resistance and reactance that equal or are less than a given SWR. The circles are drawn with a compass by using the distance from the SWR linear graph at the bottom and drawing a circle with that radius from the center of the chart, or use the numbers along the horizontal axis to the right of the center point. For instance, where you see 1.6 on the horizontal line, a circle drawn with radius distance from the center to that point is SWR 1.6:1 as shown in Figure C.

Now, any combination of impedance on the circle will be equal to SWR 1.6:1 and anything inside the circle will be less than 1.6:1. The example impedance that was plotted before should lie on the 1.6:1 circle.

Also useful is to know that rotating around the outer diameter of the Smith Chart also represents a half wavelength of distance in a transmission line. That is, as you move along the outer circle it's the same as moving along a transmission line away from the load. One time around the circle and you're electrically λ/2 away. This is also very powerful feature of the chart since it allows you to see how your load impedance changes along a transmission line again, without doing the math.

Here's another example. If your coax cable has a 1.6:1 terminating SWR, as you move along the transmission line away from the load, you move along the constant SWR circle on the chart. Remember from the article text that a 1.6:1 SWR can be equal to either 80 Ω or 31 Ω resistive? (1.6 = 80/50 or 50/31) From the Smith Chart, where the SWR circle crosses the horizontal axis, the impedance is purely resistive! Where the circle crosses 1.6, it's equal to 80 Ω and crossing at 0.62, it's equal to 31 Ω. This is the basis of how impedance transformers work. Remember to multiply any numbers from the chart by your working impedance (50 Ω in this example) to get their actual value.

Where do these purely resistive points lie on the transmission line? From the chart, looking at the line extended from the center dot through our Z point, find where it crosses the "wavelengths toward generator curve" on the outside of the chart as shown in Figure D. The line crosses at approximately 0.07 wavelengths on the chart, which will be the starting point. Note that the 80 Ω point (1.6) is at 0.25 λ and the 31 Ω point (0.62) is at 0.50 λ on the chart. Subtracting the starting point of 0.07, the chart is telling us that at 0.18 λ (0.25 – 0.07) from the load, the impedance is 80 Ω and at 0.43 λ away, it's 31 Ω.

To find the distance in a real piece of cable, multiply the chart wavelengths by the free space wavelength by the cable velocity factor. For example, if your frequency is 144 MHz then a full wavelength in air would be 300/144 = 2.08 meters. Multiplying by the velocity factor of 80% gives 1.67 meters. Multiplying by the chart wavelengths and then at 30 cm, you'd find 80 Ω and at 72 cm it's 31 Ω.

