Understanding Standing Wave Ratios

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We worry a lot about Standing Wave Ratio (SWR) in amateur radio since SWR is one indication of how well our antenna system is working. Most HF transceivers and antenna tuners have built in SWR meters.

SWR is a measure of a transceiver's output power (P_f) verses the portion of that power reflected by the antenna system (P_r). If the antenna system is working well, most of the forward power will be radiated by the antenna with very little power reflected back to the transceiver. That is, the reflected power will be much less than the forward power ($P_r << P_f$). The difference between the forward power and the reflected power is the actual or true power (P_t) radiated by the antenna ($P_t = P_f – P_r$), assuming that losses in the transmission line are negligible.

If the output impedance of the transceiver, the characteristic impedance of the transmission line, and the impedance of the antenna itself are all equal (if we have a perfectly matched system), then the SWR will be 1:1. This is the best or ideal case in that all of the transceiver's output power P_f will be radiated by the antenna ($P_r = 0$). In practice, this case is rarely achieved. Normally the antenna system will reflect some power back to the transceiver. Typically then, the first number in the SWR ratio will be greater than 1. If SWR is represented as S:1, then S > 1 in most cases. From a practical point of view, SWR numbers in the range from 1:1 to 1.5:1 (1 < S < 1.5) are very good, meaning that the antenna is radiating most of the power sent to it.

The term Standing Wave Ratio, SWR, relates to the variation in the voltage (or current) along the length of the transmission line from the transceiver to the antenna. If the antenna is perfectly matched to the transmission line, there will be no variation in the voltage. The voltage measured at each point along the transmission line will be the same. However, if the antenna impedance is different from that of the transmission line, then some of the forward power will be reflected by the antenna and travel back toward the transceiver. The forward power traveling in one direction along the transmission line and the reflected power traveling in the opposite direction creates an interference pattern along the length of the transmission line. Because of this interference pattern, the voltage measured at various locations along the transmission line will no longer be the same. At some point the measured voltage will be V_m. A short distance from that point the voltage will be less than V_m. A little further on the voltage will be even less. As we continue to move away from that point toward the antenna, the voltage will reach a minimum value and then start increasing again. If we measure the voltage along the entire length of the transmission line, we find that the voltage varies sinusoidally. Furthermore, this sinusoidal voltage waveform is stationary, it does not move, it appears frozen in place along the length of the transmission line. Thus the name standing wave. The ratio of the highest voltage (V_h) to the lowest voltage (V_l) along the transmission line is called the standing wave ratio (SWR). Thus SWR = $V_h : V_l$. If the impedance of the antenna and the transmission line are the same, there is no reflected power, there is no standing wave, and the voltage everywhere along the transmission line is the same. That is $V_h = V_l$, and SWR = $V_h : V_l = V_l : V_l$ = 1:1, a perfect match. If the impedance of the antenna and the transmission line are not the same, some of the forward power will be reflected by the antenna, a sinusoidal voltage interference pattern will develop along the transmission line, and V_h will not equal V_l . In this situation $V_h = SV_l$, where S is some number greater than 1. Thus in this case the SWR = $V_h : V_l = SV_l : V_l = S : 1$.

The output impedance of commercially available amateur radio transceivers is 50 ohms. The characteristic impedance of the various types of coax cable transmission lines used in amateur radio is also approximately 50 ohms. However, the impedance of the antenna is rarely 50 ohms. The radiation resistance of a quarter wavelength vertical antenna with a very good ground plane is about 35 ohms. The radiation resistance of a half wavelength center fed dipole is about 70 ohms. In each case, this is the approximate impedance of the antenna at its resonant frequency. In both cases the antenna impedance is pure resistive (the antenna appears to be a resistor). Above its resonant frequency, the antenna's impedance is inductive (the antenna appears to be an inductor in series with a resistor). Below the resonant frequency, the antenna impedance is capacitive (the antenna looks like a capacitor in series with a resistor). The impedance of the antenna is not equal to 50 ohms in any of these situations. As a result, part of the transmitted power will be reflected by the antenna back to the transceiver.