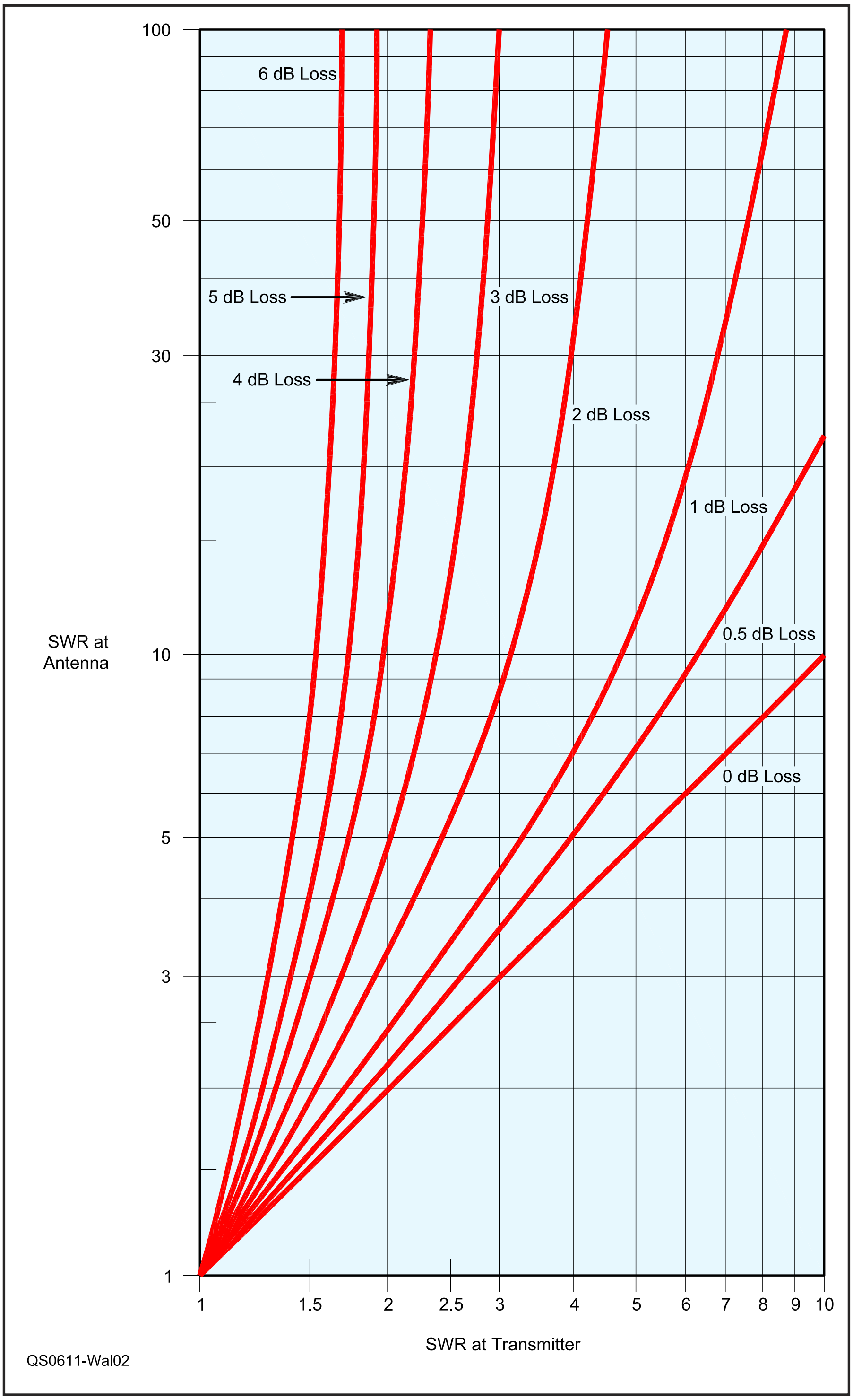

Figure 2 — A graph showing the actual SWR at an antenna based on measured SWR at the transmitter end of a transmission line with loss.

cable is still 50 Ω. The SWR for this setup is calculated as 100/50, or 2:1. Now the energy wave hits the antenna and part of it is radiated by the antenna, but part of it is reflected back down the line toward the transmitter. That is, the antenna is not matched to the line, so there is a reflection. It turns out that for a 2:1 SWR, 33 percent of the voltage wave is reflected like an echo back down the line. Table 1 lists how much voltage and power is reflected for various SWR values.

In the case of a mismatched condition, something interesting happens along the transmission line. Before, with the matched antenna, the same voltage existed anywhere along the line. Now as you move along the distance of the line, the voltage will change. It now has peaks and valleys. The 33 percent reflection from the antenna alternately adds to and subtracts from the forward voltage wave. At some places on the cable the reflected voltage adds to 133 percent, and others it subtracts to 66 percent of the matched transmitter output. The voltage ratio is 133/66 or 2.0. That voltage ratio defines the SWR. The fact that the voltage along the line changes with position and is different from what the transmitter would produce is called a standing wave. Standing waves are only present when the line is mismatched.

Does Higher SWR Lead to Lower Power Being Transmitted?

Not always so dramatically. Believe it or not, 100 percent of the power is actually transmitted in both of the previous examples. In the first case, with a 50 Ω antenna, it's easy to see how all the power is transferred to the antenna to be radiated since there are no reflections. In the second case, the 33 percent voltage reflection travels back down to the transmitter where it doesn't stop but is re-reflected from the transmitter back toward the antenna along with the forward wave. The energy bounces back and forth inside the cable until it's all radiated by the antenna for a lossless transmission line. An important point to realize is that with extremely low loss transmission line, no matter what the SWR, most of the power can get delivered to the antenna. A later example will show how this can happen.

Is High SWR Bad, or Not?

Now that you have a sense of what SWR is, a few examples can show why under some conditions, high SWR can lead to less power radiating and in other cases, it's no big deal. The easiest way to see how SWR affects an antenna system is to use a set of charts. Figures 1 and 2 are taken from *The ARRL Handbook* in the chapter discussing transmission lines. There is much more theory in the *Handbook* than I'm presenting here, so if you want to be an expert on transmission lines, that's one place to learn more.

In the previous examples, the transmission line had no loss and all our power was being delivered to the antenna. That's a nice way to visualize what is happening with the reflections, but it doesn't match the real world because all transmission lines have some loss. Here's a more practical, straightforward situation. This time we have a length of 50 Ω cable with a total loss of 3 dB (50 percent power), and a 50 Ω antenna. SWR is therefore 1:1. Transmitting 1 W would result in 0.5 W applied to the antenna. Since the SWR is 1:1 there is no mismatch loss to worry about. A very simple situation and no charts are needed. If life were only that simple!

Next try the 100 Ω antenna with the same coax. The SWR is then 2:1 at the antenna since 100/50 = 2.0. According to Figure 2, expect a mismatch loss of 0.35 dB in addition to the cable loss. In this case we lose a total of 3.35 dB of our signal and send the antenna 0.46 W. Not much difference from a perfect SWR of 1:1.