In terms of SWR ratios, the reflected power $P_r = [(S-1)/(S+1)]^2 P_f$ and the power radiated by the antenna (P_t) is given by $P_t = [1 – [(S-1)/(S+1)]^2]P_f$. As an example, suppose that the power output of a transceiver is $P_f = 100$ watts and the antenna system is perfectly matched with an SWR of 1:1 (S = 1), then

$$P_t = [1 – [(S-1)/(S+1)]^2]P_f = [1 – 0] P_f = P_f = 100 \text{ watts.}$$

That is, all of the transceiver's output power is actually radiated by the antenna. As a second example, suppose that the SWR of the antenna is 3:1 (S = 3). In this case

$$P_t = [1 – [(S-1)/(S+1)]^2]P_f = [1 – [(3-1)/(3+1)]^2] 100 = [1 – [1/2]^2] 100 = 75 \text{ watts.}$$

In this example only 75 watts of the transceiver's output is actually radiated by the antenna. The remaining 25 watts is reflected by the antenna back to the transceiver. Expressing the true power P_t actually radiated by the antenna relative to the transceiver's output power P_f as a db power gain (or loss if a negative number) we have

$$db = 10 \log (P_t / P_f) = 10 \log [1 – [(S-1)/(S+1)]^2].$$

If the antenna system SWR = 3:1 then the gain = 10 log [0.75] = -1.25 db. Since the gain is negative, the antenna system will actually produce a loss which is what would be expected. What is interesting is that an SWR of 3:1 is considered to be a high undesirable SWR, and yet it results in a loss of only 1.25 db, hardly noticeable to anyone receiving the transmission. Remember that a 3 db gain or lost in power is required at the transmitter before a person receiving the signal will notice any change in received signal strength. However, there is more to the SWR story.

Power reflected by the antenna will travel back through the transmission line and arrive at the output of the transceiver. Modern day semiconductor transceivers do not handle this reflected power well. If the reflected power is sufficiently high, it can severely damage the transceiver's power output transistors. To avoid damage, manufacturers design protective circuits into the power output stage. The protective circuit reduces the transceiver's output until the magnitude of the reflected power is below that which would cause damage to the transceiver. In terms of SWR ratios, transceiver's typically operate at their full nominal output power P_n, for example 100 watts, at SWR values of less than 1.5: 1 ($S < 1.5$). For SWR values greater than 1.5:1, the transceiver's protective circuitry kicks in, typically limiting the transceiver's forward output power P_f to approximately $P_f = [1/(S-0.5)^2] P_n$, where $S > 1.5$. If the antenna system SWR is 3:1 and the transceiver's nominal output power $P_n = 100$ watts, the output power of the transceiver will be limited to $P_f = [1/(S-0.5)^2] P_n = [1/(3-0.5)^2]100 = 16$ watts! In terms of db change, the protective circuitry drops the transceiver's power output by

Power reduction = 10 log [P_f / P_n] = 10 log [$1/(S-0.5)^2$] for S > 1.5.

For an SWR of 3:1, the power reduction = 8 db. This power reduction will clearly be noticeable at the receiving end.

The total loss in power due to a high SWR is the sum of the db power reduction imposed by the transceiver's protective circuitry and the loss resulting from reflection at the antenna. Thus:

Total SWR loss = 10 log [$1/(S-0.5)^2$] + 10 log [$1 – [(S-1)/(S+1)]^2$] , for S > 1.5.

The interesting observation from this equation, and the above discussion, is that the power reduction imposed by the transceiver's protective circuitry is considerably greater than the loss at the antenna due to mismatch reflection. At an SWR of 3:1, the total SWR loss is 9.25 db, a considerable loss. However, the total SWR loss at an SWR of 2:1 is approximately 4db, which is just barely perceptible at the receiving end. For an SWR less than 1.5:1, power loss is negligible since the transceiver operates at full output power and the mismatch reflection loss at the antenna is less than 0.18 db.