How about a SWR of 3:1 with the same cable? According to Figure 1 again, we would have an additional loss of 0.9 dB, which makes a total loss of 3.9 dB and 0.41 W to the antenna. This is still not a lot of additional loss even with an SWR of 3:1. Under most conditions a power reduction of 0.9 dB is not noticeable over the air. Even at a 3:1 SWR, the signal it not significantly reduced.

The SWR vs loss tables make it easy to figure out what your additional loss might be for any given antenna system, as long as you know the matched cable loss.

Is that the Whole Story?

No, not exactly. There's even more to explore in the world of SWR. One very strange situation occurs on a long and lossy transmission line, which causes your SWR to appear good at your transmitter even if it's terrible at the antenna. It's entirely possible to have a good measured SWR, huge losses in your feed line and no power getting out. Here's an example.

You've just set up your new 2 meter antenna and are feeding it with 120 feet of RG-8X cable. The manufacturer's data says you should expect 4.5 dB of cable loss for this length of cable at 2 meter frequencies. Not great, but you accept it. You measure the SWR at your transmitter and record a 2:1, which isn't great but not too terrible either. But wait — how bad is it? Remember all those reflections bouncing back and forth in the cable? Earlier I told you that they eventually radiate, but that was without cable loss. The story is different now — we have loss. Each one of the reflections is attenuated in the cable by 4.5 dB every time it goes from one end to the other or 9 dB round trip. The cable loss is attenuating the reflections and they die out in the cable instead of being radiated.

So, how bad is it really? Take a look at Figure 2. With a SWR at the transmitter of 2:1, and a 4.5 dB cable loss, the chart shows a 20:1 SWR at the antenna! Wow! That's much worse than the 2:1 measured at the transmitter. Looking back at Figure 1, that 20:1 SWR at your antenna is costing you another 7 dB of mismatch loss. In reality, the antenna system that you thought has only 4 dB of loss has 11 dB. Less than 1/10th of your transmitter power is being radiated! Good grief!

If this same cable had an open circuit instead of an antenna, and was several hundred feet long, the SWR meter at the transmitter would read 1:1. Why? Because cable loss tends to make a very long cable appear like a virtual resistance to the transmitter as the reflections die out in the cable. Remember, no reflections looks like a SWR of 1:1. The value of that virtual resistance in this case is 50 Ω which is the definition of characteristic impedance, or why some cables are called 50 Ω and some are 75 or 300 Ω. That number is the impedance the RF would see if the cable were infinitely long. Or, it is also the resistance of the load needed in order to cause no reflected energy and match the cable.

The moral of this story is to measure the SWR at the antenna, especially if you have a long cable run. SWR measurements at the transmitter can be deceiving. The second moral is to know that when a cable manufacturer quotes loss numbers, they are based on an SWR of 1:1, or a perfect match. Anything less than a perfect match can cause additional losses.

Why Ladder Line Works for High SWR

Open wire line, window line or ladder line has been used since the early days of radio. There is a good reason, since the loss of this type of cable is quite low at HF frequencies — lower than all but the very best coax cable. For instance, 300 feet of 450 Ω ladder line has a loss of less than 0.5 dB at 30 MHz when matched. A good quality expensive coax might have 1 dB of loss in the same length, but most high end amateur coax cable will have more than 2 dB attenuation under those conditions. It is because of this low loss that air dielectric (or mostly air in the case of window line) line can be used effectively on antennas that have high SWR, if the matching is provided at the transmitter. The lower loss of this type of line allows most of the reflections to radiate instead of being lost within the cable.

One last example shows how this works. You have just installed a full wave HF dipole. To feed it, you use 300 feet of 450 Ω ladder line with a loss of 0.5 dB at 30 MHz. You've modeled your antenna for 10 meters and you just happen to know that the impedance is 4500 Ω. That corresponds to a SWR of 4500/450 or 10:1 on your ladder line. Pretty bad, right? Not so fast. Consulting Figure 1 and knowing your matched loss is 0.5 dB shows an additional loss of 0.9 dB at an SWR of 10:1. The total loss of this antenna system is 1.4 dB. Not bad. Toss in a balanced line tuner and you're ready to go!

Your smart aleck buddy decides to install the same antenna but he springs for the best and most expensive coax figuring his antenna is only 40 feet away from his radio and he doesn't like the look of ladder line. He boasts that his coax loss is specified at 0.25 dB, which is half that of your ladder line. He figures he can also use a tuner to take care of the mismatch. You quietly smile at him because you know that the 4500 Ω of the antenna will present an SWR of 90:1 on his 50 Ω cable resulting in a mismatch loss of 12 dB beyond the 0.25 dB cable loss. Sure he can tune his SWR to 1:1 with the tuner at his radio, but guess who will be working the DX?

Conclusion

I hope I have been able to show by example that SWR can be a serious issue, or something not so important. With the help of the graphs and a little information about your transmission line and antenna, it's easy to determine how much of your signal is actually getting on the air or how much is being lost in the transmission line.

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