So far the discussion has assumed that the transmission line loss is negligible. But suppose this is not the case. Suppose that there is 3 or 4 db of loss in the transmission line, as might be experienced at UHF frequencies. How will this loss affect SWR readings? A transmission line with loss will cause the SWR measured at the transceiver to be better than the actual SWR at the antenna. It is easy to see why this is the case. The transceiver determines the SWR it sees by comparing the amount of power that it transmits to the antenna verses the reflected power that it receives back from the antenna. However, some of the power that it transmits is consumed by the lossy transmission line, so the power actually reaching the antenna is less than that output by the transceiver. Part of the power arriving at the antenna is then reflected by the antenna. However, since the power arriving at the antenna is lower, because of the lossy line, the amount reflected is also lower. The reflected power is then attenuated by the lossy transmission line as it travels back to the transceiver. The result is the amount of reflected power actually arriving back at the transceiver may be quite small, indicating to the transceiver that the SWR is better than it really is. Working through the numbers illustrates this point. Suppose that the forward output power of the transceiver P_f = 100 watts, the actual SWR at the antenna is 3:1 (S = 3), and the loss of the transmission line L = 4 db. What is the SWR of the antenna system seen by the transceiver? The actual power arriving at the antenna $P_A = \log^{-1} [-L/10]\, P_f$ = 40 watts. The amount of power reflected by the antenna is $P_{rA} = [(S-1)/(S+1)]^2 P_A$ = 14.4 watts. This reflected power travels back to the transceiver being attenuated by the lossy transmission line as it goes. The amount of reflected power that arrives back at the transceiver is $P_{rT} = \log^{-1} [-L/10]\, P_{rA}$ = 5.7 watts. The SWR equation seen by the transceiver is $P_{rT} = [(S-1)/(S+1)]^2 P_f$. Rearranging this equation and solving for S yields a value of S = 1.6. So while the actual SWR at the antenna is 3 : 1, the SWR seen by the transceiver is only 1.6 : 1. The antenna system looks a lot better to the transceiver than it actually is. In the chapter on transmission lines (Chapter 24) of the 15th Edition of The ARRL Antenna Book (1988), there is a nice chart (Fig. 18) that allow you to figure out all of this graphically. I assume that this chart has been retained in more recent versions of the antenna book..

This example raises an interesting situation. When perfect no loss transmission line was used, the transceiver saw the real antenna SWR of 3 : 1. As a result of this high SWR, the transceiver's protective circuitry kicked in limiting the transceiver's output to 16 watts. Since the transmission line was lossless, 16 watts was delivered to the antenna. In the above example, the antenna SWR is still 3 : 1, but the transceiver sees the SWR as only 1.6 : 1. The transceiver thinks the antenna system is great, its protection circuitry does not kick in, and it pumps a full 100 watts into the transmission line. Of that 100 watts, 40 watts actually reaches the antenna. With the lossy line over twice as much power is delivered to the antenna. The lossy line actually produces a 4 db system gain! Building a poor antenna and then trying to compensate for it by using lossy coax is no way to design an antenna system. However, it does point out the fact that when designing a system, you have to consider all the parameters. There are broadband applications in which a 3 : 1 antenna SWR may not be avoidable. In such a situation, the system designer may have to look more closely at the loss characteristics of the transmission line.

The conclusion that can be drawn from this is that the threshold SWR, as seen by the transceiver, is about 2:1. An SWR above 2:1 will result in a power loss that will be noticeable at the receiving end. An SWR of less than 2:1 will not create a noticeable drop in power. In terms of perfection, tuning your antenna system for an SWR of less than 1.5:1 will result in full output power from your transceiver and negligible reflection losses at the antenna. Spending a lot of time trying to reduce your SWR from 1.5:1 to a perfect match of 1:1 is generally not time well spent. From a practical stand point, an SWR of 1.5:1 is indistinguishable from a perfect match of 1:1.

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